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Study on Cloud Properties derived from
Meteosat Second Generation Observations

Final Report

Rutherford Appleton Laboratory
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Prepared by Rutherford Appleton Laboratory.

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P.D.Watts, C.T.Mutlow, A.J.Baran¹, A.M.Zavody

¹ Affiliation: UK Meteorological Office
Executive Summary

This report contains the results of a study into the potential for cloud parameter retrieval of the Meteosat Second Generation satellite SEVIRI instrument to be launched in 2000.

An extensive literature survey was completed and from this, and our experience with ATSR-2, a selection of the SEVIRI channels, cloud products and retrieval methodology were identified for detailed study. These areas are reported in WPs 1.1, 1.2, 1.3 and 1.4.

The proposed retrieval methodology of optimal estimation (OE) required a detailed study of cloud and atmospheric radiative transfer and the derivation and testing of the resulting models constitute WPs 2.1 and 2.2.

The instrument data adopted for testing of the proposed retrieval method are described in WPs 2.3, 2.4 and 2.4a. The principal instrument used was the Along Track Scanning Radiometer–2 (ATSR-2) which carries all but one of the identified SEVIRI channels and has sufficient data coverage and ground resolution to test all aspects of the proposed method. It was originally conceived that High Resolution Infrared Sounder (HIRS) data would be used to supply measurements for the channel not covered by the ATSR-2 (8.7 µm). However, the limitations of the HIRS data both spectrally and in spatial resolution, and the availability of much better specified MAS (MODIS (Moderate resolution Imaging Spectrometer) Airborne Simulator) data shifted the emphasis during the execution of the study. In the event, HIRS data was not studied, a limited amount of MAS data was studied but most of the analysis of the retrieval behaviour was performed using ATSR-2 data.

The original workpackage description included WPs 3.1, 3.2 which was to thoroughly test the visible and infrared radiative transfer models. However, this testing was completed during the derivation of the models and is thus contained within WPs 2.1 and 2.2. There is no separate documentation covering the original WP3 as was agreed at the Second Progress meeting.

The proposed retrieval method and its application to the data described above constitutes WP4.

Suggested adaptations of the methodology in the light of the results of the study and the especial characteristics of SEVIRI and the geostationary platform are discussed in WP5.

Acknowledgements

In addition to the useful comments and feedback received from the staff at EUMETSAT during the study progress meetings we are indebted to the NASA Langely Research and Goddard EOSDIS Distributed Active Archive Centers for prompt and helpful supply of the MODIS AS data used in the study.
Outstanding Issues

All issues relating to the study, its outcome and potential adaptation in an operational scheme are dealt with in detail within the report. The study successfully demonstrated the proposed cloud parameter retrieval method using ATSR-2 and MAS data but raised many issues relating to the details of its implementation. Those issues which we regard as requiring special attention, further work or suggest a different approach are highlighted here.

- **Ice cloud optical properties.** The properties used in the study were ‘state of art’ but limited to a single cloud type definition and particle shape. There were clear inconsistencies between the short and long wavelength measurements using these properties which could partly be due to the cloud type used. The issue here is to more fully represent the known characteristics of different types of ice cloud and establish a method of type discrimination from the data. A related issue is whether these problems, through the combined retrieval method, are seriously compromising the accuracy of some parameters that would be better estimated using a less ambitious approach.

- **Nighttime data inversion.** The scheme showed that SEVIRI information as studied was too limited to robustly estimate the selected cloud parameters using nighttime data. This issue needs to be studied either with regard to reducing the retrieved state vector, or by the addition of extra information so that the problem becomes soluble.

- **Additional channels.** The value of SEVIRI channels not considered in the study to the retrieval needs to be established. It is possible that the information supplied by additional channels will increase the daytime retrieval accuracy and may enable nighttime retrievals.

- **Computational burden.** The studied retrieval method is moderately computationally intensive but, by the use of LUTs etc, not excessively so. If the method is to be adopted operationally, an estimate of its computational feasibility is required. In the event that it is not feasible in its suggested form, there are many options available to increase speed.

- **Radiative transfer model functionaliy.** The compatibility of the MSG MPEF (cloud-free atmosphere) radiative transfer models with the incorporation of the cloud model needs to be established. A related question is the inclusion of model parameter equivalent noise in the retrieval, which requires radiative transfer model gradients to be available.
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  - WP 1.2 Phase II base channel definition
  - WP 1.3 Phase II base product definition
  - WP 1.4 SEVERI strategy recommendation

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**APPENDIX A Bibliography Reviews**

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WP 6.1
1st progress meeting

WP 6.2
2nd Progress meeting

WP 6.3
Final presentation

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WP 5
Adaption to SEVERI

WP 4
Cloud property retrievals

WP 3
Radiative transfer calculations

WP 2
Descriptions

WP 1
Literature survey
1. Introduction

A survey of literature pertaining to the retrieval of cloud parameters has been completed. Bath Information Data Services science citation index has been used in part, covering years 1990–present but many entries are from citations within the later papers.

Forty three papers have been reviewed in detail and these reviews appear in Appendix A to this report. The reviews include the journal specification, a keyword classification of the paper contents and a brief summary of the points of interest therein. Any features of particular relevance to this contract are commented on, and if the paper is considered to be especially important as a model, or reference source, for further work within this contract it is flagged as such.

The 43 papers are not an exhaustive list by any means although we feel that within them the current state of art for cloud property retrieval is contained. 58 Further papers which we have not reviewed in detail but which are relevant or cover more peripheral subject matter are listed in Appendix B.

In the following discussion, references to the reviewed set of papers is given by a number [30], and to the unreviewed list as (30). Papers identified as key to the study are flagged as [30 U ].

2. Overview

Derivation of cloud properties from satellite sensors has been investigated and pursued from the earliest days of global monitoring satellites (). However, it is not the purpose of this report to describe the history of cloud monitoring, rather to review the literature pertaining to the key aspects of such. Hence the following discussion is based around the key areas of importance:

Detection identification of pixels containing cloud
Classification classification as to cloud type
Optical Properties particle single scattering properties
Cloud Radiative Transfer cloud multiple scattering
Atmospheric Radiation gaseous transmission and clear atmosphere radiance
Cloud-Atmosphere-Surface RT radiative transfer in the full system
Channels and Products
Auxilliary information constraints from information other than the satellite measurements
Data inversion deriving properties from measurements

2.1 Detection

Clearly a crucial first step in an operational cloud properties algorithm, this task is not directly an objective of the present study and is dealt with comprehensively as part of the MSG MPEF (hereafter MM). Consequently, we have not attempted to review the state of knowledge on this subject. Of the reviewed papers, [2], [9], [18], [19], [23], [29], [33], [36], [39] and [40] are concerned, in part, with cloud detection.

2.2 Classification

Classification in the sense of determination of the ‘traditional’ cloud type (altocumulus etc), does not feature significantly in the literature reviewed. The notable exception is the case of thin cirrus [14], [16], [22], [23], [26], [27], [39], [41]. This is a little surprising considering the wealth of available classification methods and the constraints that the determined class could place on the retrieval of properties. At the very least, a class decision could provide a good initialisation of a retrieval procedure.

The reasons for this apparent omission may be that cloud modelling for parameter retrieval is still a relatively primitive business, clouds are normally assumed to be single plane-parallel layer, single phase and to consist of a particular particle shape and size distribution. Class information is therefore only useful to suggest whether the results are reliable or appropriate given the cloud conditions.

A recent surge of effort towards modelling the radiative transfer of realistic three-dimensional cloud structures (2), (6), (14), (15), (16), (17), (36), may eventually lead to proper handling of these effects in property retrieval. In the shorter term it is perhaps likely that correction factors for 3-D to plane-parallel radiative properties may become available, in which case class information may become useful. (See also section 4.)

Perhaps the most useful aspect of classification is in the specification of the particle size and shape distribution to be used in the interpretation of the measurements. Such information is very unlikely to obtained from the measurements alone and a growing body of information on size distributions in (particularly) ice clouds [20], (38), (39), (40), (41), may lead to the
possibility of including class information usefully in a retrieval system. This sort of approach appears not to be in common use; water clouds are represented adequately by standard size distributions of spheres and the radiative properties are determined by the effective radius. Treatment of ice clouds is at a primitive stage where only recent developments have made it possible to move away from equivalent spheres to realistic crystal shapes and size distributions are poorly characterised. As noted, we may expect this situation to change.

2.3 Fundamental optical properties.

Although there are a few references to the use of statistical or empirical relations in cloud parameter retrieval [14], [23], [25], [38], all the reviewed methods rely fundamentally on theoretical calculation of cloud radiative effects. This is for the reason that empirical relations require substantial amounts of empirical data of which, in the field of cloud microphysical and bulk properties, there is very little.

Consequently, the fundamental optical properties of the absorbing / scattering cloud particles are central to the interpretation of remote radiance measurements. These properties can be reduced to two areas; a) wavelength dependent refractive indices of the hydrometeors and b) single scatter properties of the particular size and shape distribution.

a) Regarding refractive indices, the hydrometeor composition is universally assumed to be pure water. Any exceptions can be regarded as of too rare occurrence to concern us here.

The latest and most accurate values of refractive index derived from the literature should be used. At the moment, it would seem that Kou et al. (59) is state of art for the shortwave region. For water, differences of around 15% were found compared to the most used Hale and Querry (60) but good agreement with others (61), (62). Warren’s (63) view of possibly 100% errors for ice in the near-infrared region appear ‘pessimistic’ according to Kou et al. and agreement to within 22% (at 1.85µm) was found. At 1.6 micron, agreement to better than 5%. The situation for the infrared would need to be reviewed similarly.

State of art water refractive index measurements are generally assumed to be be effectively error-free although some authors have used it to explain errors in their retrieved cloud properties [34]. It is not a question which need concern us here; the best available refractive index information should naturally be used.

b) The single scattering properties of spheres are obtained straightforwardly and accurately through Mie calculations (42). The situation with ice crystals is less favourable and the specification of both the shape and size distributions and the calculation of optical properties of these complex shapes not generally subject to an exact treatment.

On the question of shapes, or ‘habits’, the available data from aircraft mounted probes suggests a range of possibilities from pristine hexagonal columns and plates to more complex and random aggregates and quasi-spherical objects (41). Mixtures are common if not the norm, although there is perhaps evidence that the simpler shapes prevail in the dynamically uplifted air of midlatitude frontal systems whilst complex shapes prevail in convectively active clouds (43). Size distributions are equally hard to pin down with difficulty measuring the occurrence of the smallest (< 20µm) crystals (40), (41). Parameterisations of the size and shape distributions have been attempted [20], [39].
Retrieval schemes reviewed use treatments which range from the (mostly) early efforts using Mie theory and equivalent spheres [14], [21], [22], [29]; to early attempts to simulate crystals with infinite cylinders [41], [27]; and more recently using hexagonal columns and plates [13], [26], [30], [31], [32], [35], [38], and fractal polycrystals to simulate aggregates [6], [7], [10], [12], [42].

The treatment of crystalline shapes has become possible for large size parameters (i.e. visible/near-infrared wavelengths or very large crystals at all wavelengths) using geometric optics (GO) approaches (44), (45), with sufficient accuracy. For small size parameters, which includes infrared channels and most common crystal sizes, there is still a fundamental problem calculating the single scatter parameters; the GO assumptions are invalid. There is some promise in the following methods: Discrete Dipole Approximation (46) (for arbitrarily shaped particles but so far only small size parameters); Finite Difference time domain methods (47) and Discretised Mie Formalism (48) (for hexagonally based objects of arbitrary size, but computationally very expensive); T-Matrix (49) (for oblate and prolate spheroid approximations to real crystal shapes); Anomalous Diffraction Theory (50), (51) and variants (an approximate method for large irregularly-shaped particles; no phase function information). This is a rapidly developing area of research and these methods cannot be regarded presently as having reached conclusions. An overview of the current state of the subject is given in Mishchenko et al. (28).

What is in no doubt is that application of Mie theory (i.e. spheres) for ice cloud radiative properties leads to substantial errors (3). It is a largely avoidable problem at visible wavelengths through GO but a real solution is awaited at infrared wavelengths.

A related question is how, or indeed whether, to attempt to link visible and infrared cloud optical properties. In terms of the property retrieval methods very few attempt [35], [17], [43] a direct link although authors using daytime 3.7 µm data in emission retrievals implicitly link the two wavebands when they remove the reflectance component [18]. The qualitative link has been made of course since the very earliest VIS/IR pictures of clouds and detection methods at least have used the combined information. This important subject will be discussed further in WP 1.4 SEVIRI strategy recommendation.

2.4 Cloud radiative properties.

Once the single scatter properties for a certain size and shape distribution are obtained, the radiative properties of the cloud are determined through multiple scattering calculations. A general review of multiple scattering methods is (52).

The first consideration, and one which is common to all methods in one way or another, is the diffraction peak of the scattering phase function. This can be several orders of magnitude stronger than off-peak scattering and to explicitly treat the unadjusted phase function leads to loss of accuracy either at angles away from forward scattering, or in the aureole region (at forward scattering), depending on the method used. For remote sensing of anything other than solar transmission in the forward scattering area, it is found to be quite accurate to consider the energy in the diffraction peak to be not scattered at all, but to be transmitted unaffected. This leads to a more isotropic phase function and requires only straightforward adjustments to the single scatter parameters (52). This method is widely used.

The multiple scattering methods employed are largely determined by the degree of inhome-
geneity required in the simulation of the cloud. This ranges from inhomogeneity only in the vertical (IHV) to inhomogeneity both in the vertical and horizontal (IHH, which might include cloud top structure and internal variations). Simulated clouds with only IHV are accessible to various methods: Successive Orders of Scattering, Doubling or Adding and Discrete Ordinates are common. The discrete ordinate method (31) is perhaps most used and has been shown to be sufficiently accurate providing enough ordinates (radiation streams) are employed in the solution. For space-based (backscatter) remote sensing of clouds, >16 streams are generally sufficient.

Clouds with IHH require the use of Monte Carlo methods (14), (15), (36), (53), although some IHH features can be handled with a method of Spherical Harmonics (2), (16), (17). Monte Carlo methods can in principle handle any degree of inhomogeneity although the computational requirements can become very large. A great deal of literature is appearing on the effects of IHH, generally in terms of the effect on global albedo rather than the effect on directional radiances and hence remote sensing. As we noted in section 2 current cloud retrieval schemes are generally of a simplistic nature and assume plane parallel clouds. Again, this is partly because of the difficulty of modelling realistic clouds and partly because current spaceborne sensors lack the spatial resolution and depth penetration to warrant anything more sophisticated.

IHV is rarely handled explicitly in retrieval although some authors have examined its effect on properties retrieved from single layer plane-parallel models [3], [4], [42], (26), and some have proposed corrections based on these studies (23).

The question of multilayer cloud has been most often avoided until recently. Methods to identify it through classification are suggested [26], [41] and some attempts to retrieve properties suggested (30) albeit in a case-study situation. Mixed-phase clouds have received still less attention [27], (56), (57), (58).

Although the discrete ordinates method is well established and commonly used for cloud property retrieval, it is still a relatively time consuming method and to slow to deal with the large tasks imposed by high resolution satellite image data. The most common solution is to store results of offline calculations and access them through look-up tables (LUTs) [1], [7], [9], [10], [11], [15], [17]. Another approach is to use LUTs for thin clouds but switch to analytic expressions of asymptotic theory for optically thick clouds [9], (23); analytic expressions often allow much faster inversion of the data.

The above discussion has centred around methods which are either in principle exact or are limiting cases (asymptotic). Various approximate methods can be used of which the most common are the class of two-stream methods (54). Although representing the radiation field as simply one upward and one downward stream (it is a specific case of discrete ordinates), non-isotropic behaviour is retained in the solution and through specification of the angular characteristic of the source function. The cloud model is necessarily simple. Because of the anisotropic nature of the scattering phase functions for cloud particles and the collimated nature of solar illumination, two-stream methods are not suited to interpretation of reflectance measurements (visible, near-infrared and daytime shortwave infrared). However, sufficient accuracy may be available in the infrared region because the Planck source function is isotropic, radiance fields (internal and external to the cloud) are generally diffuse and absorption is generally high; thus details of the scattering phase function become much less important. Various authors have used two-stream methods to interpret infrared measurements.
Another approximate approach often used in the infrared region is to model the cloud as simply non-scattering, leading to a very simple treatment [5]. The effects of multiple scattering can be calculated using one of the standard methods described and the results incorporated into a parameterised wavelength dependent emissivity [37], [38].

2.5 Atmospheric radiation

Effects of the ‘clear’ atmosphere path on radiance observations arise through gaseous and aerosol absorption and emission and, in the shorter wavelengths, aerosol and Rayleigh scattering. If we leave aside the question of cloud top pressure analysis through ‘CO2 slicing’ and related methods (comprehensively dealt with in MM), then the principle absorbing gas that need concern us is water vapour. It has a moderate effect on the infrared channels and a rather smaller effect at the visible wavelengths. Being of high variability and low predictability makes it an awkward gas to deal with, but it is mostly confined to the lower part of the troposphere and is often therefore mostly below cloud level.

Other gases such as ozone and CO2 are of less importance to the ‘window’ channels. Ozone is relatively well measured by several platforms (including MSG) and being mostly located well above cloud levels has readily quantifiable radiative effects. CO2 is stable and well mixed although present at all levels.

Aerosols are consistently present in the atmosphere and are poorly quantified both in their abundance and radiative properties. Some types of aerosol are mostly confined to the tropospheric boundary layer and therefore considered to be below cloud level. This is not true of stratospheric aerosols, both background and as a result of volcanoc eruption. Their low temperatures can mean that infrared radiances are significantly affected. Visible reflectances from aerosol are generally quite low but not necessarily so especially at the shorter wavelengths. The same is true for Rayleigh scattering but in this case the effects are quantifiable. Very little of the reviewed literature considered the effect of aerosol on the particular measurements employed.

Footnote 1: Two stream methods assume some simple form for the scattering and source functions and these are necessarily near-isotropic and cannot represent the sharp forward peak of real phase functions. The overall asymmetry (g) is accounted for however by correct balance between forward and backward hemispheres. The result is generally good accuracy for hemispheric fluxes but directional radiances can be poor, particularly in the case of thin clouds. The reason in this case is that forward scattered (transmitted) radiance is modelled as exiting the cloud in a near isotropic manner whereas it mostly exits at small (near nadir) angles. Hence calculations using two-stream tend to underestimate near nadir radiances and over estimate near limb radiances. As an example; the somewhat extreme case of ice cloud at 200K overlying a surface radiating at 290K, optical depth 4 and for 11 microns (ssa=.473, g=0.969), the nadir BT is around 10 K cold (compared to exact DISORT calculations) and the 80deg zenith BT 1.5K warm. The Two-stream model used was a hemispheric mean implementation. (In this case, ignoring scattering all together and using an absorption formula based on the absorption part of the extinction coefficient was much more accurate.) [We should note here that we have found that by applying the standard formulae (to ssa, optical depth, and g) following truncation of the scattering forward diffraction peak, we appear to improve the two-stream results considerably. Errors in the above example using this method are reduced to less than 1 K at all angles. However, the method would need to be checked more rigorously and under more variable conditions.]
The above perhaps over-emphasises the problem of atmospheric effects. We should note that cloud effects on visible reflectance and infrared radiance is mostly far greater than the atmosphere effect. Thick high cloud, for example, will reflect typically > 60% of incident solar radiation compared to ~1-4% from aerosols and Rayleigh scattering; the transmission of the atmosphere above it will be in excess of 98% for all window wavelengths. Atmosphere effects start to become significant as the cloud either thins to allow transmission of radiance from lower levels, or lowers in altitude to leave a scattering and absorbing atmosphere above.

The reviewed literature shows clear atmosphere effects being handled in three different ways.

A) Assumption there is no effect

Clearly a straightforward method, this is applied almost always for above cirrus transmission at all wavelengths [13], [14], [15], [18], [22] etc.; here it is probably justified especially if straightforward ozone effects are included. Visible reflectances for clouds at all levels are often assumed unaffected [7], [10], [11], [12], etc., and this may be a good approximation for narrow band radiometers for the longer wavelengths (> 0.8 µm). Special cases like stratocumulus decks in anticyclonic conditions are also often assumed to have little absorbing or scattering above the cloud. All these examples could be invalidated by the presence of a heavy stratospheric aerosol loading.

The decision to neglect atmospheric effects depends on the characteristics of the target and the wavelength and bandwidth. [8] for example discusses the effects of aerosol and gaseous transmission in the (relatively clean) 3.9 µm window channel of GOES and concludes there is no significant effect. On the other hand (37) shows that even the particular LOWTRAN version used to correct 2.2 µm reflectances for above cloud (stratocumulus) absorption can affect the outcome of effective radius retrieval significantly.

B) Estimate from local clear pixels

This is by far the most popular method judged by the reviewed papers. Local clear pixels are used to specify the upwelling reflectance or radiances [16], [17], [18], [29], [27], [29], [38], (55) due to the clear atmosphere alone. By so doing it circumvents actual knowledge of the atmospheric state and for some parameters (e.g. land surface reflectance, aerosol loading) may be the only way of proceeding. What the method cannot achieve is to estimate where in the atmosphere the radiance originates or therefore what is an above cloud or below cloud effect. Thus, for infrared retrievals, the main utility has been in estimating upwelling radiance at cirrus cloud base on the reasonable grounds that there is no above cloud absorption in this case.

Other limitations of the method are the relatively complex (multi-pixel) analysis required, awkward decisions required concerning area sizes and thresholds and the reliance on clear pixel detection. There is also the inherent assumption that the atmospheric / surface state is only slowly changing locally.

C) Radiative transfer using auxiliary data
In this case, atmospheric radiance effects are predicted using radiative transfer models from a knowledge of the atmospheric state. The information can come from sondes ([8], [30], generally in case study scenarios), other instruments (e.g. TOVS soundings, [36]) or numerical weather prediction (NWP) fields (e.g. see MM). This is clearly an attractive method because in principle an exact treatment of the effects can be calculated. It does rely however on a) the auxiliary data being sufficiently accurate and comprehensive (NWP water vapour might be inaccurate and NWP aerosol probably does not exist) and b) the radiative transfer being accurate and fast.

2.6 Cloud-atmosphere-surface system

The radiative transfer of the combined system, that is; surface, atmospheric gaseous and non-cloud particulate scattering and absorption and cloud scattering and absorption, is achieved in a variety of ways. For the most part, and as alluded to in section 5, authors model the system in a simple manner; atmospheric effects are considered as boundary influences on the cloud. Thus, by estimation of upwelling infrared radiance at cloud base, authors deduce cirrus parameters by the differential transmission and emission resulting at top of atmosphere [13], [16], [17], [18], [22], [26], [27], [28].

Where possible, assumptions are often made to simplify the processes. Ozone absorption is a single transmission correction to the incoming and outgoing visible radiance (22); for the purposes of cloud-surface multiple reflection, both are considered lambertian reflectors (22), (23); upwelling infrared radiances are considered isotropic; radiances in one pixel are assumed not to be affected by emissions in adjacent pixels; etc.

Most of these approximations could be treated in an exact manner using standard multilayer implementations of the multiple scatter methods outlined in section 4. Some examples of ‘exact’ treatment in this way exist in the literature but mostly these calculations are done to show the approximations are valid. The problem is of course the large computational burden performing discrete ordinate calculations (for example) on a many layer system. The option of storing precalculated values in LUTs becomes cumbersome if the tables have to be expanded from three-dimensional geometry and two cloud parameters to also include a multitude of further variable (varying amount of Rayleigh scattering, different levels of surface reflection etc).

Consequently, in many areas, exact calculations are performed and ‘undesirable’ atmospheric effects parameterised in a simple fashion [15]. Examples are Rayleigh scattering correction for cloud reflectance (1) and effective emissivity for ice cloud multiple scattering effects [37], [38].

A related methodology, and one for which there seems to be a predilection in the literature, is to ‘remove’ unwanted radiance contributions from the measurements. Thus there are schemes to remove the solar component of daytime 3.7 µm radiances [18], [32], to allow use of thermal emission retrieval methods, or indeed, remove the 3.7 µm emission component [1], [8] to allow use of reflection measurements. Whilst in some cases (e.g. optically thick cloud) the removal of these terms may be unambiguous and subject to straightforward parameterisation, there are times when such effects cannot be physically separated quite so easily. In the above example, if the cloud becomes optically thin, the solar component is partly transmitted and then its reflection from the surface becomes a contribution to the diffuse transmission part of the radiative transfer. More discussion on this slightly philosophical
subject of data inversion is given in section 9.

2.7 Channels and cloud products

This section summarises the wavelength regions used for cloud parameter retrieval and attempts to give some idea of their importance as gauged by the weight of literature devoted to them. Although some (future) radiometers (e.g. MODIS, [9], (22)) and aircraft based spectrometers have significantly many more wavebands than SEVIRI we restrict ourselves to comment on those equivalent or closely related to the SEVIRI complement, and then only in detail on those which are related to cloud parameter retrieval. The discussion naturally leads to the cloud parameters that are derived from the information. Note that this section is an overview of the literature; for detailed discussion on the products and retrieval methodologies refer to section 1 of the WP1.4.

7.1 Visible channels 0.6, 0.8 µm

Visible channels have been used extensively for daytime cloud detection and, because of the negligible cloud particle absorption, for estimation of optical depth [1], [2], [3], [7], [8], etc. The 0.8 µm channel is preferred by some authors [9], (22) because of the lower Rayleigh and aerosol scattering and a very black ocean surface. Over vegetated land the 0.6 µm channel is preferred in the case of transmitting clouds because of the high surface reflectance at 0.8 µm. There is some ozone absorption at 0.6 µm.

Visible channels on Meteosat, GOES and AVHRR are all relatively broad and include some, although not the strongest, water vapour lines. The ATSR-2 (and future AATSR) 0.87 µm channel and MODIS equivalents are narrower and better placed to avoid absorption features.

In conjunction with 11 µm window channel infrared, visible channels are used in bi-spectral classification techniques [1] [2], [16], [23], [28], [39], [40], [41]; and with 1.6 or 2.2 µm reflectances for optical depth and particle size estimation [3], [7], [9], [10], [11], [12], [34], [42], (22), (26), (27). Optical depths typically in excess of ~60 can be retrieved before reflectance saturates.

7.2 Near infrared 1.6 µm

1.6 µm channels have only been present on a few spaceborne instruments; Landsat and ATSR−1 and −2. On the ATSR instruments its main perceived role was as a reflectance channel for cloud-clearing with the advantage over visible channel of discrimination of water cloud over snow/ice surfaces. There is a relatively clean and wide window at 1.6 µm except for a small amount of CO₂ absorption which is readily quantifiable. At 1.6 µm Rayleigh scattering and ocean reflectance are negligible and land surface reflectance is moderate. Cloud particle absorption is only moderate so that although the channel is used for particle sizing [3], [7], [9], [10], [11], [12], [34], [42], (22), (26), (27), visible channel optical depth information is required for thinner clouds. A further characteristic is the cloud phase identification allowed by the higher absorption by ice phase particles [9], [11], (22), (25).

7.3 Infrared 3.9 µm
The 3.9 µm (or in its AVHRR and ATSR form 3.7 µm) channel has been extensively used both as a solar reflection channel and as a thermal emission channel. Of the three wavelengths traditionally used for sea surface temperature retrieval (3.7, 11 and 12 µm) 3.9 µm lies in the cleanest window. This would make it the most useful were it not for the lower signal levels at terrestrial temperature levels and the presence of a solar reflection component during the day. The principle absorber is water vapour and there is effectively no Rayleigh scattering and low aerosol effects [8].

Cloud particle absorption is strong making it the most sensitive of the ‘shortwave’ reflectance channels used for particle sizing (1.6, 2.2, 3.9 µm) and the one which senses sizes closest to cloud top (26). Its use in this context is not helped by the thermal emission which is also present and typically of the same magnitude. Consequently it is always used in conjunction with 11 or 12 µm measurements to specify the thermal component [1], [2], [3], [8], [9], [22], [27].

Because 3.9 µm radiance is scattered significantly it can be used with the 11 µm at night (or less convincingly during the day with the solar component estimated and removed) for the estimation of particle size and longwave optical depth [13], [14], [17], [18], [19], [22], [26], [32], [38], (30). The effects are strong enough (22) that even opaque low clouds of small drop size (e.g. fog) can be detected with 3.9/11 µm brightness temperature differences (BTDs).

Infrared channel calibration with precision blackbodies give the reflectance aspects of the 3.9 µm channel something of an advantage over near infrared wavelengths which are difficult to calibrate accurately.

7.4 Water vapour 6.2, 7.3 µm

The strong atmospheric absorption present in these channels has largely precluded them from use in cloud retrieval methods. Differences in cloud optical properties between 7 and 11 µm are also small so that little signal results from the cloud. Because they are in absorbing regions they can be used for cloud top height assessment (MM, [21]). Their principle use for the cloud parameter retrieval under study here, is likely to be to supply information on water vapour for correction of other channels (there is no reference to this technique in the reviewed literature).

7.5 Infrared 8.7 µm

There are relatively few references to this channel in the literature since only the HIRS instrument has (temporarily) carried it in space [5], [27]. Most recent work has been based on theory and spectrometer or interferometer data [6], [19], [33]. Placed in a relatively poor window region (again, water vapour being the principal absorber) its usefulness lies in the significantly lower particulate absorption than in the 11–12 µm region. The prospect therefore is of improved cirrus detection and estimation of optical depth and particle size [27]. An 8-11 µm combination, although unlikely to be able to estimated sizes larger than possible with a nighttime 3.9-11 µm combination, can be expected to achieve this during also the daytime. Another potential advantage is that the size parameters of 8 and 11 µm are much closer than 3.7 and 11 µm (see section 3) so that the derived optical properties are likely to be more consistant.
7.6 Infrared 9.7 µm

Not a wavelength used for cloud parameter retrieval, the ozone information derived could have some potential application for correction of absorption effects in other channels, notable the 0.6 µm visible. There are no references to 9.7 µm channels in the reviewed literature.

7.7 Infrared 10.8 and 12 µm

The split window infrared pair have been on many satellite instruments (HIRS, AVHRR, ATSR) and are principally used in combination for sea surface temperature estimation through the differential water vapour absorption at the two wavelengths.

Regarding cloud properties, differences in emissivity at these two wavelengths are small but give rise to BTDs which can be used to detect thin cirrus [14], [29], [43]. Property retrieval though, is limited unless the channel is used in conjunction with 3.7 µm 8.7 µm or visible channel reflectances.

Many authors have estimated optical depth using more or less sophisticated radiative transfer models, assumptions of particle size and shape and estimates of upwelling radiation at cirrus cloud base.

7.8 Infrared 13.4 µm

This channel is used for cloud top pressure retrieval (MM) and apart from the use that this product may have in atmospheric transmission corrections and cloud typing, is not considered further here. No references to wavelengths above 12 µm were made in the reviewed literature.

2.8 Auxiliary information

By far the most common source of auxiliary information used in cloud parameter retrieval is that obtained from local clear pixels as discussed in section 5.

In the field of algorithms intended or suitable for operational use rather than campaign experiments, very little auxiliary information is used. ISCCP uses TOVS humidity and temperature soundings for specifying clear atmosphere effects [1], [36], (10, (11).

Sondes are frequently used to supply cloud top pressures from temperature measurements [8], and to calculate upwelling radiances at cirrus cloud base [30], but this is restricted to intensive campaign studies.

The use of NWP fields does not appear in the literature (except MM), although it is potentially very useful. Climatological estimates are most often used in simulation to show an insensitivity to the parameter in question [8] although background aerosol levels and ozone concentrations are occasionally employed to correct measurements (22).

Synergy between instruments has been suggested [4] and used [23], [30] occasionally; in the first case to use microwave liquid water estimates to improve near infrared particle size estimation and in the second case to use high resolution AVHRR to specify cloud fraction in the HIRS field of view.
Most reviewed papers nevertheless extract only the cloud parameters that are possible using the self-contained information of the instrument with local clear pixel information and broad assumptions to close the problem of inversion.

**2.9 Data inversion**

Methods employed to invert radiance data to cloud parameters are quite diverse. As noted earlier, however, lack of an observational database means that they are almost exclusively not of a statistical nature; no neural networks (except in classification / detection), no regressions. All methods are based on explicit radiative transfer albeit of varying degrees of complexity.

Even so, methods range from fitting of envelopes of curves to scatters of data where the fit is a function of two or more parameters [2], [14], [29], to explicit inversion of analytic forms of the radiative transfer [9], [13], [22], [35], (23), (55), statistical relations based on radiative transfer [25] and numerical inversions of numerical radiative transfer [3], [9], [11], [17], [24], (22), (23). Results therefore range from a single value for a large area, e.g. a microphysical index for a region, to individual pixel retrievals.

The methodology that is adopted depends on the nature of the problem. If well posed (for example retrieval of shortwave optical depth and effective radius from 0.87 and 1.6 μm channels with clean atmosphere and dark underlying ocean), then single pixel retrieval based on direct inversion of the radiative transfer is possible. Ill-posed problems (e.g. optical depth and particle size from 3.7 and 11 μm radiances for optically thin clouds, no knowledge of atmospheric temperature or humidity), implies that direct single pixel retrieval is not possible and constraints have to be sought elsewhere. In this case atmospheric and surface conditions are assessed by monitoring clear radiances away from but close to the cloud, and particle sizes are judged by reference to the statistical nature of the observed radiances.

As sensors start to carry more channels they are able to constrain the inversion problem more successfully and there is generally a lower tendency to resort to statistical determinations and more emphasis on combined retrieval of all relevant parameters in a single pixel. This can only go so far as there is a limit to which passive sensors can provide information from a single pixel and prior information about cloud fields from NWP will not be useful in the foreseeable future. There will probably always be a case for statistical characterisation of the cloud field from the sensor data. However, a growing availability of auxiliary data from other platforms, from NWP, from improved climatologies, combined with greater available computing power for analysis, is allowing more to be achieved from the single pixel approach.

There are some signs that inversion methods more soundly based in theory are gaining favour. This can be traced in a range of papers from the use of related iterative fitting methods [3], [17], [32], [35], [38], to those directly employing optimal estimation [3], [10], [11], [23]. Whilst this is not necessarily going to improve dramatically the accuracy of products obtained, it will lead to a more rational approach and an ability to use auxiliary data and constraints in a more powerful way.
WP 1.2 BASE CHANNEL SELECTION

The choice of channels for study in Phase II is partly a result of the literature survey but has to be mostly determined (at least in terms of the degree of modelling required) by the chosen retrieval strategy. Therefore, we are very brief here, using a table to describe the required modelling, and refer the reader to WP1.4 for justification of the recommendations.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Atmospheric / surface model</th>
<th>Cloud model</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIS 0.6</td>
<td>Online $O_3$ (0.6 µm), $CO_2$ (1.6 µm) absorption optical depth&lt;br&gt;Online simulated surface reflectance database</td>
<td>DISORT MS LUTS based on Mie $R_e$ (1–23 µm), GO Ice 25–400µm various habits; $\tau$ (1–256)</td>
</tr>
<tr>
<td>VIS 0.8</td>
<td>Offline aerosol effects (magnitude only)&lt;br&gt;Offline climatological water vapour transmission calculations&lt;br&gt;Offline Rayleigh scattering (0.6 µm)</td>
<td>Beam bi-directional and diffuse reflection and transmission functions</td>
</tr>
<tr>
<td>NIR 1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR 3.9</td>
<td>Full gaseous absorption fast model (~RTTOV)&lt;br&gt;Profile dependent surface temperature&lt;br&gt;Climatological land and sea emissivities (wind independent, angle dependent)&lt;br&gt;Offline aerosol effects (magnitude only)</td>
<td>DISORT MS LUTS based on Mie $R_e$ (1–23 µm), GO/T-Matrix/ADT (tbd) Ice 25–400µm various habits; $\tau$ (1–256)&lt;br&gt;Directional transmission, emission and, diffuse reflection, transmission functions</td>
</tr>
<tr>
<td>WV 6.2</td>
<td>Not required</td>
<td>Not required</td>
</tr>
<tr>
<td>WV 7.3</td>
<td>Not required</td>
<td>Not required</td>
</tr>
<tr>
<td>IR 8.7</td>
<td>Full gaseous absorption fast model (~RTTOV)&lt;br&gt;Profile dependent surface temperature&lt;br&gt;Climatological land and sea emissivities (wind independent, angle dependent)&lt;br&gt;Offline aerosol effects (magnitude only)</td>
<td>DISORT MS LUTS based on Mie $R_e$ (1–23 µm), GO/T-Matrix/ADT (tbd) Ice 25–400µm various habits; $\tau$ (1–256)&lt;br&gt;Directional emission.</td>
</tr>
<tr>
<td>IR 9.7</td>
<td>Not required</td>
<td>Not required</td>
</tr>
<tr>
<td>IR 10.8</td>
<td>Full gaseous absorption fast model (~RTTOV)&lt;br&gt;Profile dependent surface temperature&lt;br&gt;Climatological land and sea emissivities (wind independent, angle dependent)&lt;br&gt;Offline aerosol effects (magnitude only)</td>
<td>DISORT MS LUTS based on Mie $R_e$ (1–23 µm), GO/T-Matrix/ADT (tbd) Ice 25–400µm various habits; $\tau$ (1–256)&lt;br&gt;Directional emission.</td>
</tr>
<tr>
<td>IR 12.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR 13.4</td>
<td>Not required</td>
<td>Not required</td>
</tr>
</tbody>
</table>
WP 1.3 BASE PRODUCT SELECTION

As in WP 1.2 the rationale for the base product selection arises to a large extent from the adopted strategy from WP 1.4. So again, we make this section brief and based on a table, summarise the situation and refer the reader to 1.4 for details. We refer to two scenarios: a visible/near-infrared and infrared independent treatment, and our recommended combined treatment.

| Visible/near-infrared – Infrared Independent Scheme |  |
|---|---|---|---|---|---|---|---|---|
| **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** |
| **products** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** | **VIS/NIR** |
| **τ** | **Phase** | **Rc** | **D** | **ε** | **Phase** | **Re** | **D** | **Tc** | **ε** |
| Approximate range | 1 – ~60 | Water Ice Mixed / unknown | 3 − 23 µm | 30 – 200 µm | f(τVIS,Rc/D) | Approximate range | 0.3 – 1.0 | Water Ice Mixed / unknown | 3 – 23 µm day | < ? µm day | 180 – 290 K | f(ε,Rc/D) |

| Visible/near-infrared – Infrared Combined Scheme |  |
|---|---|---|---|---|---|---|---|---|
| **τ** | **Phase** | **Re** | **D** | **Tc** | **LWP / IWP** | **ε** |
| **Products** | **Products** | **Products** | **Products** | **Products** | **Products** | **Products** |
| ** visibly depth (@0.5µm)** | **Cloud thermodynamic phase** | **Effective drop size (water only)** | **Crystal maximum dimension (ice only)** | **Cloud top temperature** | **Liquid/ice water path (Derived)** | **Effective emissivity (Derived)** |
| Approximate range | 1 – ~60 | Water Ice Mixed / unknown | 3 – 23 µm day | 30 – 200 µm | 180 – 290 K | f(τ,Rc/D) |

*Note that in the execution of the study the combined scheme was adopted. Also, a further product was added - the fractional cloud cover in a pixel - and the cloud top temperature was represented as a cloud top pressure (an equivalent treatment). The derived products of LWP and ε were not studied further.*
1. Introduction

We firstly give a structured overview of the methodologies and techniques reviewed as part of the Phase I study. For the cloud products we discuss the ‘minimal’ requirements for retrieval and then the implications and benefits of particular enhancements to the minimal method. Enhancements are identified by bold italics. Because EUMETSAT require a recommendations as to strategy, we identify the recommended method or technique by underlined bold italics.

We should stress again; there is considerable overlap between products; particle size retrieval is intimately linked to optical depth and phase identification, for example. Therefore, rather than proceed through all products in turn with invariable repetition, we split the analysis broadly by discussing optical depth retrieval from the standpoint of daytime reflectance channels and temperature / emissivity retrieval from the standpoint of day and nighttime infrared retrievals.

This discussion leads to the strategy we recommend for retrieval of cloud parameters from MSG SEVIRI radiance data which of necessity must be at the level of overview. This recommendation is described by firstly explaining some basic guiding principles and then by expanding on the proposed methodology and demonstrating both its benefits and potential drawbacks. Going from the guiding principles to a practical implementation will require research and experimentation and in part represents the tasks of Phase II of this study.

We finally give a very brief description of products that should be available, or which we strongly recommend should be available, to a cloud retrieval system from the MSG MPEF (MM). Much of the intermediate and auxiliary information identified to be useful in preceding sections is in fact available from this source and it is therefore very important to recognise and make full use of this.

2. Overview of cloud product retrieval

The literature survey carried out covered many years of research into cloud parameter retrieval and this in accounts for some of the diversity of approaches met. The first consideration is the extraordinary increase in computer power, both speed and memory, available now compared to only recent years, and the recognition that many techniques were employed in order to make the problem simply computationally feasible. Thus two-stream radiative transfer for example can be superseded in many applications now by more exact methods or by LUTs. Similarly, both NWP and archive climatologies / databases are now very complete.
The advantages of what we may call pixel resolution auxiliary data (that is e.g. NWP fields and radiiances calculated therefrom and climatological / archived land BRDFs interpolated to pixel locations) over locally derived values (where ‘local’ may in reality be quite distant) have to be weighed against inherent errors in the auxiliary data compared to the ‘in situ’ nature of the local data. Such a balance is delicate and we can only make recommendations at this stage and note (to reiterate) the tendency to move away from the local data methods where possible.

Here we give a summary of the visible and infrared cloud products in terms of the minimal retrieval requirements and enhancements.

**Product:** Cloud optical depth from visible reflectance, \( \tau \)

**Channels:** (0.6µm) 0.8µm (1.6, 3.7µm)

**Minimal technique:** LUT conversion of 0.87 µm reflectance function \( R(\mu, \mu_0, \phi, \tau) \) to \( \tau \) by bilinear interpolation. \( R \) precalculated with multiple scatter code for Mie scattering and single (c.f. ISCCP) gamma drop radius distribution. Suitable for water clouds; thick cloud everywhere and most optical thicknesses over ocean.

**Major limitations / error sources and relevant enhancements:**

A) Effects of land surface reflection transmission become large for optically thin clouds; the 0.6 µm channel can be employed over vegetated land to help, but the problem remains. As examples; an unaccounted surface reflection of 20% (lambertian) at 0.87 µm would lead to an error in optical depth \( \sim 5\% \) for \( \tau = 50 \), \( \sim 20\% \) for \( \tau = 16 \) and \( \geq 50\% \) for \( \tau = 4 \) (calculations for solar zenith angle 30°, view zenith 15° and azimuth 30°). Snow / ice surfaces present greater problems.

The underlying reflection (\( R_s \)) effect (for non-ice surfaces) can be adequately modeled (using standard cloud-surface multiple reflection formulae) providing \( R_s \) can be obtained with reasonable accuracy (in the above example, if \( R_s \) is known to 2% (absolute) the optical depth error for \( \tau = 4 \) would be reduced from 50% to around 5%). Thus, local clear pixel estimates may be of use in some situations but in most cases spatial variability will preclude this method (e.g. an area in southern France 80x40 Km contained 0.87 µm reflectances ranging from 18-32% with a standard deviation of 4.5%; 0.65 µm reflectances ranged from 3-12% with standard deviation 2.5% for the same area, both statistics from ATSR 1 Km data). Cloud fields can easily range unbroken (or at least not clear) for many hundreds of kilometres.

More promising, and with simpler application, is the use of archive global BRDF reflectances although values at the correct wavelength are required.

A third source is from recent SEVIRI data itself, using the most recent clear values for the appropriate time of day. This source should be available through the MM clear sky reflectance map product. It is not strictly a surface reflectance product, including all clear atmospheric effects; but may represent the best available information given the obvious spectral match, the inclusion of diurnal (geometry variations) and temporal information. There is also of course the potential to post process the clear sky reflectance map to remove aerosol and rayleigh effects, i.e. retrieve the surface reflectance. (Any resulting aerosol product itself would be useful in
the cloud analysis; see below.)

[The above discussion highlights the problem of implementing the spatial methods commonly employed in retrieval procedures. We could envisage for example, a local area retrieval over an ensemble of cloudy SEVIRI pixels where the underlying Rs is assumed not to vary and is estimated, along with the cloud parameters, by some minimisation technique. Errors of the size discussed would of course be introduced by the varying Rs.]

Although not an option for solving the surface reflection problem, the discussion does raise the possibility of using infrared estimates of optical depth for thin cloud over highly reflecting or poorly quantified reflecting surfaces. Estimation from the infrared clearly involves its own set of problems and this discussion is deferred till the next section.

B) Drop size dependence of visible reflectance is relatively small but would add significant errors to optical depth estimated assuming a single effective radius. For example; an assumption of a 15 µm drop size for a cloud of optical depth 30 when in truth the drop size was 5 µm would lead to an error of around 6, or therefore 20%, in optical depth. This is around the largest effect possible as the visible reflectance dependence on drop size is largest for drops sizes less than around 10 µm.

The inclusion of the drop size in the retrieval can be achieved by extending the reflectance calculation to \( R^{\text{87}} (\mu, \mu', \phi, \tau, R_e) \). Inversion of this, given the geometry and an estimate of \( R_e \), follows as before. \( R_e \) can, in the simplest case, be estimated from the cloud class / type (e.g. available from the cloud analysis of the MM). For example, fog could be assigned \( R_e = 4 \) µm; stratocumulus \( R_e = 10 \) µm; cirrus \( R_e = 40 \) µm etc. Although crude, the method is simple and would remove the largest errors from the optical depth retrieval.

The availability of two particle sizing channels on SEVIRI allows \( R_e \) to be estimated from the data directly. Estimation using the 3.7 µm data is achieved by firstly removing the thermal component by reference to the 11 µm radiance (thus inferring cloud effective temperature). The remaining radiance represents solely the cloud reflectance and is similarly a function \( R^{\text{37}} (\mu, \mu', \phi, \tau, R_e) \). The 1.6 µm channel data has no thermal component and is therefore directly a measure of \( R^{\text{16}} (\mu, \mu', \phi, \tau, R_e) \). Both of these can be inverted directly for \( R_e \) given the geometry and an estimate of optical depth. Estimates from the two channels have different characteristics and can be expected to be more or less accurate in different situations; this is discussed further in the section following our strategy recommendation. If the sole important cloud variable were optical depth, then the estimate of \( R_e \) from the 3.7 µm data assuming optically thick (large \( \tau \)) cloud would be sufficient. However, since \( R_e \) itself is important the problem clearly becomes one of radiance fitting by iteration; essentially updating the optical depth estimation with \( R_e \), followed by updating the \( R_e \) estimation with optical depth, until convergence to some level is achieved.

C) Phase dependence of the visible reflectance is a significant effect. For example; a cloud of \( \tau = 20 \) composed of water drops of \( R_e = 10 \) µm gives the same visible reflectance as a cloud \( \tau \sim 16 \) (i.e. 20% error) composed of hexagonal columns (maximum dimension \( D_m = 100 \) µm) or a cloud \( \tau \sim 13 \) (i.e. 35% error) composed of fractal polycrystals (\( D_m = 100 \) µm).

This implies that certainly cloud phase and probably particle shape need to be specified for optical depth retrieval of reasonable accuracy. The simplest approach (used by ISCCP) is to guarantee the scene observed is water cloud by thresholding at 273 K. A slight extension would be to also threshold at \( \sim 230 \) K to ensure ice cloud. This would still severely limit the observable cloud cover but has the merit of being extremely simple. Certain amounts of thin cirrus would transmit sufficient surface radiation to have an effective temperature of >273 K and would therefore be incorrectly identified. This threshold check would therefore have to be also limited to clouds of sufficient optical depth.

Next in complexity and reliability would be to extract phase through the cloud typing / class produced in the MM cloud analysis. We are not in a position to say how reliable this may be although it is likely to be superior
to the thresholding method since the thresholds (or similar) and other analyses are included. If not adopted as the preferred method, initialising the phase determination through the cloud type is a possible strategy.

Phase determination from the 1.6 µm reflectance is possible partly because of high absorption by ice relative to water and partly because ice crystals are normally larger than water cloud drops. This leads to reflectances at 1.6 µm which are (generally) lower for ice than for water - for a given optical depth. The caveat is important - there is not a simple threshold; ice clouds of high optical depth can give 1.6 µm reflectances higher than optically thin water clouds. The identification therefore must be done based on at least a preliminary estimate of optical depth, more reliably as part of an iterative adjustment scheme. Ambiguity can arise both for optically thin clouds and for particular solar-satellite geometries. For the example above (solar zenith angle 30°, view zenith 15° and azimuth 30°) the phase identification is unique (assuming hexagonal columns with minimum \( R_{\text{m}} \) of 30 µm for ice, and maximum \( R_{\text{c}} \) of 23 µm for water) at least as low as \( \tau = 1 \). For a case where the solar zenith angle is 60°, view zenith 15° and azimuth 30°, and according to the same criteria, phase identification is not possible for cloud of any optical depth.

The identification by way of the infrared channels is also possible, particularly the 8–12 µm and 11–12 µm combinations. As with the 1.6 µm method this is a result of absorption differences between wavelengths and in the infrared this leads to differential transmission / emission of the cloud. This method should perhaps be seen as complementary to the 1.6 µm method as it applies only to low optical depth (thin cirrus) cloud and is not sensitive to solar geometry and, of course, works at night.

The remaining problem of particle shape is not solvable directly from the SEVIRI spectral channel data. Most schemes assume a single distribution, or a parameter based distribution (on temperature for example). Another method is to adopt cloud class / type dependent shape / distributions. Again, this is relatively straightforward and although the degree of certainty about crystal distributions is still low, it probably represents the best that can be achieved.

D) Shadowing and the structure of real clouds is poorly represented by a plane parallel cloud model. Broken and highly structured cloud tops most difficult with increasing difficulty with low solar angles. For example; ATSR nadir view (~0° zenith) and forward view (~55°) 0.87 µm reflectances from a frontal cirrus region at a solar zenith of ~70°, show disagreement (i.e. scatter around) the plane parallel model at a level of ~5% (absolute) reflectance for clouds giving reflectances of 30% (or therefore optical depths of around 30). The 5% error at these geometries translates to around 100% error in optical depth. With such a low sun, this represents an extreme case but demonstrates the serious deficiencies of the plane parallel model.

The options for dealing with plane-parallel deficiencies are limited. Perhaps the simplest, and most widely used, is to limit the solar angle at which reflectance channel retrievals are made. 60° (but tbd) is a reasonable value although the cut-off should presumably depend on the type of cloud; information which could come from the cloud class / type analysis and / or from structure information from the SEVIRI HRV channel.

The above example was derived from ATSR 1 Km data; by first averaging to 5x5 Km the nadir/forward disagreement from plane-parallel model is reduced to ~2% absolute, at 12x12 Km it appears to be less than 1% absolute. Thus it appears\(^1\) that larger areas behave more like plane-parallel clouds. So a second strategy, which would need substantial investigation, is to average data over an area determined by the solar angle and the intrinsic variability of the scene.

The non-plane parallel cloud problem is an area of much research at present and a further option, although not available at present, will likely be correction functions for different cloud types and conditions. These may

\(^1\) we should stress that this analysis is very preliminary and is part of the proposed phase II study. A proportion of the differences observed at the 1 Km resolution arise from different sampling of the ATSR nadir and forward pixels and thus the plane-parallel error is very likely a worst case. The lower resolution averages nevertheless, should indicate the effect of sensor resolution on applicability of the plane-parallel model.
apply to the retrieved optical depths or possibly to the radiative transfer calculations.

Shadowing is, of course, not a problem at infrared wavelengths and thus this may be another circumstance for which obtaining *optical depth from the infrared* rather than the visible data is preferable.

E) Aerosols present in the atmosphere can add reflectance to a cloud scene or remove reflectance by absorption. They are most often present at low levels and low optical depths (~0.1) but we cannot at this stage quantify with any certainty the effect on cloud optical depth retrieval.

Most often aerosol effects are neglected in cloud property retrieval. The reasons are probably twofold: a) lack of good information on amount and location in the atmosphere and b) poorly defined composition and shape and therefore radiative effect. The multiple scatter interaction with the cloud add to the complications giving no simple way of accounting for the effect on measured reflectance.

The simplest treatment is assumption of climatological aerosol loading in the cloud multiple scattering radiative transfer. LUT reflectances would include a basic aerosol effect which could be simplified into stratospheric, tropospheric and boundary layer aerosol amounts. Cloud could be assumed to be entirely above the boundary layer aerosol and entirely below the stratospheric aerosol. The degree of complexity required to deal with tropospheric aerosol would need to be established with simulation.

One feature of aerosols in the atmosphere is that they are likely to be more slowly changing than the cloud fields. Retrievals of *aerosol from local clear SEVIRI* data might prove a useful source of information although height assignment would be difficult. This may be pessimistic; continental aerosol loadings can be assumed to be confined to the boundary layer, Saharan dust outbreaks confined to the troposphere. How to incorporate the aerosol estimates into cloud retrieval is not obvious; a method recently published for Rayleigh scattering corrections may provide a guide. At the very least high local aerosol loading could be used to flag doubtful cloud retrievals.

*Extension of LUT reflectances* for variable aerosol quantities, not to be retrieved – merely specified, could be worthy of investigation.

If the cloud retrieval scheme were able to use *real-time multiple scatter code* and could handle several scattering levels then the local aerosol estimates could be included much more effectively.

E) Rayleigh scattering is a related problem but one which is more tractable. retrievals using 0.87 µm reflectances are not significantly affected, but significant effects would be encountered using the 0.6 µm channel (Rayleigh optical depths for nadir view full atmosphere are ~0.01 and 0.04 respectively).

In this case the amount of scattering atmosphere is well quantified as are the scattering characteristics. The multiple scattering interaction with the cloud remains however. With retrievals restricted to 0.87 µm the simple and accurate option is to ignore the effect. However, 0.6 µm reflectances will almost certainly be used over land. A relatively simple method in the literature for *parameterising Rayleigh effects* at 0.6 µm could be incorporated. As in the case of the aerosol, both *extension of LUT reflectances* and *real-time multiple scatter code* would allow more exact treatment.

F) Water vapour absorption is an important consideration for the reflectance channels; two-path transmittances at 0.87 µm as low as ~0.8 may be encountered (extreme tropical atmosphere, cloud at surface; LOWTRAN). For cloud of $\tau = 16$ this would lead to an error in optical depth estimation of ~3 or therefore around 20%. Although an extreme case it highlights the need to account for water vapour absorption.

A simplest option is to *precalculate path transmittances* for each channel and using climatological water vapour values and for clouds at various heights. Simple path length dependence can be assumed to account for
geometry. Reflectances are then adjusted by these transmittances in the retrieval. This may prove an adequate method given the relatively small effect but will need simulations to test.

The results of the **MM offline visible radiative transfer model** for clear scenes could be used if the transmittances are available. These calculations are based on real-time NWP fields and should therefore be reasonably accurate although NWP humidities are poor compared to other model variables.

G) Ozone and mixed gas absorptions give relatively small and quantifiable effects. Ignoring the ozone absorption (at 300 DU) on ATSR 0.65 µm reflectances for a cloud \( \tau = 16 \) gives an optical depth error of ~1 or therefore ~5%. The 0.87 µm channel is not affected. \( \text{CO}_2 \) absorption at 1.6 µm directly affects the \( R_e \) estimation; ignoring it for a cloud of \( \tau = 16 \) and \( R_e \) of 12 µm and located at 1000mb leads to a 1 µm error in \( R_e \).

Although ozone and mixed gas effects are small they are much more quantifiable than water vapour. Probably it is entirely sufficient to use precalculated climatological ozone transmittances although a value derived from a **SEVIRI operational ozone** product would be straightforward.

\( \text{CO}_2 \) effects on 1.6 µm reflectances are adequately dealt with using precalculated transmittances based on climatology, although in this case the application of these transmittances is dependent on the cloud pressure which can be obtained in principle from the MM.

**Product:** Infrared estimation of Cloud top temperature, \( T_c \)

**Channels:** (3.7 µm) 8 10 11 (0.6, 0.87 µm)

As with the visible channels this problem can be formulated as a function of two variables, \( T_c \) and cloud emissivity\(^1\), for which nominally measurements at two wavelengths are required for solution. For the visible / near-infrared measurements, one channel (the visible) is predominantly sensitive to optical depth and the other (the near-infrared) predominantly sensitive to drop size. In the infrared case, channel responses are not nearly as orthogonal and they respond to emissivity / optical depth and temperature in a similar manner. The inversion problem is therefore rather ill-posed. Subtle differences exist (in cloud particle absorption and upwelling radiances) that mean a signal is present but the constraining information (upwelling radiance, scattering properties–particle size etc) have to be known well to extract useful information.

**Minimal technique:**

Simple methods are based on the emission equation for an observed radiance;

\[
R_\lambda = \varepsilon_\lambda B_{\lambda c} + (1 - \varepsilon_\lambda) B_{\lambda a}
\]

where \( \varepsilon_\lambda \) is the cloud emissivity, \( B_{\lambda c} \) is the radiance from an opaque cloud (at the same height / composition) and \( B_{\lambda a} \) is the upwelling radiance at cloud base. This, it may be noted, ignores atmospheric effects above the cloud and any reflection effects; of downwelling radiance or surface-cloud. It does implicitly include scattering effects since the emissivity can be taken as an effective value.

\(^1\) emissivity, \( \varepsilon \), is a proxy for optical depth and scattering properties; \( \varepsilon = 1 - e^{-\tau} \) in the non-scattering case.
Major limitations, error sources and enhancements:

A) The basic balance of information versus independent variables implicit in the above equation provides a large degree of latitude to its solution.

There are as many unknowns implicit in this equation as the analysis method requires. With one unknown permitted, the simplest method of solution is to assume \( \varepsilon_\lambda = 1 \) and then the measured radiance is the planck radiation of the cloud top. For most water cloud and some thick frontal and convective centre ice cloud this may be justified and may be checked by insisting BTs at different IR wavelengths are within a small threshold. A large proportion of cirrus cloud however, will not be amenable to this method. A second possibility is estimating \( B_c \) from nearby opaque cloud and assuming it is constant is a possibility allowing retrieval of \( \varepsilon_\lambda \) from one measurement, but this is clearly unsatisfactory in anything other than a supervised selected case.

Allowing two variables, i.e. \( \varepsilon_\lambda \) and \( B_{\Lambda^a} \), to vary introduces the second term on the right hand side of the equation and requires that \( B_{\Lambda^a} \) is specified from some means or other. It can be solved by introducing extra information from local area scatter of brightness temperature differences (dBTs). This is the basis of a whole class of scatter diagram methods where a large enough area is chosen to contain clear pixels for \( B_{\Lambda^a} \) and enough pixels of variable \( \varepsilon_\lambda \) to at least indicate by extrapolation the value of \( B_{\Lambda^c} \) and to confirm that the area is in fact covered in single layer cloud of constant \( B_{\Lambda^a} \). The methods suffer because of the requirement of large homogenous areas and the presence of a more or less complete ‘arch’ (range of \( \varepsilon_\lambda \)) in the scatter. The large the particle size the larger has to be the area chosen and the less likely that the condition of homogeneous parameters is to be met. The ‘height’ (maximum dBT) of the arch indicates the particle size although this need not be determined.

With \( B_{\Lambda^a} \) estimated and with \( \varepsilon_\lambda \) linked between (at least two) channels with a parameterisation in terms of multiple scatter calculations then equation can be iteratively solved on a pixel basis. Homogeneity in the underlying \( B_{\Lambda^a} \) is still assumed but the cloud temperature and emissivity are effectively allowed to vary. Its equivalent in the scatter method is fitting an arch with a fixed end at \( B_{\Lambda^a} \) and curvature (defined by the particle distribution in the \( \varepsilon_\lambda \) parameterisation) but variable \( B_{\Lambda^c} \). So although it may be superior in that homogenous (in temperature) areas are not required, it does impose a particular cloud composition on the problem and is prone to errors from this.

By adding particle size as a variable (or some proxy variable) to the problem this restriction can be removed. This can be seen by rewriting the emission equation in terms of optical depth rather than emissivity and with explicit reference to multiple scattering effects:

\[
R_\lambda = (1 - e^{-\tau})B_{\Lambda^c} + e^{-\tau}B_{\Lambda^a} - B_{\Lambda^c}\delta_c(\tau,D) + B_{\Lambda^c}\delta_s(\tau,D)
\]

The first two terms represent emission and transmission of a non-scattering cloud (\( \tau \) is the extinction optical depth) and the third and fourth a reduction of emission and an increase in transmission due to scattering respectively. \( \delta_c \) and \( \delta_s \) are functions of the optical depth and the particle single scatter albedo and asymmetry parameter (shown here as dependency on size, \( D \)), and can be formulated through, for example, two-stream theory or be implicitly included in LUTs of multiple scatter calculations. Specifying the particle optical properties takes us back to two variables, \( \tau \) and \( B_{\Lambda^c} \), and requiring two measurements. However, keeping the dependency on \( D \) (or, as indicated, proxy variables such as asymmetry parameter, \( g(D) \), and single scatter albedo, \( \omega_0(D) \)), potentially allows more accurate estimation of \( B_{\Lambda^c} \) providing, of course, extra information is available to constrain the value of \( D \). In the infrared data alone, the combination of 3.7, 8, 11 and 12 \( \mu \)m measurements certainly contains information (otherwise the \( D \) dependency wouldn’t exist), and joint pixel based retrieval of \( \tau \), \( B_{\Lambda^c} \) and \( D \) will be possible. As discussed elsewhere, determining the optical properties of irregular crystals in the infrared is a problem but at the longer wavelength channels (8, 11 and 12 \( \mu \)m) the treatment should at least be consistent.

The particle size dependency of infrared radiances is small compared to the other effects (for example, for \( D > 30 \mu \)m there is little wavelength dependency). It is also not clear how independent the information on the three parameters may be. A very promising option is to use near-infrared particle size information in the infrared inversion. This information is certainly independent and would provide a strong (daytime only of course) constraint. Given the relatively weak dependence of infrared radiance on \( D \) and the very strong information con-
tent of the near-infrared channels this seems a powerful option. The channel used could be the 1.6 or the 3.7 µm (where the 3.7 µm reflectance component is the primary source of information, not the emission component).

A problem with combining visible and infrared wavelength information is, as we have said before, the link between the scattering properties for irregular particle shapes. In the case of particle size, the weak effect on infrared and the strong effect on near-infrared means that the procedure would most likely be beneficial. The picture is less clear for the other attractive option of using visible channel optical depth information to the infrared retrieval. In many situations the precise nature of the visible optical depth should significantly constrain an infrared retrieval made uncertain by poorly known parameters (e.g. B_{λs}) and, for example, when the cloud becomes optically thick (infrared retrieval of τ>4 is severely limited). But this relies heavily on an accurately known relation between visible and infrared optical depth which in turn relies on basic scattering theory and particle characteristics. Knowledge of this relationship is improving but cannot be said at this stage to be perfect.

B) Specification of B_{λs} has been discussed above but is presented again here since the opportunity to use results of the MM radiative transfer model (RTM) have not been explored.

The advantages of specifying B_{λs} with the RTM compared to local area searches to are in the greater reliability (in terms of availability) and simplicity of the method, and in the ability to use ‘base of cloud’ rather than ‘top of atmosphere’ radiances. Problems may be encountered with poor model (NWP) representation of humidity and surface temperature over land although these are paralleled by local variations that make the search methods inappropriate. We cannot say at present which source of information offers the best choice although with ever-increasing accuracy of NWP (particularly analysis rather than forecast fields) the RTM method would be our choice.

B) Above cloud atmospheric effects can be significant especially for lower cloud levels and moister atmospheres and low zenith views.

The simplest strategy for this effect is use of LUTs of global precalculated transmissions and radiance contributions for the above cloud (i.e. pressure dependent) atmosphere.

A better source of information would no doubt be results from the MM RTM. These would be based on NWP temperature and humidity fields and would be as accurate an estimate as is reasonably possible. The transmission from cloud level and the radiance contribution of the above cloud atmosphere are required at the MSG view geometry.

C) Multi-layer cloud systems present a considerable problem for the infrared retrieval algorithms discussed above, invalidating almost entirely the basic equation.

There are no very simple approaches to deal with multi-layer cloud. Complex analyses of dBT scatter diagrams shows some promise and may possibly automated retrieval from two layer systems. Methods following the discussions above where the inversion is over-constrained (more measurements than variables) have the potential to at least identify scenes where the plane-parallel (single layer) cloud model is inappropriate. Whether the information content of a joint retrieval using multiple channels can then extract useful information on a two-layer cloud model would need investigation.

D) Non-isothermal cloud is a further often neglected source of error. For low level water clouds it is not a problem since the penetration depth in such clouds allows for little temperature variation. Cirrus of low optical depth and several Km of vertical extent will give rise to radiances not representitative of the cloud top.

The errors due to this source are analogous to those met in the algorithms designed for cloud top pressure esti-
The conclusion of research in that area is that the retrieved parameters tend to be appropriate to the cloud ‘radiative’ centre, i.e. towards the top for optically thick clouds, and towards the geometric middle for optically thin clouds. There is very little that can be done to directly include non-isothermal cloud effects since the information content of the data would not permit any kind of structure retrieval.

3. Strategy recommendation

The discussion in the section 1 above has laid out the options broadly available in terms of cloud parameter retrieval from the visible and infrared information. We treated the two wavelength regions separately but noted several areas where joint use of visible and infrared measurements appear to offer opportunities not available from the single band. We also pointed out some of the problems with this approach. The strategy recommendation presented here is done so by way of suggesting some guiding principles followed by discussion as to how these might be carried out and what their limitations might be.

We recommend:

2.1 To invert simultaneously for all required / necessary products using all radiances with appropriate levels of confidence judged by the known channel characteristics and the estimated scene characteristics. Optimal estimation techniques are to be used.

This is a recommendation to adopt a theoretically sound and powerful methodology for the data inversion. Optimal estimation (OE) is well documented (but not in cloud retrieval literature except for some recent papers) and is powerful and flexible. It naturally utilises radiative transfer, provides an error analysis and a degree of automatic quality control. Compared to other fields of atmospheric sounding, vertical temperature and composition for example, the field of cloud retrieval has less to gain from OE. This is because in those other fields there is often a significant a priori input to the result and OE ensures proper accounting for the errors in this. Cloud retrieval rarely has any a priori input (not because it is not required, but because it is not available!). Nevertheless, the idea of using all measurements and retrieving all products together is one that ensures all the available information is used (and not over-used). There are aspects though, which would need more careful consideration. We briefly discuss them here.

Obtaining ‘all products’ by using ‘all information’ may not be possible for a particular scene, whereas ‘some products’ using ‘selected’ information may be. Optimal estimation methods should however be able to adapt. Two examples will help clarify this.

Cloud over land may be so optically thin in the visible region and the surface reflectance poorly specified so that optical depth retrieval is not possible. The infrared channels however see an effectively much more optically thick cloud and perhaps a well known surface temperature - optical depth and cloud temperature are retrievable. In this case, assuming the error characteristics of the land surface parameters are known reasonably well, the inversion would automatically weight the infrared information more highly than the visible and the error analysis would ‘report’ poor parameters that depend principally on visible channel information and good parameters that depend on infrared.

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A cloud with some top structure combined with low solar angles (near horizon) causes shadowing and an effectively unreliable visible reflectance whereas the infrared radiances remain adequately representative of a plane parallel cloud. In this case, without adjustment, the visible and infrared information would ‘disagree’

1The exciting possibility with MSG data is that cloud parameters retrieved at the previous cycle (15 mins earlier) can be used to provide a priori estimates of parameters at the current cycle. They could be used simply to initialise the current retrieval process in which case detailed accounting of errors is not required. However, they could be used more powerfully (especially if measurements are significantly noise limited) as genuine information, in which use of OE methods is appropriate.
over optical depth and the retrieval would be inaccurate. Ideally, however, the effective noise in the visible reflectance (which determines its weight in the retrieval) would be increased with solar angle and as a function of cloud type (stratus / fog would mean retained low noise for example) and the retrieval would automatically end up relying on the infrared radiances.

How difficult the error tuning would be and how generally applicable the methodology will only become clear as a result of further study. Nevertheless, the examples do illustrate the potential power of the method and also another benefit; that is the combined radiance departures (poorness of fit) at the convergence or otherwise of the retrieval is a guide to the suitability of the scene. Without error weighting, both examples would have produced high measurement–calculation differences because of the inability of the cloud model to adjust to the real situation, i.e. in the second example the cloud was not behaving as plane parallel. Retrieval from visible reflectances alone in this case would have probably been successful in that an answer was found, but that answer would have been erroneous. Such ‘model-checking’ capability may detect many situations where retrieval really should not be made (or at least flagged as potentially poor quality); multilayer cloud might be a example.

1.2 To use wherever possible the existing products of the MPEF either to provide constraints on or intialisation of the retrieval process. Where MPEF products are unavailable or unsuitable to use NWP products and where MPEF and NWP products are both unavailable or unsuitable to use climatological or other sources.

As described, the MPEF generates many of the spatially and temporally derived products that many of the methods and techniques of retrieval employ. These should clearly be used if they represent the best available information. The RTM is an additional bonus from the MPEF and is where and how most NWP data can be used. The RTMs utility needs to be examined in some detail. The potential danger of using NWP fields for parameter retrieval which are assimilated into the very same NWP model have presumably been explored in the design of the MPEF and will not be discussed further here.

If neither MPEF products nor NWP fields can supply the information then climatological or real time estimates from other reliable sources must be sought. We have implicitly assumed that there is no close synergy with other space sensors although this could be reviewed.

1.3 To use, wherever possible and reasonable, explicit radiative transfer and inversion thereof.

Explicit radiative transfer has the advantage over other methods (e.g. ‘correction’ of radiances) of being capable of representing all the necessary physics and avoids errors introduced through approximations. Pragmatism is in order though; ozone absorption can be dealt with by correcting radiances according to the transmission and without loss of accuracy; LUTs in lieu of complex multiple scattering calculations will be probably be necessary although the availability of fast MS code (and its adjoint or gradient) would enable powerful and flexible data inversion.

1.4 To invert radiances at the level of individual pixels (or averages / samples), rather than to use ensemble characteristics.

The ensemble characteristics of the data (e.g. classification, clear radiance estimation etc) have been extracted by the MPEF. Retrieval at the individual pixel level is the logical next step and is in line with MPEF products.

4. Considerations for simultaneous retrieval

To further emphasise the complementary nature of the information SEVIRI will provide, the following table lists principal channels and cloud products. It is not meant to be comprehensive, in fact, we have omitted 0.6 and 12 μm channel for reasons of space. With the method-
ology outlined, the distinction between ‘product’ and ‘factor affecting’ the measurement becomes blurred. Under each channel are the products that influence the measurements in each channel and the relative influence is indicated thus: underlined implies a primary product of that channel (the channel supplies a great deal of information on the product), plain implies some significant effect and (bracketed) implies only a small effect.

As can be seen, most channels are affected by most products to some degree, or to put it another way, most channels potentially supply information on most products. Under each primary product / channel, notes are given to suggest the sensitivity of the information to conditions, whether they be the elevation of the sun, underlying surface reflectance $R_s$ etc.

The comments include a word to indicate the reason for the sensitivity, thus **transmission** of underlying surface reflectance (specified at some error level) decreases the ability of the 0.8 µm channel to estimate optical depth. The bold face type is indicates that this effect would be naturally monitored by the optimal estimation error analysis. An underlined reason indicates a more subtle (unmodelled) effect which would need study and parameterisation; the effects of shadowing for example.
<table>
<thead>
<tr>
<th>Channel</th>
<th>0.8 µm</th>
<th>1.6 µm</th>
<th>3.9 µm</th>
<th>8.7 µm</th>
<th>10.8 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day/Night</td>
<td>D</td>
<td>D</td>
<td>D/N</td>
<td>D/N</td>
<td>D/N</td>
</tr>
<tr>
<td>Products:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau )</td>
<td>Increases with ( \theta ); shadowing and loss of signal.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T_c )</td>
<td>Decreases for high ( \tau ) (atmosphere)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R_e )</td>
<td>Decreases with ( \theta ); shadowing and loss of signal.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase</td>
<td>Decreases slowly for low ( \tau ) (transmission)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and sensitivities</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

We believe the table indicates the complementary nature of the information. Whilst one channel which supplies information on a product is losing sensitivity for a particular reason, another may be becoming more effective. In any case, the methodology is intended to assure that the best possible use is made of all the information. It does rely on a realistic and comprehensive treatment of errors. Instrument noise is just one source in this context. Errors in surface temperature, reflectance, RTM calculations, shadowing effects etc have to be included if the balance of information use is to be optimal.

\(^{(1)}, (2), (3)\) See comments in following text
The table product entries carried superscript notes and these are intended to flag another important aspect of simultaneous retrieval: the definition of a product or quantity for one wavelength is not precisely the same for another wavelength.

\footnote{1} indicates the uncertainties in the link between optical properties at visible and infrared wavelengths. Whilst this is well understood and quantified in the Mie regime, it cannot be said to be a concluded subject in the case of ice crystal clouds for the reasons discussed in WP1.1 section 3 and elsewhere. The problem (to reiterate) lies in the ability to use geometric optics at visible wavelengths but not for the infrared. However, there is some consensus on the visible-infrared ratios; in the large particle limit there is an exact value, and the situation can be expected to improve with time. Without further study we cannot answer the complex question whether errors arising from an uncertain visible–infrared link outweigh the benefit of including visible information in the infrared retrieval.

\footnote{2} highlights the fact that different penetration depths of 3.9, 8.7, 10.8 and 12 µm radiation in clouds means that the effectively observed cloud temperature is not the same in each. These effects are small but possibly not insignificant. They arise essentially because the envisaged simple cloud model and plausible radiative transfer do not handle clouds with vertical gradients.

\footnote{3} indicates that the effective drop size "seen" by a 3.9 µm channel is representative of somewhat higher in the cloud than that seen by a 1.6 µm channel. Simulations using clouds with realistic vertical structure may suggest that simple parameterisations could adequately link, for example, \( R_e \) at 1.6 µm with \( R_e \) at 3.9 µm.

None of these caveats necessarily preclude the use of simultaneous retrieval; one could simply, for example, introduce two independent optical depth parameters, visible and infrared, to be retrieved. However, as mentioned, the balance is not clear and the single variable must be the preferred option.

Simultaneous use of many channels also clearly requires that these channels have fairly precisely similar co-registration.

5. MSG MPEF products

For what could have been a complex and onerous task of specifying a complete system from level-1b data to cloud products, we are spared a great deal by the high level products that will be available. We list here the relevant products and indicate how they might be used; in an approximate order of usefulness:

3.1 Cloud detection

This appears to incorporate all the recognised threshold tests and utilises the temporal quality of the of the data. We believe it is as good a cloud detection system as is reasonably possible and could be used as the decision mask for retrieval.

3.2 Clear pixel identification and clear sky radiances

In a similar manner to 2.1, the identification of clear pixels will be rigorous and the clear
sky radiances resulting sufficiently accurate for use in constraining cloud parameter retrievals.

3.3 Radiative transfer model (infrared), RTM

Clear sky top of atmosphere (TOA) radiances for all infrared channels are computed from a fully specified radiative transfer model using NWP fields of temperature as input. Tables of contribution functions are stored. Upwelling TOA radiances from opaque/black surfaces at all levels are calculated but these are less useful for cloud retrievals than upwelling radiances at each level. At this stage we can strongly recommend to EUMETSAT that provision of variables from the RTM calculations are likely to be highly desirable in the cloud property retrieval. Although these are to be confirmed and defined more rigorously as part of Phase II studies we can anticipate the following requirements (all at view geometry):

(1) Upwelling radiances at each pressure level below 100 Hpa.

(2) Transmissions to space from each pressure level below 100 Hpa.

(3) TOA radiances from the atmosphere (only) above all levels below 100 Hpa.

3.4 We have recommended use of the off-line visible channel reflectance model and we can anticipate that the following variables will be highly desirable (again, to be defined more rigorously):

(1) Surface recent bi-directional reflectance at the correct local time and view geometry

(2) Transmittances from each atmospheric level to space (P < 100 Hpa) at satellite geometry

(2) Transmittances from each atmospheric level to space (P < 100 Hpa) at solar geometry

3.5 Cloud analysis

Cloud typing / classification on an individual pixel basis is available from thresholding visible and infrared (0.6, 3.9 and 10.8 µm) channels. Classes such as ‘cumulus’, ‘stratus’ etc are produced and could be used for initialisation of retrieval parameters and to control or aid interpretation of retrieval diagnostics. Further products include phase, optical depth, top temperature, top height, semi-transparancy flag, effective amount and quality flag. Derivations of these further products have not incorporated many of the techniques described in the WP1.1 literature review and they could be used as first guess values in retrieval procedures.
1. Overview

Although the title refers to ‘visible’ channel radiative transfer this part of the study refers to radiative transfer of the scattered and absorbed solar radiation in all channels. In practice, this means the reflection model for the VIS (0.65, 0.8 / 0.87 µm), NIR (1.6 µm) and SIR (3.7/3.9 µm) channels since solar radiation at longer wavelengths than these is negligible. We should also note that for the SIR channel an emission model is required in addition to the reflectance model. That is dealt with in WP2.2.

Section 2 here describes the origin of the particle optical properties used for water and ice phase cloud. Section 3 briefly describes the multiple scatter code used to produce LUTs of reflection and transmission and describes the radiative property terms. Demonstration of the accuracy of the MS code against a published reference case is made. The combined atmosphere / cloud system in which the cloud LUTs are imbedded is explained in section 4 and the equations describing the overall radiative transfer of this system are derived along with the gradient (or ‘tangent linear’) equations. Coded versions of these equations are implemented and run in a selection of test cases to demonstrate its behaviour is intuitively reasonably. Section 5 examines the sensitivity of the model to inadequacies in its formulation (e.g. neglect of Rayleigh scattering) and errors in input parameters (e.g. surface reflection function). Section 6 briefly reviews literature estimates of deviations of the plane-parallel cloud model from realistically structured clouds; ATSR-2 data from selected scenes is used to demonstrate and augment this discussion. In section 7 we summarise the model behaviour,
sensitivity to error sources and its range of applicability.

2. Particle optical properties

2.1 Water cloud

Water cloud particles are assumed to be spherical and the scattering properties are calculated using Mie theory using code from Wiscombe et al. (see e.g. Wiscombe W. 1980, Improved Mie scattering algorithms. Appl Opt. 19 p1505-1509). Optical properties are suitably averaged over a modified-gamma distribution where the frequency of occurrence $n(r)$ of a drop size $r$ for a mode radius of $r_m$ is given by:

$$n(r) = 2.373 r^6 \exp (-6.r/r_m)$$

In this case the effective radius $R_{\text{eff}}$ (cross-sectional area weighted average radius) is 1.5 times $r_m$.

$R_{\text{eff}}$ values of 1–23 µm in steps of 2 µm are used.

Refractive index data for liquid water is taken from Irvin and Pollock 1969 and values at central wavelengths are used.

2.2 Ice cloud

Generation of the optical properties of non-spherical ice particles is far less straightforward than that for spherical water drops. The discussion here is therefore rather more detailed and we include specific references to the literature.

Refractive index data have been taken from Warren (Optical constants of ice from the ultraviolet to the microwave. Appl. Optics, 23, 1984). However, in a recent paper by Yang et al (Yang, P., K. N. Liou and P. Arnott. Extinction efficiency and single scattering albedo for laboratory and natural ice cloud. J. Geophys. Res. 102, D18, 21825-21835, 1997) a comparison was made between laboratory measured extinction efficiencies of randomly oriented hexagonal columns and plates between 2.0 and 16 microns with Finite Difference Time Domain Theory. In the application of theory the refractive index of ice due to Warren (1984) were used. Whilst good agreement was generally found at wavelengths greater than 4 microns, between 2 and 4 microns significant departures between theory and measurements were noted. In order to obtain a better fit with the extinction measurements in this region the real part of Warren (1984) measurements had to be changed by about 10%. Since for this study there are no alternative measurements of the real and imaginary index of ice covering our spectral range between 0.5 and 12 microns we adopt the values of Warren (1984). The noted discrepancy however, may have some bearing on the results of retrievals over ice cloud presented in WP4 §3.

The size distribution functions used have originally been taken from Takano and Liou (Takano, Y., and K. N. Liou. Solar radiative transfer in cirrus clouds. Part I: Single-scattering and optical properties of hexagonal ice crystals. J. Atmos. Sci., 46, 3-19, 1989) based on the original in situ measurements of cold ice cloud, warm ice cloud, cirrostratus and cirrus uncinus due to Heymsfield (Cirrus uncinus generating cells and the evolution of cirroform clouds. J. Atmos. Sci, vol 32, 799-808. 1975) and Heymsfield and Platt (A parameterisation of the particle size spectrum of ice clouds in terms of the ambient temperature and ice water content. J. Atmos. Sci., 41, 846-855. 1984). The cirrus uncinus size distribution function is bimodal and for each distribution the size is represented by the
generalised effective dimension (D_{ge}) as defined in Fu (1996). D_{ge} is defined as the volume of the particle divided by the surface area of the particle. Such a definition is applicable to any particle geometry and is therefore suitable for a distribution of complex shapes. Using the D_{ge} definition applied to each of the size distribution functions mentioned above the following values are found:

<table>
<thead>
<tr>
<th>Cirrus type</th>
<th>D_{ge} µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold</td>
<td>15</td>
</tr>
<tr>
<td>Cirrostratus</td>
<td>30</td>
</tr>
<tr>
<td>Warm cirrus</td>
<td>36</td>
</tr>
<tr>
<td>Cirrus Uncinus</td>
<td>114</td>
</tr>
</tbody>
</table>

In this study, we have had to limit the representation of ice clouds to a single particle shape and type of distribution (albeit with an imposed overall mean size). We have taken the warm cirrus distribution with a D_{ge} value of 36 µm as a reasonably representative case. Note for instance effective dimensions found in mid-latitude cirrus of around 30-60 microns as found by the Meteorological Research Flight and analysed by Francis et al. (The retrieval of cirrus cloud properties from aircraft multi-spectral reflectance measurements during EUCREX'93. In press Q. J. Roy. Met. Soc. 1998, A test of physical theory based on aircraft observations of cirrus. In proceedings of Light Scattering from Nonspherical particles: Theory and measurement, 29-1st October, 1998. NASA/GISS, New York. 1998).

In order to generate LUTs for cloud radiative properties the Warm cirrus size distribution function was used to generate D_{ge} values other than the 36 µm. In order to achieve this a simple weighting was given to the small particle part of the distribution function, and similarly to the intermediate large sizes. The weighting was based on the particle number density. In this way a suitable (i.e. covering the smallest expected to the largest expected) range of D_{ge} values was generated: 17, 36, 71 and 107 microns.

The single scattering properties of ice were calculated as follows. Initially, a randomly oriented hexagonal crystal shape is assumed and the phase function, extinction coefficients and single scattering albedo are calculated using the ray tracing method due to Takano and Liou (1989). However, it is generally known that the ray tracing method has limited applicability at the sounding wavelengths studied here. It has been suggested by Macke et al. (Macke, A., M. I. Mishchenko, K. Muinonen, and B. E. Carlson. Scattering of light by large nonspherical particles: Ray tracing approximation versus T-matrix method. Opt. Lett., 20, 1934-1936, 1995) that the ray tracing method should only be applied at size parameters (x, where x=\pi D_{ge}/\lambda) greater than about 60 (this being the size parameter where scattered intensity calculations for cylinders of circular cross section using T-matrix and ray tracing converged). In this study, therefore, we have adopted the ray tracing method for x > 60 and the T-matrix method (Mishchenko, Light scattering by randomly oriented axially symmetric particles. J. Opt. Soc. Am. A8, 871-882. 1981) for x < 60 using prolate spheroids with aspect ratios of 3/4. Prolate spheroids will at least be representative of non-spherical shapes in terms of the phase function, exhibiting high side scattering (greater than the equivalent sphere), and relatively flat backscattering. The usefulness of spheroids as surrogates for ice crystals was initially suggested by Asano and Sato (Light scattering by randomly oriented spheroidal particles. Appl. Opt., 19, 962-974. 1980).

At visible wavelengths T-matrix was not required. In order to make the phase functions con-
sistent with those at infrared wavelengths the back scattered part of the phase functions were smoothed. This at least is more representative of nonspherical particles. The large peak in intensity at about 150 degrees and the retroreflection peak were removed. In other words the back scattering part of the column was made to look more like the randomised Koch Fractal due to Macke (Scattering of light by polyhedral ice crystals. Appl. Opt. 32, 2780-2788. 1993), usually called a polycrystal. Laboratory based experiments due to Zerull et al (In: Light scattering by irregularly shaped particles, ed. D. W. Schuerman, Plenum, NY, 334 1979) suggest that irregular particles do not have rainbow or glory features. Further, field experiments made by Francis (Some aircraft observations of the scattering properties of ice crystals. J. Atmos. Sci., 52, 1142-1154 1995, and 1998a), Descloitres et al. (Descloitres, J., J. C. Buriez, F. Parol, and Y. Fouquar. POLDER observations of cloud bidirectional reflectance comapred to a plane parallel model using the ISCCP cloud phase function. J. Geophys. Res. 103, 11411-11418, 1998) and Gayet et al. (In situ measurements of the scattering phase function of stratocumulus, contrails and cirrus. Geophys. Res. Let, vol 25, 971. 1998) report back scattering intensities similar to that of the randomised polycrystal. All these studies were made in combination with in situ microphysical measurements. However, although the polycrystal may well describe the backscattering it predicts too low asymmetry parameter as discussed in Francis et al. (1998b). For this reason the high asymmetry parameters relative to the polycrystal, as predicted by ray tracing applied to the column are kept as being more “truthful”. These asymmetry parameters were found to be generally greater than 0.80, the polycrystal predicts asymmetry parameters of only 0.74 at visible wavelengths. It is also important to note that in retrieval of crystal size the first order contribution comes from the change in single scattering albedo as one goes from small crystals to larger crystals. The phase function itself is of secondary importance in this respect.

After smoothing the phase function at backscattering angles the phase functions were renormalised to $4\pi$. To obtain the full phase function for each $D_{ge}$, the single scattering properties were integrated over each size distribution function.

Figure 2.2.1 shows the resulting phase functions and single scatter albedo for the four parti-
cle sizes $D_e = 17, 36, 71$ and $107 \, \mu m$.

At $1.6 \, \mu m$ absorption leads to values of $\omega_o < 1.0$ and somewhat differing phase functions. Haloe peaks in the larger particles start to become washed out since internal reflections are responsible for these features. It will be noted that the $\omega_o$ values decrease monotonically with increasing effective particle size; this is the signature that allows retrieval of particle size using the $1.6 \, \mu m$ measurements. The differing distributions and particle shapes that occur in different types of cirrus cloud imply the use of many different sets of optical properties. However, division of the inversion problem into multiple cloud types will almost certainly require that the retrieval method use classification information since multi-spectral data from a single pixel is unlikely to contain sufficient information to constrain cloud type in addition to the other parameters.

### 3 Multiple Scattering radiative transfer

The widely available and tested discrete ordinates code DISORT (Stamnes K., Tsay S.C., Wiscombe W., Jayaweera K. ‘Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple-scattering and emitting layered media’ Appl. Opt., 1988, 27, No.12, pp.2502-2509) for multiple scattering calculations is used to generate LUTs of cloud radiative properties given the basic optical properties of ice and water particles.

Normalised reflectances and transmissions are calculated for each drop/particle size, each wavelength and for optical depths of $1, 2, 4, 8, ..., 256$, for values of solar zenith angle $\theta_o = 0–90^\circ$ at $10^\circ$ intervals, for values of view zenith angle $\theta_v = 0–90^\circ$ at $10^\circ$ intervals and for val-
ues of relative azimuth $\phi = 0-180^\circ$ at $18^\circ$ intervals. These are stored in a table and a 5 dimensional interpolation scheme is used to obtain reflectances and the gradient of the reflectances at any particular geometry and cloud specification. Optical depths are referenced to the value at 0.55 $\mu$m; in calculations the optical depth used for a channel $i$ is related to the 0.55 $\mu$m value by the ratio of the extinction coefficients: $\tau^i = \tau^{55} \times Q^i_{\text{ext}} / Q^{55}_{\text{ext}}$.

The cloud radiative properties required are shown in Table 3.1 with their geometric and cloud property dependencies marked by an *. Transmittances are fractional and reflectances are equivalent Lambertian, i.e. $R = \pi I / F_0$ where $I$ is the reflected radiance and $F_0$ is the solar irradiance.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>symbol</th>
<th>$\lambda$</th>
<th>$R_e$</th>
<th>$\tau$</th>
<th>$\theta_v$</th>
<th>$\theta_o$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Beam bi-directional reflection</td>
<td>$R_{BD}$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>b) Beam transmission: Direct</td>
<td>$T_B$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>c) Diffuse</td>
<td>$T_{FBD}$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>(*)</td>
<td></td>
</tr>
<tr>
<td>d) Diffuse Transmission</td>
<td>$T_D$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e) Diffuse Reflection</td>
<td>$R_{FD}$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>(*)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>f) Emissivity</td>
<td>$\varepsilon_c$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not used</td>
</tr>
</tbody>
</table>

Table 3.1. Cloud bulk visible radiative properties

a) Beam bi-directional reflection, $R_{BD}$, is the direct reflection from the cloud layer of the solar beam. It is therefore a function of the full three dimensional geometry.

b) Beam transmission: Direct, $T_B$, is the fraction of the solar beam transmitted through the cloud layer unscattered and unabsorbed.

c) Beam transmission: Diffuse, $T_{FBD}$, is the fraction of the solar beam transmitted through the cloud having been (multiply) scattered. Strictly a function of the full three dimensional geometry (hence the (*)), we use the flux version (integrated over zenith and azimuth) since any underlying Lambertian reflecting surface removes any angular dependence. It would be important to retain this angular dependence for, for example, solar occultation measurements from below cloud. The two beam transmission terms can therefore essentially be added (and hereafter are referred simply as $T_B$), but they are stored in the LUTs as separate entities for the time being. If there is a reflecting surface below the cloud then the beam transmissions are required to calculate surface–cloud multiple reflections.

d) Diffuse transmission, $T_D$, is the transmission by the cloud layer of isotropic radiation. There is a dependence on view angle.

e) Diffuse reflection, $R_{FD}$, is the reflection by the cloud layer of isotropic radiation. We use a flux version because $R_{FD}$ is involved with reflections to the Lambertian surface. $R_D$ is often
called the cloud spherical albedo. Diffuse transmissions and reflections are required to estimate the effect of the return radiance from the underlying surface.

f) Emission is not significant for the VIS and NIR channels. It is required for the SIR channels - see WP2.2 section 2.

### 3.1 DISORT standard intercomparison

The scattering model DISORT was run with input Mie parameters, cloud specification and geometry as per test case 3 (Haze) from the International radiation Commission intercomparison (Standard procedures to compute atmospheric radiative transfer in a scattering atmosphere. IAMAP, 1977). The conditions in this test are given in table 3.1.1.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total optical depth</td>
<td>1.0</td>
</tr>
<tr>
<td>Drop distribution n(r)</td>
<td>$4.9757 \times 10^6 \cdot r^2 \cdot \exp(-15.1186 \cdot r^{0.5})$ - mode radius 0.07 µm</td>
</tr>
<tr>
<td>Single scatter albedo</td>
<td>0.90</td>
</tr>
<tr>
<td>Complex r.i.</td>
<td>1.33 + 0.00i</td>
</tr>
<tr>
<td>Solar flux</td>
<td>$\pi$</td>
</tr>
<tr>
<td>Solar angle</td>
<td>$\cos^{-1}(0.5)$</td>
</tr>
<tr>
<td>Output optical depth</td>
<td>0.0, 0.05, 0.1, 0.2, 0.5, 0.75, 1.0</td>
</tr>
<tr>
<td>Output $\cos(\theta_v)$</td>
<td>1.0, 0.8, 0.6, 0.4, 0.2, 0.0, -0.2, -0.4, -0.6, -0.8, -1.0</td>
</tr>
<tr>
<td>Output azimuth °</td>
<td>180, 90, 0</td>
</tr>
</tbody>
</table>

Table 3.1.1 IAMAP case 3 cloud properties

The published material contains results from various methods against which we can compare the DISORT results. Since all methods are computational, none are exact and we merely wish to confirm that the DISORT model, which has a long pedigree and is well known, has been successfully implemented. Since the number of models and output conditions is large, we restrict ourselves here to table 3.1.2 showing calculated intensities for the output zenith angles at $\tau = 0.1$ only, and for the azimuth $0^\circ$ case only. Full tables of results are available from the authors of this report. For the DISORT run, Mie parameters were averaged over the specified distribution having been calculated for radius intervals of 0.01 µm. DISORT itself was run with 48 streams (although the phase function only required 38 moments in this case).
<table>
<thead>
<tr>
<th>(\cos(\theta_v))</th>
<th>DISORT</th>
<th>Successive scattering</th>
<th>Spherical Harmonics</th>
<th>Dart</th>
<th>Monte Carlo MK</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau = 0.1)</td>
<td>1.0</td>
<td>1.886e-2</td>
<td>1.997e-2</td>
<td>1.999e-2</td>
<td>4.50e-2</td>
</tr>
<tr>
<td>0.8</td>
<td>5.736e-2</td>
<td>5.712e-2</td>
<td>5.741e-2</td>
<td>9.79e-2</td>
<td>5.60e-2</td>
</tr>
<tr>
<td>0.6</td>
<td>1.379e-1</td>
<td>1.358e-1</td>
<td>1.363e-1</td>
<td>1.42e-1</td>
<td>1.34e-1</td>
</tr>
<tr>
<td>0.4</td>
<td>3.124e-1</td>
<td>3.069e-1</td>
<td>3.081e-1</td>
<td>2.17e-1</td>
<td>3.07e-1</td>
</tr>
<tr>
<td>0.2</td>
<td>6.630e-1</td>
<td>6.473e-1</td>
<td>6.496e-1</td>
<td>4.15e-1</td>
<td>6.45e-1</td>
</tr>
<tr>
<td>0.0</td>
<td>1.165e-1</td>
<td>1.188e-0</td>
<td>1.188e-0</td>
<td>9.26e-1</td>
<td>1.19e-0</td>
</tr>
<tr>
<td>−0.2</td>
<td>9.651e-1</td>
<td>9.053e-1</td>
<td>9.068e-1</td>
<td>8.21e-1</td>
<td>9.10e-1</td>
</tr>
<tr>
<td>−0.4</td>
<td>1.074e-1</td>
<td>1.164e-0</td>
<td>1.169e-0</td>
<td>1.11e-0</td>
<td>1.15e-0</td>
</tr>
<tr>
<td>−0.6</td>
<td>7.206e-1</td>
<td>7.759e-1</td>
<td>7.781e-1</td>
<td>7.46e-1</td>
<td>7.65e-1</td>
</tr>
<tr>
<td>−0.8</td>
<td>1.717e-1</td>
<td>1.655e-1</td>
<td>1.652e-1</td>
<td>1.73e-1</td>
<td>1.78e-1</td>
</tr>
<tr>
<td>−1.0</td>
<td>9.991e-2</td>
<td>1.012e-2</td>
<td>1.011e-2</td>
<td>1.11e-2</td>
<td>1.00e-2</td>
</tr>
</tbody>
</table>

Table 3.1.1 IAMAP case 3 selected intensities

Apart from the Dart (Dodecaton Approach to Radiative Transfer) method the results are in reasonable agreement. The Successive Scattering and Spherical Harmonics are very close to each other and DISORT and the Monte Carlo code differ from these by about the same amount.

4. Cloud - Atmosphere - Surface model

4.1 Cloud-surface interactions

The cloud radiative model described above is coupled to the atmosphere and surface using a three-layer absorbing-only atmosphere and assuming a Lambertian surface reflector. The three layers are ozone (assumed to be always above cloud), the above-cloud atmosphere and the below-cloud atmosphere. Rayleigh scattering is ignored at present. The model is shown diagramatically in the figure 4.1, firstly, for simplicity, without the atmosphere and with the solar flux set equal to 1. Dependency of functions on cloud \(\tau\), \(R_{eff}\) is not explicitly shown. Note that only the first few terms of the multiple reflection series is shown.

\[
F=1 \quad R_{BD}(\theta_o, \theta_v, \phi) \rightarrow T_B(\theta_o) \cdot R_s \cdot T_D(\theta_v) \rightarrow T_B(\theta_o) \cdot R_s^2 \cdot T_D(\theta_v) \cdot R_{FD} \rightarrow \]

\[
T_B(\theta_o) \rightarrow T_B(\theta_o) \cdot R_s \rightarrow T_B(\theta_o) \cdot R_s^2 \cdot R_{FD} \rightarrow \]

\[
T_B(\theta_o) \cdot R_s \cdot R_{FD} \rightarrow \]

\[
\tau \rightarrow R_s
\]

Figure 4.1. Cloud surface interactions neglecting atmospheric effects
Totalling the output reflectance we have:

\[
R = R_{BD}(\theta, \theta_v, \phi) + T_B(\theta_o)R_S T_D(\theta_v) + T_B(\theta_o)R_S^2 T_D(\theta_v)R_{FD} + \ldots
\]

\[
= R_{BD}(\theta, \theta_v, \phi) + T_B(\theta_o)T_D(\theta_v)R_S[1 + R_S R_{FD} + R_S^2 R_{FD} + \ldots]
\]

\[
= R_{BD}(\theta, \theta_v, \phi) + \frac{T_B(\theta_o)T_D(\theta_v)R_S}{[1-R_S R_{FD}]} + \ldots
\]

4.2 Cloud-surface-atmosphere interactions.

The atmosphere is specified, figure 4.2, as above cloud and below cloud optical depths, \(\tau_{ac}\), \(\tau_{bc}\), or equivalently transmittances \(T_{ac}(\theta), T_{bc}(\theta)\).

The optical depths are specified at nadir (zero zenith angle) values. It is easy to see that the (overcast) reflectance, \(R_*\), from the three layer atmosphere model becomes:

\[
R_* = T_{ac}(\theta_o)T_{ac}(\theta_v)\left\{R_{BD}(\theta_o, \theta_v, \phi) + \frac{T_B(\theta_o)T_D(\theta_v)R_S}{[1-R_S R_{FD}T_{bc}(\theta_d)]}\right\} \ldots (1)
\]

Note that the above-cloud and ozone transmittances could be treated as a single value. We choose to keep them separate because we can consider the ozone transmission to be independent of the cloud height whereas the above-cloud transmittance will tend to unity for high cloud. Also note the introduction of a third zenith angle in addition to the solar and view values. Transmission of diffuse radiation in the below cloud atmosphere can be approximated by assuming the average path is represented by a slant angle of around \(\theta_d = 66^\circ\).

![Diagram showing atmospheric absorbing layers](image)

Figure 4.2. Cloud surface interactions showing atmospheric absorbing layers

The reflectance from the cloud-free atmosphere, \(R_o\), is given by

\[
R_o = R_S T_{tot}(\theta_o)T_{tot}(\theta_v)
\]

where \(T_{tot}\) is the transmittance of the whole atmospheric column, surface to space.
The reflectance of a field with fractional cloud cover \( f \) is therefore:

\[
R = fR_\star + (1 - f)R_o
\]

### 4.3 Model gradient.

The gradient version of the reflectance model, i.e. \( \partial R/\partial x \) where \( x \) is any of the input variables, is useful for two purposes. The gradient with respect to parameters which we expect to derive from SEVIRI measurements is a vital quantity for the efficient inversion of the non-linear reflectance model. The gradient with respect to parameters which might be considered known and not part of the inversion procedure, e.g. surface reflectance, can be used to judge the sensitivity to these parameters and therefore estimate the required accuracy in their specification. They also have an important role is the technique of adding ‘equivalent model parameter noise’ to the inversion procedure is adopted (see WP4 §3.3.3).

Firstly the derivative of the reflectance equation with respect to fractional cover \( f \) is given by

\[
\frac{\partial R}{\partial f} = R_\star - R_o
\]

and the derivatives of the reflectance with respect to all other variables, generally denoted \( x \) here, are given by

\[
\frac{\partial R}{\partial x} = f \frac{\partial R_\star}{\partial x} + (1 - f) \frac{\partial R_o}{\partial x}
\]

The above notation starts to become cumbersome when derivatives of \( R_\star \) are taken and so we shorten the expression to:

\[
R_\star = T \left\{ R_{BD} + \frac{T_B T_D R_\star T_{BC}^2}{[1 - R_\star R_{FD} T_{BC}^2]} \right\}
\]

and further write the second term in \{ \} as \( S \) to indicate it represents the cloud-surface interaction terms;

\[
R_\star = T \left\{ R_{BD} + S \right\}
\]

It is not useful to present the somewhat messy algebra of the differentiations, and we restrict ourselves to giving the expression for the gradient terms. Gradient values for the cloud properties themselves are available from the LUT interpolation routines and a prime \( \prime \) is shorthand for a derivative with respect to the current variable.

#### 4.3.1 Gradient \( R_\star \) wrt \( R_e \) (all \( \prime \) indicate \( \partial/R_e \)):

\[
\frac{\partial R_\star}{\partial R_e} = T \left\{ R'_{BD} + \frac{S [T_D T'_B + T'_D T_B]}{T_B T_D} + \frac{R'_\star T_{BC}^2}{[1 - R_\star R_{FD} T_{BC}^2]} \right\}
\]
4.3.2 Gradient \( R_\bullet \) wrt \( \tau \)

This is exactly analogous to the \( R_e \) gradient and the expression is the same except that, of course, all \( \cdot \) indicate \( \partial / \partial \tau \):

\[
\frac{\partial R_\bullet}{\partial \tau} = T \left\{ R_{BD} + \left[ \frac{T_D T_B'}{T_B T_D} \right] + \frac{R_c T^2_{FD}}{1 - R_c R_{FD} T^2_{bc}} \right\}
\]

4.3.3 Gradient \( R_\bullet \) wrt \( R_s \) (all \( \cdot \) indicate \( \partial / \partial R_s \)):

\[
\frac{\partial R_\bullet}{\partial R_s} = TS \left\{ \frac{1}{R_s} + \frac{R_{FD} T^2_{bc}}{1 - R_c R_{FD} T^2_{bc}} \right\}
\]

4.3.3 Gradient \( R_\bullet \) wrt \( T_{bc} \):

\[
\frac{\partial R_\bullet}{\partial T_{bc}} = 2TST_{bc} \left\{ \frac{1}{T^2_{bc}} + \frac{R_{FD} R_s}{1 - R_c R_{FD} T^2_{bc}} \right\}
\]

This can be related to the partial wrt optical depth by:

\[
\frac{\partial R_\bullet}{\partial \tau_{bc}} = -T_{bc} \sec(\theta_d) \frac{\partial R_\bullet}{\partial T_{bc}}
\]

as \( T_{bc} = \exp(-\tau_{bc} \sec(\theta_d)) \)

4.3.4 Gradient \( R_\bullet \) wrt \( \tau_{ac} \):

\[
\frac{\partial R_\bullet}{\partial \tau_{ac}} = -R \left[ \sec(\theta_o) + \sec(\theta_v) \right]
\]

4.3.5 Gradient \( R_\circ \) wrt \( R_s \):

\[
\frac{\partial R_\circ}{\partial R_s} = T_{tot}(\theta_o) T_{tot}(\theta_v)
\]

4.3.6 Gradient \( R_\circ \) wrt \( \tau_{tot} \):

\[
\frac{\partial R_\circ}{\partial \tau_{tot}} = -R_\circ \left[ \sec(\theta_o) + \sec(\theta_v) \right]
\]

since

\[
R_\circ = R_s T_{tot}(\theta_o) T_{tot}(\theta_v) = R_s \exp(-\tau_{tot} \sec(\theta_o)) \exp(-\tau_{tot} \sec(\theta_v))
\]

\[
= R_\circ \exp(-\tau_{tot} [\sec(\theta_o) + \sec(\theta_v)])
\]

\( R_\circ \) is of course independent of all the cloud variables.

4.4 Model behaviour

In this section we test the model behaviour expressed by equation (1). The following table is a summary of the experiments; variables which are being tested in each section are shown italicised. Water clouds only are used for model testing.
<table>
<thead>
<tr>
<th>Test of:</th>
<th>Run</th>
<th>Cloud</th>
<th>Surface</th>
<th>Atmosphere</th>
<th>Geometry</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\tau$</td>
<td>$R_{\text{eff}}$</td>
<td>$R_s$</td>
<td>$\tau_{bc}$</td>
<td>$\tau_{ac}$</td>
</tr>
<tr>
<td>Cloud</td>
<td>1</td>
<td>1−128</td>
<td>8.</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1−128</td>
<td>1−20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Surface</td>
<td>3</td>
<td>1−128</td>
<td>8</td>
<td>0−50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>1−20</td>
<td>0−50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Geometry</td>
<td>5</td>
<td>1, 4, 16, 64</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1−128</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>7</td>
<td>1, 4, 16, 64</td>
<td>8</td>
<td>0−50</td>
<td>0−1.0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>16</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0−1.0</td>
</tr>
</tbody>
</table>

**Run 1** is a basic test of cloud reflectance or albedo change as optical depth is increased from 1 to 128. There are no atmospheric effects or surface reflection included and the cloud drop size is set to 8 µm; figure 4.4.1 shows the model output.

![Simulation cloud and atmospheric state](image)

Figure 4.4.1 Cloud reflectance as a function of optical depth.
All channels show monotonic increase of reflectance with optical depth. The conservative scattering at the VIS wavelengths (0.65, 0.8 µm) means that reflectance is still increasing even at optical depths of greater than 100 whereas absorption at the longer wavelengths causes the reflectance to saturate; at around \( \tau = 10^{1.5} \) for the 1.6 µm channel and \( 10^{0.7} \) for the 3.7 µm channel. The longer wavelengths give higher reflectances at low optical depths because of a slightly higher extinction efficiency caused by resonances in the Mie scattering which at these drop sizes (\( R_{\text{eff}} = 8\mu\text{m} \)) is around the limiting value of 2.0 but varying with oscillations of size around ±0.2.

The two VIS channels show very similar behaviour because of their near identical optical properties and for the remainder of this section we restrict ourselves to showing the 0.87 µm channel results. The utility of one VIS channel or the other in practice will come from their different surface and atmospheric absorption characteristics.

**Run 2** shows the behaviour of the reflectance function for varying \( R_{\text{eff}} \) and \( \tau \). The function for the 0.8 µm channel is a straightforward increase with \( \tau \) and very little dependence on \( R_{\text{eff}} \), what there is is due to small changes in extinction efficiency. The 1.6 µm channel shows similar behaviour for low \( \tau \) (<10^{1.0}) but with a more marked drop size effect especially around the 3 µm area.

For higher \( \tau \) the behaviour becomes markedly different, tending towards virtually no \( \tau \) dependence and a strong decrease with increasing \( R_{\text{eff}} \). The physical reason is the relatively small chance of absorption of photons by the water drops (typically 1% per encounter). For thin clouds and only a small number of scattering interactions, the reflectance remains dependent on the total number of water drops in the path, i.e. on \( \tau \). For thick clouds, the number of scattering events for photons reaching deeper parts of the cloud becomes large and the chance of these photons re-emerging from cloud top becomes correspondingly small. Consequently, adding more cloud depth has little effect on the reflectance. Larger drops are
more effective absorbers and consequently the reflectance is further suppressed. At 3.7 \( \mu \)m the chance of photon absorption per drop encounter is more like 10% and reflectances are considerably lower than at 1.6 \( \mu \)m and the region of dependence on \( \tau \) restricted to only the thinnest clouds.

**Run 3** is intended to check the dependence on surface reflectance and for this we show the reflectance as a function of \( \tau \) and \( R_s \).

![Graphs showing reflectance as a function of optical depth and surface reflectance for 0.8 \( \mu \)m, 1.6 \( \mu \)m, and 3.7 \( \mu \)m channels.](image)

**Simulation cloud and atmospheric state**
- Cloud: \( \tau = 128.0 \), \( R_{eff} = 8.0 \), Phase = 0
- Geometry: \( \theta_o = 30.0 \), \( \theta_v = 0.1 \), \( \phi = 30.0 \)
- Surface: \( R_s = 0.0 \)
- Atmosphere: \( \tau_{bc} = 0.00 \), \( \tau_{ac} = 0.00 \), \( \tau_{o3} = 0.00 \)

*Figure 4.4.2 Reflectance as function of optical depth and surface reflectance.*

We may expect asymptotes at optical depths corresponding to both vanishingly thin and semi-infinite clouds. In the first case the cloud-surface system should asymptote to the surface reflectance; and although the thinnest cloud displayed is \( \tau = 1 \), this behaviour does appear in all channels. (Note that for the thinnest clouds the contours of reflectance are nearly horizontal; the information on optical depth will become hard to extract for a given accuracy in the surface reflectance.) For very thick clouds the reflectance might be expected to be independent of the surface. This is especially true for the channels with some cloud absorption; it is less obvious perhaps where the scattering is strictly conservative. Again, the plots appear to support the expected behaviour.

The 3.7 \( \mu \)m plot has a different appearance to the other channels albeit with the same asymptotic behaviour. The reason is that the absorption is so strong in this channel that the addition of cloud can actually lead to lower reflectivities than the surface alone; the threshold in this case is around 16% (but dependent on \( R_{eff} \), and geometry of course).

**Run 4** shows again the effect of surface reflectance but this time with the drop size dependence and the cloud optical depth fixed at 2.0. As expected, the 0.8 \( \mu \)m channel reflectance is largely unaffected by drop size. Both the 1.6 and 3.7 \( \mu \)m reflectances for a given surface reflectance are reduced by increasing drop size as the absorption increases. The effect at 1.6
μm is small, at 3.7 μm it is substantial.

**Figure 4.4.4 Reflectance as function of effective radius and surface reflectance.**

**Run 5** essentially examines the reflectance function over all angular space. We have taken clouds with \( \tau = 1, 16 \) and 64 and a black surface.

**Figure 4.4.5 Reflectance as function of view zenith and relative azimuth angles.**

One feature of the plots which is physically necessary is that there should be no azimithal
dependence when the view angle is zero; azimuth is then effectively undefined. There is no strong angular dependence in any of the plots until the view angle reaches 40° or so. Then the forward (low azimuth) and backscattering peaks and the intervening low side reflectivity characteristic of Mie scattering becomes apparant. It is worth noting that even at $\tau = 64$ these features are not significantly removed by multiple scattering effects.

**Run 6** examines the dependence of reflectance on solar zenith angle. We show just the 0.8 µm channel here but both the reflectance function $\pi I/F_0$ and the normalised (effectively by the input energy per *unit area*) reflectance $\pi I/\mu_0 F_0$ (where $\mu_0 = \cos(\theta_o)$.)

**Figure 4.4.6** Reflectance as a function of solar zenith and optical depth. Normalised function on right.

Taking the left-hand plot first, the inflexion point at around $\theta_o = 10^\circ$ is the rainbow scattering feature. It *appears* to become washed out for thicker clouds but the right-hand plot of the normalised reflectance shows it retained up to very high optical depths. Thus scattering phase function effects are present in heavily multiple scattered radiance and this probably explains why the thick cloud normalised reflectance is lower with high solar angle in this case since this corresponds to side scattering. It is noticeable that the thin cloud limit for the un-normalised reflectance has approximately zero dependence on solar angle. This is intuitively and physically reasonable since in the limit of single scattering it is the *volume* of illuminated scatterer that determines the reflected energy, not the projected area. The volume is not a function of illumination angle. The normalisation thus ‘over-corrects’ in the thin cloud case.

**Run 7** examines the effect of the absorbing atmosphere below cloud. Values of $\tau_{bc}$ of 1 are extreme for window channels but this section is intended to demonstrate the behaviour of the model. The plots show reflectance, for cloud $\tau = 1, 16, 64$, and also as a function of $R_s$ since without surface reflection the below cloud absorption can have no effect. This can be seen as zero dependence at the bottom of each plot. In the top left plot for $\tau = 1$ the reflection is mostly generated by the surface term and the below cloud absorption has maximum effect in reducing it. By the time the cloud $\tau = 64$ most reflection is originating from the cloud itself, surface effects are relatively unimportant and the below cloud absorption has a
Figure 4.4.7 Reflectance as a function of below cloud optical depth and surface reflectance.

**Run 8** shows the effect of above cloud absorption for a cloud of $\tau = 16$. Again, values of $\tau_{ac}$ of 1 are unrealistically high and are for illustrating model behaviour only.

Figure 4.4.8 Reflectance as a function of above cloud optical depth and surface reflectance.

The simple and strong dependence of the reflection function on the above cloud optical
depth and the effect of view angle is seen. There is only a relatively small angle dependence present when there is no atmosphere (due to scattering angle), and a high dependence when an absorbing atmosphere is present.

Almost equivalent behaviour is found (not shown) for the dependence on solar zenith angle.

4.5 Gradient model behaviour

The sensitivity of the reflectance functions to the model input parameters is demonstrated in the figures of the previous section. How these sensitivities relate and impact parameter retrievals is a subject of later report sections. Here we simply test the coded gradient model, \( \partial R/\partial x \), by comparisons with finite differencing, \( R(x+\delta x) - R(x) \), for a selection of cloud-atmosphere states and channels.

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \tau )</th>
<th>( R_{\text{eff \mu m}} )</th>
<th>( R_% )</th>
<th>( \tau_{ac} )</th>
<th>( \tau_{bc} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. State: 0.8 ( \mu )m</td>
<td>4</td>
<td>8</td>
<td>5</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>( R(x+\delta x) - R(x) )</td>
<td>4.12741</td>
<td>−0.202274</td>
<td>32.2328</td>
<td>−30.1115</td>
<td>−7.70893</td>
</tr>
<tr>
<td>( \partial R/\partial x )</td>
<td>4.12242</td>
<td>−0.204805</td>
<td>32.3143</td>
<td>−29.7881</td>
<td>−7.51633</td>
</tr>
<tr>
<td>2. State: 1.6 ( \mu )m</td>
<td>4</td>
<td>8</td>
<td>5</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>( R(x+\delta x) - R(x) )</td>
<td>4.09870</td>
<td>−0.577354</td>
<td>28.0844</td>
<td>−36.0960</td>
<td>−6.71577</td>
</tr>
<tr>
<td>( \partial R/\partial x )</td>
<td>4.09357</td>
<td>−0.584908</td>
<td>28.1581</td>
<td>−35.7085</td>
<td>−6.54799</td>
</tr>
<tr>
<td>3. State: 0.8 ( \mu )m</td>
<td>1</td>
<td>8</td>
<td>2</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>( R(x+\delta x) - R(x) )</td>
<td>5.87435</td>
<td>−0.113702</td>
<td>0.662732</td>
<td>−7.95126</td>
<td>−0.063586</td>
</tr>
<tr>
<td>( \partial R/\partial x )</td>
<td>5.84529</td>
<td>−0.113659</td>
<td>0.662734</td>
<td>−7.86594</td>
<td>−0.062046</td>
</tr>
<tr>
<td>4. State: 3.7 ( \mu )m</td>
<td>16</td>
<td>4</td>
<td>2</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>( R(x+\delta x) - R(x) )</td>
<td>9.53674e-05</td>
<td>−0.782824</td>
<td>0.00338554</td>
<td>−11.5967</td>
<td>−0.00166893</td>
</tr>
<tr>
<td>( \partial R/\partial x )</td>
<td>5.02850e-05</td>
<td>−0.782844</td>
<td>0.00339056</td>
<td>−11.4723</td>
<td>−0.00165471</td>
</tr>
</tbody>
</table>

The differences are for the most part acceptably small and physically well behaved. The tests adequately demonstrate the validity of the coded gradient model.

5 Gaseous atmospheric transmission

In this section we examine the absorption of reflectance channel radiance by the atmosphere. In the model described above this absorption is accounted for with the above and below-cloud optical depths, \( \tau_{ac} \) and \( \tau_{bc} \) respectively. Transmittance calculations are made using LOWTRAN7 code (Kneizies et. al. Users guide to LOWTRAN7, AFGL Hanscom AFB, MA). We believe this model to be adequate for the present study given the low spectral resolution requirement of a radiometer like SEVIRI and the somewhat secondary nature of the atmosphere absorption effects on the reflectance wavelengths compared to the effects of
cloud and the surface. This position will be reviewed in the light of the results of this section and any recommendations to use more accurate / higher resolution modelling will be made there.

5.1 Transmission spectra

A modification was made to LOWTRAN7 – the contribution of molecular Rayleigh scattering was removed from the attenuation and hence transmittance calculation. This is done because the Rayleigh optical depth contributes entirely to scattering and not at all to absorption and it is inappropriate to include it as an absorption. That is not to say it is inconsequential; but it is a difficult effect to model simply and the size of the effect is studied in a later section. Figure 5.1 shows the transmittance spectrum (to space) from 0.5 to 2.0 µm for nadir (0° zenith) viewing in the standard LOWTRAN tropical atmosphere, with the surface at 0 Km. All transmittances and optical depths referred to in this section are for a single path; the reflectance model in section 4 deals with the two path absorption. Shown also is the transmittance spectrum if Rayleigh scattering is included.

![Figure 5.1]

Figure 5.1 Tropical atmosphere nadir transmittance spectrum. Rayleigh scattering is included in the spectrum shown by the dotted line.

The strong wavelength dependence of Rayleigh scattering is seen and we may conclude that it could have a significant effect on 0.6 µm reflectances, only a small effect on 0.8 µm reflectances, and no significant effect on any channels of longer wavelength.

We also at this stage do not include aerosol in the transmittance calculations. As for the Rayleigh effect, aerosols predominantly scatter at these wavelengths and they do not contribute a simple absorption effect.

Figure 5.2 shows transmittance spectra in detail around the 0.6 µm region, with spectra for paths to space from 0, 0.5, 1, 2, 4 and 8 Km representing the above cloud atmosphere for clouds at these heights. Water vapour absorption features with transmittances as low as 0.88 are apparent and these quickly disappear as the cloud base rises. Even for very high cloud
the transmittances do not rise above 0.97 or so and this remaining feature is due to ozone in the stratosphere.

Figure 5.2 Tropical atmosphere nadir transmittance spectra for different cloud heights around 0.6 µm.

Figure 2 gives the same information for the 0.8 µm region. Here, there is no ozone absorption and all the features are due to water vapour and disappear as the cloud becomes high.

Figure 5.3 Tropical atmosphere nadir transmittance spectra for different cloud heights around 0.8 µm.

A similar plot around 1.6 µm shows a substantial ‘clean’ window in the water vapour spectrum interrupted by the double peaked CO$_2$ lines around 1.57 and 1.60 µm. Because, unlike water vapour, CO$_2$ is well mixed throughout the atmosphere, the feature persists even for the
8 Km cloud surface.

Figure 5.4 Tropical atmosphere nadir transmittance spectra for different cloud heights around 1.6 µm.

The 3.7 − 4 µm window is much less transparant than that for the other regions shown here, figure 5.5, note the transmittance scale compared to previous plots. Again, the predominant absorber is water vapour. Note that in all these figures where water vapour is the main absorber, that the transmittance increases rapidly as the cloud top rises from the surface and more slowly for greater altitudes.

Figure 5.5 Tropical atmosphere nadir transmittance spectra for different cloud heights around 3.9 µm.
We should also note here, that unlike for the 0.6 – 1.6 µm channels where the absorption can be modelled according to the simple method described in section 4, at 3.9 µm absorption implies emission and the reflectance model will not be adequate.

5.2 Channel transmissions

The following figures show the relationship of the SEVIRI channel response functions to the transmittance features. Also shown are the equivalent ATSR-2 functions since the proposal is to use the ATSR-2 to demonstrate the potential of SEVIRI measurements.

![Transmittance spectra](image)

Figure 5.6 Nadir tropical transmittance spectrum (0 Km – TOA) and SEVIRI (....) and ATSR−2 (- - -) response function for the 0.6 and 0.8 µm channels.

Figure 5.6 shows the SEVIRI 0.6 and 0.8 µm channels to be significantly broader than the ATSR-2 equivalents. In the case of the 0.6 µm channels the SEVIRI version encompasses the whole of a double peaked water feature but the ATSR-2 version, despite being narrower, appears misplaced (in this context at least) by being coincident with the large peak. Channel, or band averaged transmittances are defined as $T_i = \int \phi_i(\lambda) . T(\lambda) / \int \phi_i(\lambda)$ where $\phi_i(\lambda)$ is the i\textsuperscript{th} channel filter response and $T(\lambda)$ the spectral transmittance. For the 0.6 µm channels and this transmittance profile we find $T_{0.6} = 0.964$ for the SEVIRI version, and $T_{0.6} = 0.950$ for the ATSR-2 version corresponding to optical depths of 0.0363 and 0.0513 respectively.

For the 0.8 µm channel the ATSR-2 function is well placed to avoid a strongish water feature which the SEVIRI version again totally covers giving rise to a SEVIRI $T_{0.8}$ of 0.911 and an ATSR $T_{0.8}$ of 0.950 ($\tau_{ac} = 0.093, 0.022$ respectively).

Figure 5.8 shows the 3.9 µm channels although we should note that the SEVIRI version is,
at the time of writing, a simulated filter response based on a central wavenumber and a spread (derived using MSGFILTER routine supplied by EUMETSAT). The window is, as described, relatively dirty compared to the shorter wavelength channel windows.

Figure 5.7 Nadir tropical transmittance spectrum (0 Km – TOA) and SEVIRI (....) and ATSR−2 (- - -) response function for the 1.6 µm channel.

Figure 5.7 Nadir tropical transmittance spectrum (0 Km – TOA) and SEVIRI (....) and ATSR−2 (- - -) response function for the 3.7 / 3.9 µm channel.

With the caveat that the SEVIRI 3.9 µm filter response shown is synthetic, it does appear to run to wavelengths too high to be considered still in the window region. Nevertheless, because the SEVIRI function is biased towards the cleaner end of the window, the channel averaged values for this case are not too dissimilar with $T_{3.9} = 0.660$ for SEVIRI and 0.682 for ATSR-2 ($\tau_{ac} = 0.416, 0.383$ respectively).
5.3 Above-cloud optical depths, $\tau_{ac}$

We now examine the effect of the cloud altitude on the channel transmittances (cf figs 5.3 through 5.5). Again, we show both SEVIRI and ATSR-2 values for the tropical profile nadir view and express the values now as equivalent optical depths ($\tau = -\ln(T)$) since this is the variable on which the reflectance model is based. Figure 5.8 shows the four channels separately, with the ATSR-2 lines marked by + symbols.

![Figure 5.8 Channel above-cloud optical depths as a function of cloud height.](image)

Note the variation in optical depth scale between the plots. All channels show the fast decrease as the cloud rises above low-level water vapour and most decrease to near zero for very high levels. The exception to this is the 0.6 \(\mu\)m channel where both instrument optical depths tend to a non-zero value because of the previously noted ozone absorption. The SEVIRI asymptote is slightly higher because the channel is shifted nearer the ozone line centre around 0.58 \(\mu\)m. The ATSR-2 optical depths are higher for low cloud because of the coincidence with the water vapour feature at 0.65 \(\mu\)m. Maximum differences are around 0.01.

As expected from previous results, the 0.8 \(\mu\)m channels differ markedly because the SEVIRI channel overlaps a strong water feature and the ATSR-2 version misses it. Maximum differences of 0.07 at the surface are possibly quite significant in the interpretation of ATSR-2 and SEVIRI measurements.

It is perhaps a little surprising that the 1.6 \(\mu\)m channels appear so well matched given the observation earlier that the SEVIRI channel is on the edge of the water window and the ATSR-2 version covers the CO$_2$ feature. However, the slightly faster initial decrease in the SEVIRI optical depth is consistent with this.

The 3.9 \(\mu\)m (ATSR-2 ~ 3.7 \(\mu\)m) shows distinctly, by a slow asymptote at high levels, the
fact previously noted that the supplied SEVIRI filter significantly runs into the 4.3 µm CO₂ band.

These plots show that, although we can expect to simulate SEVIRI capabilities quite well with ATSR-2 data, there are significant differences. We may expect the SEVIRI 0.6 µm channel to be easier to interpret than the ATSR-2 version since ozone effects are more readily estimable than water vapour. The water contamination of the SEVIRI 0.8 µm channel is very apparent and the impact of this must be considered carefully as an examination of figure 4.3.8 with \( \tau_{\text{ac}} \sim 0.08 \) will confirm. Similar considerations apply to the 1.6 µm channel although both instruments have similar levels of atmospheric contamination in this case. For the 3.9 µm channel, assuming the filter response given, interpretation of the SEVIRI channel will be more sensitive to atmospheric temperatures at high level than the ATSR-2, but less sensitive to water vapour. This could turn out to be an advantageous.

5.4 Sensitivity to specification of the atmosphere

In this section we aim to show the sensitivity of the atmospheric channel transmittances to the specification of the atmosphere. In practice, it is likely that the atmosphere assumed in a cloud property algorithm would be based on NWP model output and therefore relatively accurate compared to an assumption based on climatology. Therefore, the ‘errors’ in SEVIRI channel transmittances simulated in figure 5.9 by way of LOWTRAN tropical and midlatitude summer profiles are therefore is probably significantly higher than we may expect in an operational scheme.

![Graphs showing atmospheric channel transmittances and differences](image)

Figure 5.9 SEVIRI channel above-cloud optical depths as a function of cloud height for LOWTRAN tropical and midlatitude summer profiles.

Only in the 0.6 µm channel case are midlatitude profile optical depths higher than tropical values and this is no doubt due to higher ozone column amounts away from the tropics. Maximum differences are around 0.03–0.04. In all other channels the drier midlatitude pro-
file leads to lower optical depths and errors that are only likely to be significant for cloud tops below 5 Km. Maximum differences are around 0.01–0.02 for the 0.8 and 1.6 µm channels and 0.03–0.04 for the 3.9 µm channel.

5.4 Below-cloud optical depths, $\tau_{bc}$

Below cloud optical depths are calculated using a mean transmission angle of 66° to represent the net effect of diffuse transfer through the absorber. Figure 5.10 shows optical depths for the four channels for tropical and midlatitude atmospheres. The 3.9 µm goes off-scale but because for this channel the simple transmission model is not appropriate we don’t consider it further here.

![Figure 5.10 SEVIRI channel below-cloud optical depths as a function of cloud height for LOWTRAN tropical and midlatitude summer profiles.](image)

All optical depths almost reach their maximum values by the time the cloud is at 5-6 Km, and all midlatitude values are lower than the tropical ones. Note that the values are quite high compared to nadir above cloud values shown earlier, simply as a result of the effective angle used. The difference between midlatitude and tropical is small but significant. NWP based atmospheres would probably reduce errors in transmittance from this source to an insignificant level, but this needs to be ascertained.

5.6 Accuracy of the path-length approximation

The reflectance model developed in section 4 makes use of what we may call a path length approximation to scaling optical depths according to view angle. That is, we assume $\tau(\theta) = \tau(0) \times \sec(\theta)$. This is strictly only true for monochromatic radiation but is quite often valid for weakly absorbing finite bandwidth situations. We test the approximation here by calculating channel optical depths for nadir (0°) and 60° zenith views and compare to the path-
length approximation (which in this case is $\tau(60^\circ) = 2 \times \tau(0^\circ)$).

![Graphs showing SEVIRI channel above-cloud optical depths as a function of cloud height for LOWTRAN tropical profile at 0 and 60° view zenith compared to the path length approximate values.](image)

Figure 5.11 SEVIRI channel above-cloud optical depths as a function of cloud height for LOWTRAN tropical profile at 0 and 60° view zenith compared to the path length approximate values.

Generally speaking the approximation works best, as expected, for channels with low optical depth. The approximate value is nearly always greater than the ‘exact’ value because it does not allow for overlapping spectral lines. For the 0.6 μm channel the approximation is extremely good with errors less than 0.002. At 1.6 μm also, maximum errors of 0.01 for near surface cloud levels are less than, for example, the tropical-midlatitude difference found in section 5.4. Errors in the 0.8 μm channel are somewhat higher at around 0.03 near surface, and comparable or greater than the tropical-midlatitude difference. Finally, the high optical depths at 3.9 μm mean the approximation is quite poor with errors as large as 0.15 when the total optical depth is 0.7, but to reiterate, the need to calculate radiative emission means that we are unlikely to use the path length approximation at this wavelength.

These figures will be useful in judging whether transmittances will ultimately need to be calculated at all relevant geometries (solar, view, diffuse equivalent angle) or whether the more economical path-length method is acceptably accurate. We suggest, for the present purposes of simulating SEVIRI radiances and retrievals that the approximation is valid. For any real data interpretation the effect of the errors will have to be addressed.

6. Errors due to molecular and aerosol scattering

The visible (and infrared) radiative transfer models used in the study do not include any effects due to molecular or aerosol scattering. The difficulties in adequately modelling these scattering effects were outlined in WP1.4 §1. Rayleigh (molecular) optical depths can be simply obtained from an accurate parameterisation by Hansen and Travis (Space Sci. Rev. 16,
527 1974) which gives the full atmosphere \((p_s = 1013 \text{ mb})\) value as

\[
\tau_s = 0.008569 \lambda^{-4} (1 + 0.0113 \lambda^{-2} + 0.00013 \lambda^{-4})
\]

and the corresponding value for the atmosphere above a certain pressure, \(p_c\), is

\[
\tau(p_c) = \tau_s p_c / p_s
\]

Figure 6.1 shows the nadir rayleigh optical depths to space as a function of \(p_c\); values can be seen to be negligible in the 1.6 \(\mu\)m channel, small in the 0.87 \(\mu\)m and perhaps significant in the 0.67 \(\mu\)m channel.

Equally straightforward is the reflectance this optical depth produces in the single scattering case:

\[
R_s(\mu_v,\mu_o) = \tau P(\phi) / 4 \mu_v \mu_o
\]

where \(\mu_v\) and \(\mu_o\) are the cosines of the view and solar zenith angles respectively. \(P(\phi)\) is the scattering phase function which is given by

\[
P(\phi) = \frac{3}{4} (1 + \cos^2(\phi))
\]

where \(\phi\) is the scattering angle. Over a dark (non-reflecting surface) this single scatter expression is quite accurate as the comparison in figure 6.2 shows. The calculation in this case is for 0.55 \(\mu\)m full atmosphere so that the reflectances are about 2 times higher than for the 0.67 \(\mu\)m SEVIRI channel for example. The strong increase towards high view zenith angles is the 1/\(\mu\) ‘airmass’ effect of viewing through a larger scattering volume. The azimuthal structure is the effect of the phase function which varies from 0.75–1.5 depending on scattering angle. Errors in the single scattering model are 5% or less up to view zenith angles of 70°.

A simple single scatter model is also possible given a Lambertian reflecting underlying surface; in this case the reflection of the surface-molecular layer system is given by
R_{ss}(\mu,\mu_o) = \tau P(\phi)/4\mu\mu_o + R_s(1-\tau/2\mu_o)

where $R_s$ is the underlying surface reflectance. This approximation also works well (compared to exact calculations using DISORT) for $R_s < 30\%$ above which the single scattering overestimates the reflectance (results not shown). In any case, the assumption of isotropic scattering is not good for clouds (see figure 4.4.5) so a simple model may not be appropriate for this reason also. Rayleigh scattering is fairly isotropic (see form of P(\phi) above) so that a Rayleigh layer above a cloud layer can potentially increase the total reflectance (if the geometry is near side scattering – low cloud reflectance) or decrease it (if the geometry is near forward scattering). The other inadequacy of a simple single scatter model is that is cannot account for under-cloud effects.

We have been unable therefore to simply answer the question of the effect of molecular scattering of the accuracy of the reflectance radiative transfer model, but hope to have given an idea of the size of the problem. Certainly for measurements from channels other than the 0.67 \mu m and within reasonable viewing and solar angles, the noise effect will be small.

The question of the aerosol effect is, of course, still more complicated. The optical depths are liable to be larger (0.1 at 0.55 \mu m is a reasonable quantity); the location, composition and scattering characterisits are much less well known. The question of aerosol effects on the SEVIRI measurements constitutes a large research area and is not one we can answer to any useful level here. For cloud parameter retrieval, the only mitigating circumstance is that tropospheric aerosols at least will be mostly located below the cloud level.

7 Channel co-registration and non-plane-parallel cloud errors

Apparant errors in the radiative transfer models arise from two further sources. Firstly, any co-registration errors will mean that different scenes are viewed by the SEVIRI channels and, depending on the scene contents, this will lead to a degree of discrepency in the measurements that the plane-parallel cloud model will not represent. This can be considered as a noise source. The second apparant error is due to the cloud in the scene approximating poorly to a plane-parallel cloud. Structure in the cloud top, for example, can give rise to different effective solar geometries; finite extent clouds ‘leak’ radiation from the side and interact with neighbouring clouds. It is a large subject and all we hope to do here is obtain some broad indication of the level of effective noise that non plane-parallel clouds produce.

Both these apparant sources can be estimated to some extent using ATSR-2 data. Results are presented for both reflectance and infra-red channels since the same techniques are used.

7.1 Co-registration noise estimates

In the case of the co-registration error, the estimation is possible because the 1 km ATSR pixel is much smaller than the SEVIRI pixel (~6 km) and of the same order as the expected co-registration shifts (~0.6 km, MSG Data format description document). Small areas of ATSR data over selected cloud types are chosen and the SEVIRI measurements simulated by averaging measurements over 6×6 ATSR pixels. SEVIRI measurements derived with a 1
ATSR pixel shift are also derived and the two are compared. This results in an estimate of co-registration noise for a 1 km co-registration error. This a reasonably accurate estimation and the only difficulty lies in translating the error found for a 1 km shift into an error for a 0.6 km shift. Here we have simply divided the resulting errors by a factor of 2; doubtless more sophisticated methods are possible but do not seem warranted at this stage, i.e. pre-launch. Post-launch there are several techniques available to estimate co-registration noise and even the co-registration error, assuming it is reasonably constant.

Using this method, estimates were made for each of the ATSR-2 channels over a variety of cloud types and solar-angles. Areas were chosen that did not include obvious cloud edges. Such areas would clearly give larger noise estimates and could be studied to obtain values appropriate to retrieval situations were the SEVIRI pixel was only fractionally covered in cloud; this has not been done here. Effects at 0.67 and 12 µm are assumed to be the same as at 0.87 µm and 11 µm respectively. Nighttime results for the 3.7 µm channel are also assumed to be the same as the 11 µm channel. Results are shown in table 7.1, values for the reflectance channels are in absolute reflectance×100 (%). The 11 µm results are of course not expected to depend on solar angle and they serve only to show the level of variation resulting from different scenes of the same type. There are clearly significant variations suggesting that these figures can only be used as a guide.

The table results are shown graphically in figures 7.1 and 7.2 for the reflectance and thermal channels respectively. The values for the reflectance channels are now normalised by the mean signal for the scene and expressed as a %, i.e. δR/R×100. Expressed in this way, we see from figure 1 that there is surprisingly no distinct trend in the reflectance channel noise with solar angle. There is a suggestion that the 1.6 µm noise levels are higher than the 0.87 µm for the more stratified cloud and lower for the cumuliform. The overall variation with cloud type is obvious and intuitively reasonable. Similar comments apply to figure 7.2 for the infrared channels where we expect no variation with solar angle.

From the results shown we have designated noise levels due to co-registration errors in SEVIRI according to the values in table 7.2. The factor of 2 to allow for the 0.6 km (rather than 1 km) co-registration error has been incorporated and any dependence on solar angle has been removed.

Finally, we make a brief examination of the effect of the size of the SEVIRI pixel on the noise levels from this source. Figure 7.3 shows the noise found for a 1 km co-registration error for a variety of cloud types and for a SEVIRI pixel of sizes ranging from 3 to 15 km. In all cases and for all channels the noise reduces as the size of the pixel increases.

The general levels of noise are comparable to the figures in the tables given the variability of the estimates and the dependency on scene. In the cumulus case, some edges were present giving rise to the rather high values. A low dependency on pixel size is seen for the cumulo-nimbus case (CnNm) because of the low scene variability in the convective anvil. In the stratocumulus case, the 0.87 ( and 0.67) µm channel has the highest values because of small scale variations in optical depth giving rise to large reflectance variations. In the infrared, the higher cloud opacity and low contrast of cloud and surface temperature in this case lead to low noise estimates.
Co-registration noise estimates: 1 km shift

<table>
<thead>
<tr>
<th>Cloud scene</th>
<th>Solar zenith</th>
<th>0.87 µm %</th>
<th>1.6 µm %</th>
<th>3.7 µm (day) K</th>
<th>11 µm K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratus/fog</td>
<td>20°</td>
<td>1.9</td>
<td>1.0</td>
<td>0.6</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>50°</td>
<td>1.9</td>
<td>0.4</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>70°</td>
<td>0.3</td>
<td>0.1</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Stratus/Sc</td>
<td>20°</td>
<td>1.0</td>
<td>1.1</td>
<td>–</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>50°</td>
<td>3.0</td>
<td>1.0</td>
<td>0.4</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>70°</td>
<td>0.7</td>
<td>0.3</td>
<td>0.3</td>
<td>0.21</td>
</tr>
<tr>
<td>Cumulus</td>
<td>20°</td>
<td>5.8</td>
<td>3.2</td>
<td>3.2</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>50°</td>
<td>2.1</td>
<td>2.7</td>
<td>2.3</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>70°</td>
<td>1.2</td>
<td>0.6</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Cumulonimbus</td>
<td>20°</td>
<td>0.9</td>
<td>0.3</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>50°</td>
<td>1.6</td>
<td>0.5</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>70°</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cirrus/ Cs</td>
<td>20°</td>
<td>1.2</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>50°</td>
<td>1.0</td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>70°</td>
<td>0.4</td>
<td>0.2</td>
<td>0.6</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 7.1. Co-registration noise estimates for various scenes and solar angles

---

Co-registration noise estimates: 0.6 km shift

<table>
<thead>
<tr>
<th>Cloud scene</th>
<th>0.87 µm % of signal</th>
<th>1.6 µm % of signal</th>
<th>3.7 µm (day) K</th>
<th>11 µm K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Stratus/fog</td>
<td>3</td>
<td>2</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>2 Stratus/Sc</td>
<td>4</td>
<td>3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>3 Cumulus</td>
<td>6</td>
<td>10</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>4 Cumulonimbus</td>
<td>2</td>
<td>3</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>5 Cirrus/ Cs</td>
<td>2</td>
<td>2</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 7.2. Co-registration noise estimates used in study
Figure 7.1 Co-registration noise levels for the reflectance channels at various scene types and solar angles

Figure 7.2 Co-registration noise levels for the infrared channels at various scene types and solar angles
Homogeneity noise estimates

In the case of what we may call cloud ‘homogeneity’ errors, two comparisons can be made from using ATSR-2 data: from ‘nadir’ and ‘along-track’ views of the same cloud scene at one wavelength and two different wavelengths from one view. In either case, plane parallel clouds should show a simple co-linear fit (assuming a small enough region is chosen so that basic cloud and atmospheric parameters are constant). Deviations from the co-linear fit show the deviations from plane-parallel cloud. The nadir/along-track comparison will normally tend to overestimate homogeneity noise because there may be perfectly good plane-parallel cloud equivalents at both views angles which, however, are not the same. It also has the potential to underestimate noise because, by comparing only single wavelengths, it will hide any inter-channel inconsistencies. This latter drawback is perhaps avoided in the nadir/nadir interchannel comparison but this method fails to detect any angular effects.

An example is shown in figure 7.4; a nadir/along-track comparison for the 0.87 µm channel.
over a stratus region with the solar angle of 70°.

Figure 7.4. Homogeneity effects from nadir/along track comparison at 0.87 µm over stratus field with solar angle 70°. Results at ATSR (1km, top) and SEVIRI (6 km, bottom) resolutions shown. Left plots show comparisons with the cloud height parallax effect in ATSR dual-view data, right plots are with parallax removed.
Figure 7.5 shows an example of nadir/nadir comparisons; 0.67/0.87 and 1.6/0.87 µm channels, over stratocumulus with a solar angle of 50°.

![Graphs showing at upper and lower precision between ATSR and SEVIRI resolutions](image)

Figure 7.5. Homogeneity effects from nadir/nadir comparison at 0.67/0.87 (top) and 1.60/0.87 µm (bottom) over Sc field with solar angle 50°. Left plots show comparisons at ATSR resolution, right plots at SEVIRI resolution.

Figure 7.4 demonstrates that clouds appear more plane-parallel when the broader SEVIRI pixel is used to measure them. Figure 7.5 demonstrates one of the problems of the nadir/nadir approach; the area selected, although small, probably has a range of drop sizes causing varying signal in the 1.6 µm channel. This is not a noise source - it is the signal.

The test cases used above for the co-registration results were used in the homogeneity study and we do not present the tabulated details in this case. Again, we find no significant dependency on solar angle and the dependence on cloud type is obvious and intuitively reasonable (not shown). Table 7.3 gives the values we have extracted from the study on homogeneity effects. They are somewhat conservative estimates to allow for the difficult nature of the estimation.
Homogeneity noise estimates

<table>
<thead>
<tr>
<th>Cloud scene</th>
<th>0.87 µm % of signal</th>
<th>1.6 µm % of signal</th>
<th>3.7 µm (day) K</th>
<th>11 µm K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Stratus/fog</td>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td>0.05</td>
</tr>
<tr>
<td>2 Stratus/Sc</td>
<td>2</td>
<td>1</td>
<td>1.0</td>
<td>0.04</td>
</tr>
<tr>
<td>3 Cumulus</td>
<td>4</td>
<td>8</td>
<td>3.0</td>
<td>0.5</td>
</tr>
<tr>
<td>4 Cumulonimbus</td>
<td>3</td>
<td>5</td>
<td>1.0</td>
<td>0.05</td>
</tr>
<tr>
<td>5 Cirrus/ Cs</td>
<td>2</td>
<td>5</td>
<td>1.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 7.3. Homogeneity noise estimates used in study

In summary:

Estimation of co-registration noise to be expected in the SEVIRI system by the method described above are expected to be reasonably representative given the uncertainty in the exact nature of the co-registration errors and the scene dependency of the effect.

The homogeneity noise estimation is a much less certain process and subject to many problems of interpretation. We have estimated and present figures according to the method proposed but cannot express much confidence in them. Experience with the inversion procedure developed and implemented on real data (WP2.5 and WP4 respectively) has suggested that a more powerful and reliable method of estimating homogeneity errors will be available. Diagnostics of the inversion, especially the measurement residuals at the solution, are a strong indication of the ability of the the plane-parallel model to fit the measurements. One component of this fitting ability, is of course the homogeneity error, but there are other components and these have to be interpreted carefully to extract the required information. For more discussion on these points see WP4.

With these caveats in mind, we have used the figures described above in retrieval simulation studies (WP2.5 §3.4) and in data retrieval experiments (WP4).
1. Overview

Cloudy atmosphere radiative transfer in the thermal region (3 – 12 µm) differs from that in the visible (0.6 – 4 µm) in two significant ways. The non-zero Planck function at thermal wavelengths means that the gaseous atmospheric effects involve emission as well as absorption, and the simple transmission model employed in WP2.1 for the visible channels is not adequate. However, the cloud effects are simpler in the thermal channels since the solar flux is essentially zero; there are no directional beams and the geometry required reduces to a simple function of the view zenith angle. The SIR channel of course is exceptional in that it requires consideration of both solar beam and emission / absorption terms.

Line by line (lbl) calculations for the thermal channels are too time consuming to be considered as an option, certainly in an operational sense, and cumbersome even for studies. Here, we use an existing fast model (Eyre, 1989) which parameterises lbl results.

Section 2 describes the cloud particle optical properties and the multiple scattering calculations. Section 3 documents the treatment of the atmospheric or gaseous absorption; calculation of channel transmittances using a line by line model, parameterisation of these transmittances in a fast model and the cloud-atmosphere model adopted. Section 4 tests the model behaviour in a variety of situations.

2. Optical and cloud bulk properties

Optical properties at IR wavelengths have been derived in the same manner as that derived for VIS wavelengths and described in WP2.1 section 2. The comments made in that section on the current problem with optical properties of ice apply here also since the same size distributions have been used. We show in figure 2.1 the phase functions and single scatter albe-
dos, $\omega_o$, for the SIR and IR channels for the four ice cloud types described in WP2.1.

DISORT multiple scatter code is used to derive the cloud bulk radiative properties and the results stored in LUTs. Table 1 is analogous to Table 1 of WP2.1 and shows the relevant radiative properties and their dependencies.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>symbol</th>
<th>$\lambda$</th>
<th>$R_e$</th>
<th>$\tau$</th>
<th>$\theta_v$</th>
<th>$\theta_o$</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity</td>
<td>symbol</td>
<td>wavelength</td>
<td>cloud particle size</td>
<td>cloud optical depth (at 0.55 µm)</td>
<td>solar zenith angle</td>
<td>view zenith angle</td>
<td>relative azimuth</td>
</tr>
<tr>
<td>Beam bi-directional reflection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam transmission: Direct</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffuse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffuse Transmission</td>
<td>$T_D$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffuse Reflection</td>
<td>$R^2_D$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emissivity</td>
<td>$\varepsilon_c$</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Except for the SIR channel - see WP2.1 section 2.

2Note that, unlike for the VIS model where a flux value is used, a directional (view zenith angle) diffuse reflection is required for the IR.
Values of the bulk radiative properties are obtained from the LUTs by linear interpolation (in $R_e$, $\tau$ and $\theta_v$). The following figures give the essential characteristics of emission, reflection and transmission for water clouds. Figure 2.1 shows the behaviour with optical depth. The drop size is 8 µm and the view zenith 0°.

The emissivity in the IR channels asymptotes to very nearly unity for $\tau > 7$ with the 12 µm channels showing greatest absorption and hence emissivity, and the 8.7 µm showing the least. The SIR channels, as expected, show significant effects of scattering (see WP2.1) and emissivity for these never exceeds 80% even for optically thick clouds. Reflectivities are negligible for the IR channels except marginally the 8.7 µm where there are values of around 2%. The SIR channels are not surprisingly quite reflective, 15 – 20% for optically thick clouds, with the 3.9 µm SEVIRI channel slightly more reflective than the ATSR-2. Transmissions follow consistently, with the 12 µm channels most absorbing and therefore least transmitting and the SIR channels transmitting most. These results are consistent with the basic optical properties of the drop distribution as shown in the following table.

<table>
<thead>
<tr>
<th></th>
<th>SEVIRI 3.9 µm</th>
<th>8.7 µm</th>
<th>11 µm</th>
<th>12 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_o$</td>
<td>0.926</td>
<td>0.775</td>
<td>0.445</td>
<td>0.345</td>
</tr>
<tr>
<td>$g$</td>
<td>0.768</td>
<td>0.879</td>
<td>0.882</td>
<td>0.856</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ATSR-2 3.7 µm</th>
<th>11 µm</th>
<th>12 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_o$</td>
<td>0.908</td>
<td>0.413</td>
<td>0.350</td>
</tr>
<tr>
<td>$g$</td>
<td>0.750</td>
<td>0.880</td>
<td>0.855</td>
</tr>
</tbody>
</table>

Table 2.1 IR optical properties for an $R_e$ of 7 µm

Notice the high single scatter albedo, $\omega_o$, for the SIR channels, the low values for the 11 and
12 µm and intermediate value for the 8.7 µm channel. The asymmetry parameter probably does not have much of an effect on the radiative properties in these strongly absorbing cases. The SEVIRI and ATSR-2 $\omega_o$ for the SIR channels differ appreciably leading to the lower emission at 3.9 µm; however, significant differences between the 11 µm channels do not lead to differences in the bulk properties. The explanation for this probably lies in a compensating effect from the extinction efficiencies; the small wavelength shift means that $Q_{\text{ext}}(\text{SEVIRI})/Q_{\text{ext}}(\text{ATSR}) \sim 1.3$ for the 11 µm channel and the lower absorption for SEVIRI given by the $\omega_o$ value is balanced by the greater extinction.

Figure 2.2 shows emissivities at $\tau = 5$ for the four SEVIRI channels as functions of both view zenith angle, $\theta_v$, and drop effective radius, $\mu$.

In all cases the emissivity increases with increasing drop size in accordance with the lower $\omega_o$ for larger drops (e.g. the 8.7 µm $\omega_o$ for $R_e = 3$ is 0.689; for $R_e = 15$ it is 0.666). The SIR channels show the lowest emissivities. Emissivities also increase slowly for increasing view angle, the cloud effectively appears thicker away from nadir. There is a curious decrease for angles greater than 55 − 60°, certainly in the 3.9 and 8.7 µm channels if not the 11 and 12 µm. This is probably due to scattering phase function effects.

Figure 2.3 are the channel transmissivities shown in the same way. In all cases there is a decrease in transmission as the view angle increases such that for angles greater than 60 − 70° there is effectively no transmission. Transmission also increases for small drop sizes because of the increased scattering. Similarly, the 3.9 µm channel is most transmissive, and the 12 /µm channel the least. Again, there is an angular effect, this time around nadir; the nadir transmissions are slightly lower than values around 10 − 20°. The transmission case is a little easier to argue intuitively than the emission, and it is reasonable to suggest the minimum at nadir is due to strong backscatter (the ‘Glory’) of the incident diffuse radiation a few de-
The reflectivities shown in figure 2.4 show a gradual increase with decreasing drop size as expected from the increasing scattering albedo. A sharp change in contour at $R_e = 3 \mu m$ is due to rapid changes in both $Q_{ext}$ and $\omega_o$ at small drop sizes. There is a quite rapid increase in...
of reflectivity with view angle as expected from the increased cloud path length observed. There is some evidence, perhaps, of enhanced backscatter as reflectivities do not continue to fall off rapidly around nadir.

3. Atmospheric emission and absorption

3.1 LOWTRAN transmissions

In this section we present results of LOWTRAN7 transmittance calculations in order to gain a broad feel for the atmospheric effect on SEVIRI and other instrument channels. We have dealt with the SIR channels, the ATSR-2 3.7 µm and the SEVIRI 3.9 µm, in WP2.1 section 5.2 and do not repeat here.

![Figure 3.1 LOWTRAN tropical nadir transmittance spectra for cloud tops at 0, 1 and 4 Km and superimposed 8 µm channel filter functions.](image)

The HIRS filter is a measured function, the SEVIRI is (as with the other SEVIRI IR channels) a synthetic function, and the MODIS function is a gaussian fitted to the quoted central and half power wavenumbers. (The MODIS channel given here is relevant to the FIRE campaign MODIS airborne simulator, MAS, measurements.) The main atmospheric window is between water absorption below 8 µm and ozone at 9.6 µm. The HIRS channel is not well placed and for the 0 Km calculations gives a channel transmittance of 0.31. Both the SEVIRI and MODIS filters are better placed in the window and have channel transmittances of 0.55 and 0.54 respectively. The gaussian fits to the MODIS information we have is likely to give broader functions than actual. We are currently making enquiries for better information on the MODIS filters and do not include further analysis here in the meantime.

The rapid increase in transmission as the lower surface is raised shows the absorption is mainly by water vapour. For cloud at 4 km the channel transmittances are 0.78, 0.91 and 0.89 for HIRS, SEVIRI and MODIS respectively.

The ATSR-2 and SEVIRI 11 µm channels are well matched and since the 11 µm window
region beyond the 9.6 µm ozone feature is quite broad, the differences between them will be quite small. Figure 3.2 shows the two channels, again for LOWTRAN tropical nadir transmittances.

Figure 3.2 LOWTRAN tropical nadir transmittance spectra for cloud tops at 0, 1 and 4 Km and superimposed 11 µm channel filter functions.

Channel averaged transmittances for 0 Km cloud level are 0.561 and 0.551 for the SEVIRI and ATSR-2 respectively. For 4 Km cloud the values are 0.960 and 0.963 and the figure shows the slope of the water continuum absorption has essentially gone and only mixed gas absorption remains.

Figure 3.3 LOWTRAN tropical nadir transmittance spectra for cloud tops at 0, 1 and 4 Km and superimposed 12 µm channel filter functions.
Figure 3.3 shows a similar situation regarding the ATSR-2 and SEVIRI 12 µm channels. They are well matched as is indicated by the channel transmittances of 0.393 and 0.387 for the 0 Km cloud and 0.932 and 0.932 for the 4 Km cloud; SEVIRI and ATSR-2 respectively.

3.2 Line by line reference calculations

The radiative transfer model (RTM) of Zavody et. al. 1995 uses atmospheric transmission values calculated at a resolution of 0.04 cm$^{-1}$. The HITRAN database of Rothman et al (1996) was used for the line parameters, and even contributions from gases having a very minor effect (NH3, N2O, etc) have been considered. In order to speed up the computations, the model uses a data base holding absorption data pre-calculated for standard pressures and temperatures. The total absorption at any height is obtained by interpolating to the appropriate pressure and temperature, and then scaling by the absorber amount.

For the fast model parameterisation, RTM is run for 32 profiles covering a large range of conditions from polar to tropical atmospheres; these are shown in figure 3.4.

![Figure 3.4 Temperature and humidity profiles for the 32 profiles used in the fast model parameterisation. Mean profile is shown by a solid line.](image)

Note that we expect the variations in humidity to be of greatest importance for the radiative transfer. The profiles have been interpolated to the standard set of pressure levels given in table 2 which are the levels employed by the fast model.

<table>
<thead>
<tr>
<th>Standard pressure levels (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>115</td>
</tr>
<tr>
<td>500</td>
</tr>
</tbody>
</table>

Table 2. Standard pressure levels
Monochromatic attenuations from each level to space are calculated by the RTM and the attenuation due to variable gases (i.e. water vapour) and ‘constant’ mixed gases (mostly CO₂) stored separately. Calculations are also performed over five zenith angles equally space in sec(θ) from sec⁻¹(1.0) to sec⁻¹(3.0). Mean attenuations over the channel filter response functions are calculated.

Figure 3.5 shows transmission profiles from two of the atmospheres for the SEVIRI 11 µm channel.

The mixed gas contributions are relatively small in both profiles and decrease consistently towards the top of atmosphere. The water transmission however, shows a sharp decrease over the lower 2-300 mb as expected.

Figure 3.6 shows the same for the SEVIRI 3.9 µm channel. It is noticeable that the mixed gas transmissions are much lower than for the 11 µm case; a consequence of the filter running into the 4.3 µm CO₂ band. The 3.9 µm window is much cleaner than the 11 µm and the water transmissions are significantly higher.

Finally we show in figure 3.7 the transmission profiles for the SEVIRI 8.7 µm channel. The behaviour and relative contributions are very similar the 11 µm for the profiles shown.
Figure 3.6 As figure 3.5 but for the SEVIRI 3.9 µm channel.

Figure 3.7 As figure 3.5 but for the SEVIRI 8.7 µm channel.
3.3 RTTOV fast model

The fast parameterised radiative transfer model used in this study is a version of RTTOV (Eyre, 1991) modified to obtain increased accuracy for the ATSR window channels (Watts, 1997). The model is based on regression fitting of lbl layer optical depths to deviations of temperature and humidity from a reference profile. The method is well proven and has a long history of development in the TOVS sounding community (e.g. see McMillin and Fleming 1976, 1977, 1979). The modifications made were to change the predictor base for the water part of the transmission and for a comprehensive discussion and details of the RTTOV the RAL internal report RAL-TR-97-047, Watts, 1997, is annexed at the end of this WP.

RTTOV is used in operational assimilation of TOVS radiances and is probably accurate enough for SST retrieval although the situation is borderline here. Model brightness temperature errors reported in Watts 1997 for 11 and 12 µm were less than 0.1 K (compared to the input lbl values) and around 0.13 K for the 3.7 µm channel. For the present purposes of cloud parameter retrieval these accuracies are certainly adequate. The model includes a gradient version which may be used for sensitivity studies. The gradient version is also potentially useful (and indeed was designed) for atmospheric profile retrievals, but we do not anticipate this use here. The profile information in window channel radiances is relatively low (especially compared to the cloud effects) and we anticipate using RTTOV with fixed atmospheric profile input to provide background radiance and transmittance information against which to retrieve cloud properties.

The RTTOV model used at RAL has the facility to model cloud but not to the level required for this study. Model clouds are currently limited to opaque (i.e. non-transmitting) but reflecting and non-unit emissivity and are based on the LUTs described earlier. It would be perhaps ideal to have RTTOV extended for cloud of all optical depth but the scope of this study does not permit this. Here we intend to use RTTOV to provide the atmospheric radiative transfer and couple the results to the cloud LUTs externally. There is no loss of utility in this providing we restrict ourselves to a fixed atmospheric component in any retrievals and, as we have said, this is a reasonable approach certainly in the shorter term.

We present here, output statistics of the coefficient generation for RTTOV for, at the present time, the 3.9/3.7, 8/-, 11 and 12 µm channels of SEVIRI and ATSR-2. This will be extended to include an additional eight channels, four for HIRS and four MODIS if this is thought necessary at a later stage. The ATSR-2 8 µm channel is a dummy channel present for the purposes of neatness, the data are copied from the 11 µm channel.

Firstly, table 3 gives the mean and standard deviation of transmittances due to the mixed gases as a function of pressure for the 32 profiles and the five angles.

<table>
<thead>
<tr>
<th>Mean Press:</th>
<th>S 3.9</th>
<th>S 8.7</th>
<th>S 11</th>
<th>S 12</th>
<th>A 3.7</th>
<th>(A 8)</th>
<th>A 11</th>
<th>A 12</th>
</tr>
</thead>
<tbody>
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<td>115.0</td>
<td>95.82</td>
<td>99.74</td>
<td>99.42</td>
<td>99.74</td>
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<td>99.36</td>
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<tr>
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<td>99.19</td>
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<td>99.28</td>
<td>99.28</td>
<td>99.63</td>
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<tr>
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<td>98.99</td>
<td>99.40</td>
<td>94.86</td>
<td>99.10</td>
<td>99.10</td>
<td>99.45</td>
</tr>
</tbody>
</table>
The main points of note are the generally high transmittance values and low standard deviations. Both the 3.7 μm region channels have lower transmittance, particularly the SEVIRI 3.9 μm, with somewhat higher variability.

Table 4 gives the mean and standard deviation of transmittances due to water vapour.

Table 4: Mean and standard deviation of transmittance (%) Water Vapour

<table>
<thead>
<tr>
<th>Press:</th>
<th>S 3.9</th>
<th>S 8.7</th>
<th>S 11</th>
<th>S 12</th>
<th>A 3.7</th>
<th>(A 8)</th>
<th>A 11</th>
<th>A 12</th>
</tr>
</thead>
<tbody>
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<td>99.99</td>
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<td>96.94</td>
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<td>96.94</td>
<td>100.00</td>
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<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
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<td>80.89</td>
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<td>65.38</td>
<td>65.38</td>
<td>51.16</td>
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</table>

81
The rapid increase with height and the high variability are characteristics of the water vapour transmission. In this case, the 3.7 µm channels have significantly higher transmission and low variability, particularly the SEVIRI 3.9 µm channel.

We now turn to the accuracy of the fast model coefficients in reproducing these transmittances. The tests were performed on the dependent data set, i.e. on the profiles used to derive the coefficients. Thus the errors are best case; we may expect some small degradation for an independent sample profile set. Table 5 gives the mean and standard deviation of the errors in mixed gas transmittance prediction.

<table>
<thead>
<tr>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press:</td>
</tr>
<tr>
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</tr>
<tr>
<td>135.0</td>
</tr>
<tr>
<td>150.0</td>
</tr>
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<table>
<thead>
<tr>
<th>Standard deviation</th>
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<td>Press:</td>
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<td>115.0</td>
</tr>
<tr>
<td>135.0</td>
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</tbody>
</table>
All mean errors are around or less than 0.002% and standard deviations less than 0.015% in all channels except the SEVIRI 3.9 µm where, because of the higher mixed gas absorption, values are slightly higher; 0.003 and 0.025% respectively. To give an idea of the effect of a transmittance error, $\delta t$, in terms of a brightness temperature error, $\delta T_B$, for a given scene temperature, $T$, we can use the expression

$$\delta T_B = T - B^{-1}[\nu, B[v,T] \times (1-\delta t)]$$

where $\nu$ is the channel central wavenumber. Using this, $\delta t = 0.025\%$ gives $\delta T_B < 0.02$ K for all channels and for a scene temperature of 280 K. Thus transmission errors of this size are totally negligible.

The water vapour transmittance errors are higher as shown in table 6.

Table 6: Mean and standard deviation of transmittance error (%) Water Vapour

<table>
<thead>
<tr>
<th>Press</th>
<th>S 3.9</th>
<th>S 8.7</th>
<th>S 11</th>
<th>S 12</th>
<th>A 3.7</th>
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<td></td>
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<td>-0.003</td>
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<tr>
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<td>-0.392</td>
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<td>0.000</td>
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<td>-0.017</td>
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<tr>
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<tr>
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<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
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<tr>
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<td>0.003</td>
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<td>-0.019</td>
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<td>-0.387</td>
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<td>0.000</td>
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<td>-0.018</td>
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<tr>
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<td>0.010</td>
<td>-0.017</td>
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<td>-0.379</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
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<td>0.018</td>
<td>-0.014</td>
<td>0.012</td>
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<td>0.003</td>
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<td>0.045</td>
<td>0.014</td>
<td>0.055</td>
<td>-0.317</td>
<td>0.032</td>
<td>0.032</td>
<td>0.056</td>
</tr>
<tr>
<td>1000.0</td>
<td>-0.024</td>
<td>0.051</td>
<td>0.024</td>
<td>0.057</td>
<td>-0.303</td>
<td>0.039</td>
<td>0.039</td>
<td>0.059</td>
</tr>
</tbody>
</table>

<p>| Standard deviation |</p>
<table>
<thead>
<tr>
<th>Press</th>
<th>S 3.9</th>
<th>S 8.7</th>
<th>S 11</th>
<th>S 12</th>
<th>A 3.7</th>
<th>(A 8)</th>
<th>A 11</th>
<th>A 12</th>
</tr>
</thead>
<tbody>
<tr>
<td>115.0</td>
<td>0.004</td>
<td>0.011</td>
<td>0.015</td>
<td>0.003</td>
<td>0.410</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>135.0</td>
<td>0.005</td>
<td>0.010</td>
<td>0.015</td>
<td>0.003</td>
<td>0.410</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>150.0</td>
<td>0.005</td>
<td>0.010</td>
<td>0.015</td>
<td>0.003</td>
<td>0.410</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>200.0</td>
<td>0.005</td>
<td>0.010</td>
<td>0.015</td>
<td>0.003</td>
<td>0.410</td>
<td>0.001</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>250.0</td>
<td>0.006</td>
<td>0.013</td>
<td>0.015</td>
<td>0.004</td>
<td>0.411</td>
<td>0.001</td>
<td>0.001</td>
<td>0.005</td>
</tr>
<tr>
<td>300.0</td>
<td>0.008</td>
<td>0.030</td>
<td>0.015</td>
<td>0.013</td>
<td>0.411</td>
<td>0.004</td>
<td>0.004</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Mean errors are still relatively low; converting the 1000 mb values to brightness temperatures gives 0.0048, 0.024, 0.014 and 0.036 K for the 280 K scene temperature and the SEVIRI channels and 0.06, 0.018, 0.023 and 0.038 K for the ATSR-2 channels. The ATSR-2 3.7 µm has a significantly higher mean error than the others, even the SEVIRI 3.9 µm; the reasons for this are not clear but may be connected with the multiplicative approximation used to combine water and mixed gas transmittances (see Watts, 1997). Nevertheless, all the resulting $\delta T_B$s are very small.

The 1000 mb standard deviations convert to $\delta T_B$s of 0.04, 0.24, 0.13 and 0.20 K for the SEVIRI channels and 0.09, 0.11, 0.13 and 0.20 K for the ATSR-2 channels. This sort of accuracy might be a concern for precision sea surface temperature retrieval but is unlikely to be significant for cloud property retrievals.

Finally, table 7 shows the outliers of the error distribution, giving the maximum transmittance (water) error found and the profile number, pressure level (1=0.1 mb, 40=1000 mb) and angle index (1=nadir, 5=sec$^{-1}(3)$) at which it occurred. The $\delta T_B$ for the 280 K scene temperature is also given.

### Table 7. Maximum Transmittance (water) errors:

<table>
<thead>
<tr>
<th>Channel:</th>
<th>$\delta$Tau %:</th>
<th>Profile:</th>
<th>Level:</th>
<th>Angle:</th>
<th>$\delta T_B$s K:</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEVIRI 3.9</td>
<td>0.862</td>
<td>32</td>
<td>38</td>
<td>5</td>
<td>0.17</td>
</tr>
<tr>
<td>SEVIRI 8.7</td>
<td>2.258</td>
<td>7</td>
<td>36</td>
<td>5</td>
<td>1.04</td>
</tr>
<tr>
<td>SEVIRI 11</td>
<td>0.820</td>
<td>32</td>
<td>37</td>
<td>5</td>
<td>0.48</td>
</tr>
<tr>
<td>SEVIRI 12</td>
<td>1.278</td>
<td>32</td>
<td>37</td>
<td>5</td>
<td>0.78</td>
</tr>
<tr>
<td>ATSR-2 3.7</td>
<td>3.846</td>
<td>18</td>
<td>13</td>
<td>1</td>
<td>0.78</td>
</tr>
<tr>
<td>(ATSR-2 8)</td>
<td>0.840</td>
<td>32</td>
<td>37</td>
<td>5</td>
<td>0.38</td>
</tr>
<tr>
<td>ATSR-2 11</td>
<td>0.840</td>
<td>32</td>
<td>37</td>
<td>5</td>
<td>0.48</td>
</tr>
<tr>
<td>ATSR-2 12</td>
<td>1.302</td>
<td>32</td>
<td>37</td>
<td>5</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The maximum errors occur at the extreme angle used with the exception of the ATSR-2 3.7 µm channel. Most maximum errors are less than 1 K and it should be noted that the crude method of evaluating the $\delta T_B$s almost certainly overestimates the effect.

This section has documented the derivation of fast model coefficients and shown that transmittance errors arising from the fast model approximations are small. They can be considered small in light of the likely requirements for cloud property retrieval and in relation to typical errors in the profiles that will ultimately be used. For example, NWP temperature errors are typically 1–2 K throughout the troposphere and relative humidity errors of order 10–30%. Consequently, profile errors are likely to dominate transmittance errors even when a fast, rather than lbl, model is employed.
3.4 Cloud - atmosphere model

As we indicated earlier the fast model RTTOV could be extended to comprehensively treat the effects of non-opaque clouds by using emission, reflection and transmission functions obtained from LUT stored results of multiple scatter calculations. Here we have decided to use RTTOV to supply fixed boundary conditions on the atmospheric radiative transfer and calculate the combined cloud-atmosphere radiative transfer in an external program. This has been done for several reasons. Firstly, although the `forward’ calculation of RTTOV is relatively straightforward and modifications quite feasible in a study of this scope, the complications arising from coding and testing the tangent linear, adjoint and gradient versions can be formidable. Experience of exactly this has been gained from the limited cloud implementation present in the RTTOV version at RAL (reflecting, emitting but non-transmitting cloud). The gradient version is, of course, required for minimisation techniques employed in the retrieval of cloud parameters. A second reason for presently keeping the cloud treatment outside of RTTOV is that there is no provision in RTTOV for visible channel atmospheric radiative transfer, although again, this might ultimately be a desirable facility. It is more consistent at present to therefore to treat visible and infrared cloud properties as distinct from the atmospheric radiative effects. Finally, we suggest that this approach is justifiable in that we do not anticipate or propose to retrieve atmospheric (as distinct from cloud) parameters from SEVIRI measurements: the atmosphere can be regarded as fixed and supplied from the best available NWP or similar source.

Consequently we require an interface between the atmospheric effects and the cloud LUT properties analogous to the visible model described in WP2.1 section 4. The lack of, in the infrared case, directional radiances and significant cloud-surface interaction, simplifies the infrared model. The presence of emission in addition to absorption complicates it. Consequently, the model is similar to the reflectance model (WP2.1 figure x) except that the atmosphere is specified by radiances (from RTTOV) rather than transmissions. Figure 3.8 is a schematic of the cloud-atmosphere infrared model.

Figure 3.8. Schematic of infrared cloud-atmosphere model

Where:

- $B_s$, $\varepsilon_s$ are the Planck radiance and emissivity of the surface.
- $P_c$, $B_c$, $r_e$, $\tau$ are the cloud pressure, Planck radiance (unit emissivity), effective drop size and optical depth and $\varepsilon_c$, $R_c$, $Tr_c$ are the cloud emissivity, diffuse reflectivity and transmissivity. 
obtained from $r_e$, $\tau$ and the view zenith angle via the LUTs.

$R_{o}^\uparrow$ is the clear column radiance at TOA, $R_{ac}^\uparrow$ is the radiance at TOA arising from the atmosphere above the cloud, $R_{ac}^\downarrow$ is the downward radiance at cloud pressure and $R_{bc}^\uparrow$ is the upward radiance at cloud base. $\tau_{ac}$ is the above cloud transmission to TOA. $R_{o}^\uparrow$, $R_{ac}^\uparrow$, $R_{ac}^\downarrow$ and $\tau_{ac}$ are calculated within RTTOV and stored in common (see Eyre 1991) and are therefore readily available. $R_{bc}^\uparrow$ is not directly computed but is also readily calculable if we note that $R_{o}^\uparrow = R_{bc}^\uparrow \cdot \tau_{ac} + R_{ac}^\uparrow$ and therefore

$$R_{bc}^\uparrow = (R_{o}^\uparrow - R_{ac}^\uparrow) / \tau_{ac} \ldots (1)$$

With these quantities the expression for the overcast cloudy TOA radiance $R_{\bullet}^\uparrow$ becomes:

$$R_{\bullet}^\uparrow = R_{bc}^\uparrow \cdot T_{c} \cdot \tau_{ac} + B_{c} \cdot e_{c} \cdot \tau_{ac} + R_{ac}^\downarrow \cdot e_{c} \cdot \tau_{ac} + R_{ac}^\uparrow \ldots (2)$$

A field of view covered with fraction $f$ of cloud gives a radiance of

$$R_{\bullet}^\uparrow = fR_{\bullet}^\uparrow + (1 - f)R_{o}^\uparrow \ldots (3)$$

All quantities except Planck radiances are implicitly functions of viewing angle. The first term on the RHS of equation (2) is the below cloud upwelling radiance transmitted by the cloud and the atmosphere above the cloud, the second term is the cloud emission, the third is reflected downwelling radiance and the fourth is the contribution of the atmosphere above the cloud.

Note that the model does not exactly treat the effect of non-unit surface emissivity. The RTTOV value of $R_{o}^\uparrow$ for $e_{s} \neq 1$ is exact and includes surface reflection of downwelling clear-column radiance, but from (1), $R_{bc}^\uparrow$, is approximate in this case because instead of implicitly including overcast downwelling radiance, it includes downwelling clear-column radiance. The error would be greatest in the case of optically thin atmospheres and low level cloud. In any event, the effect is likely to be small because of the normally high surface emissivities and for now we assume $e_{s} = 1$.

### 3.4.1 Radiance tests

In this section we examine the RTTOV output radiances and transmittances in a variety of situations to check their physical behaviour. We use profiles number 3 and 4 as in section 3.2 since represent dry and moist atmospheres respectively. Results are presented for the 3.9, 8.7, 11 and 12 $\mu$m channels of SEVIRI and the 3.7, (8), 11 and 12 $\mu$m channels of ATSR-2. (Since the ATSR-2 has no 8 $\mu$m channel and the coefficients are duplicated from the 11 $\mu$m channel, the results for ATSR-2 8 and 11 $\mu$m overlay.)

The first test, of $\tau_{ac}$, essentially duplicates figures 3.5 through 3.7 above but with all channels. Figure 3.9 shows the $\tau_{ac}$ profile for the dry atmosphere #3 and figure 3.10 that for at-
The view zenith angle is 0°. In both cases the transmittances appear physically reasonable and entirely consistent with the results shown in figures 3.5 – 3.8. The 3.7 / 3.9 µm channel transmittances are similar for each profile because of the low water absorption and the high mixed gas absorption and there are significant differences between the SEVIRI and ATSR-2 versions. The 11 and 12 µm channels are largely indistinguishable between instruments.
Figures 3.11 and 3.12 examine the behaviour of the transmittances as the view zenith angle varies.

The general behaviour with angle is as expected with approximate dependence on the secant. However, at zenith angles greater than 55° the transmittances become unreliable and when the angle reaches 60° RTTOV fails. This is not too surprising considering the coefficients are based on lbl transmittances calculated for angles from 0 to 60° (a legacy of the use of this version of RTTOV for TOVS and ATSR use, both with maximum scan view angles.
around 55°). It is nonetheless surprising that angles around and slightly greater than 55° are treated correctly. This will be investigated further; the coefficients for SEVIRI should be designed to cover much greater zenith angles.

RTTOV TOA brightness temperatures, \( B^{-1}(R^1_o) \), for the cases in figures 3.11, 3.12 are shown in figures 3.13 3.14 respectively.

![Figure 3.13](image1.png)

**Figure 3.13.** As fig 3.11 but channel TOA brightness temperatures

![Figure 3.14](image2.png)

**Figure 3.14.** As fig 3.12 but channel TOA brightness temperatures

The plots show the expected limb-darkening and a reasonable relationship between channel brightness temperatures given their transmittances. It is interesting to see the 3.7 µm chan-
nels ‘warmest’ in the wet profile (#4) because of their low water absorption, but ‘coolest’ in the dry profile. All following figures are based on zero zenith angle calculations.

We now examine the profiles of radiance upwelling from the atmosphere above the cloud, $R_{\text{ac}}$. Figure 3.15 shows this for profile #3 as a brightness temperature profile and 3.16 as a radiance profile.

![Figure 3.15](image1)

**Figure 3.15.** $B^{-1}(R_{\text{ac}})$ as a function of cloud pressure for profile #3

![Figure 3.16](image2)

**Figure 3.16.** As figure 3.15 but $R_{\text{ac}}$ as a radiance.

The radiances fall off rapidly with as expected and asymptote to zero for a cloud height of around 600 mb. Also as expected the 12 µm values are highest but the behaviour of the
Planck function causes variations; radiances at 3.9 µm are too low to see on the same scale as the longer wavelengths. The brightness temperature plot, figure 3.15, normalises the figure to some extent, but the non-linearity of the Planck function means that even very low radiances at 3.9 µm appear as quite high temperatures and are quite misleading in this respect.

Figures 3.17 and 3.18 show the same for the wet profile #4.

![Figure 3.17. As figure 3.15 but for atmospheric profile #3](image1)

![Figure 3.18. As figure 3.16 but for atmospheric profile #3](image2)

The behaviour is qualitatively similar, but the radiance values are high (note the different
scales) for the wetter, more absorbing profile.

Downwelling radiances at cloud top are shown for profiles #3 and #4 in figures 3.19 and 3.20.

Figure 3.19. $B^{-1}(R_{\text{down}}^\text{c})$ as a function of cloud pressure for profile #3

Figure 3.20. As figure 3.19 but for profile #4

The profiles are qualitatively similar to the upwelling radiance profiles for atmospheric profiles #3 and #4 shown in figures 3.16 and 3.18 respectively. This is especially true for the optically thinner profile #3; for an isothermal slab atmosphere they would be expected to be identical. When the atmosphere is non-isothermal, we expect radiances at the high tempera-
ture end to be greater, hence the larger values of $R_{ac}^\downarrow$ compared to $R_{ac}^\uparrow$, especially in the optically thick case.

Finally, we examine the radiance upwelling at cloud base, $R_{bc}^\uparrow$. When the cloud base is at the surface the radiance should be equivalent to the surface leaving value, and when the cloud base is very high, the radiance should roughly equate to the clear column radiance $R_{o}^\uparrow$.

Figure 3.21 shows the profiles of $R_{bc}^\uparrow$ for atmospheric profile #4. The 1000 mb (and hence surface) temperature for this profile is 301.8 K and so clearly the first condition is met. The clear column brightness temperatures for this profile can be seen from the zero angle end of figure 3.14, and are 297.9 294.1 294.8 291.4 and 297.3 294.7 (294.7) 291.4 for the SEVIRI 3.9, 8.7, 11, 12 and ATSR-2 versions respectively. For all but the 3.7 / 3.9 µm channels, these values check with the values at 50 mb in the figure. The discrepancy in the SIR channels is because there remains significant absorption above 50 mb as is evidenced by a continuing slight decrease of brightness temperature with altitude.

The above figures appear to show the various components of the fast model radiances and transmittances are physically reasonable and asymptote to expected values where these are possible to specify.

**3.4.2 IR Cloud-atmosphere model tests**

This section briefly presents results of the combined cloud-atmosphere model in terms of the TOA brightness temperatures it produces for various cloud and atmosphere situations. Firstly, figure 3.22 shows channel BTs as a function of cloud pressure. In all cases the drop size is 8 µm, the atmospheric profile is #4 and the view zenith angle is 0°. The four plots show, clockwise from top left, results for optically thick cloud, $\tau = 32$, through to optically thin cloud, $\tau = 1$. 

Figure 3.21. As figure 3.19 but for profile #4
For $\tau = 32$ all channel BTs are within 5 K of each other; the 11 and 12 $\mu$m channels are very close, to each other and the temperature profile (shown as a +...+ line) unless the cloud is below ~700 mb where the absorption and reflection of downwelling radiance has some effect. The SIR channels have BTs somewhat lower than the temperature profile as a result of their lower emissivity.

Figure 3.22. TOA BTs as a function of cloud pressure for profile #4 and nadir viewing; various cloud optical depths. $R_e = 8 \mu$m. +...+ line shows temperature profile.

The behaviour of the 8.7 $\mu$m channel appears to follow that of the 11 $\mu$m channels quite closely. As the cloud optical depth decreases, the BTs increase because of transmission and become higher than the local temperature; by $\tau = 4$ this is the case for all channels except for cloud pressures greater than ~800 mb where the above-cloud absorption-emission is strong enough to reduce the BTs to below the local temperature. Because of their higher transmission, BTs for the SIR channels rapidly increase from an emission deficit at $\tau = 32$ to become significantly higher than the IR channel BTs for $\tau = 2$. As the cloud becomes still thinner, the BTs start to converge to the clear atmosphere values (approximately given by the values for $\tau = 1$ and $P_c=1000$ mb).

Figure 3.23 shows the effect of varying drop size for cloud $\tau = 4$ at a variety of pressures. When the cloud pressure is 1000 mb and the transmission effects are therefore small, the most striking effect of drop size is the increase in BT with drop size of the SIR channels caused by increasing emissivity. As the cloud becomes higher, the higher transmission caused by greater scattering of smaller drops becomes obvious as a strong increase in BTs, particularly in the 8.7 and 11 and 12 $\mu$m channels. This is a very large effect for the 400 mb case shown bottom right; the 11 $\mu$m BT difference expected from clouds with $R_e = 12$ and 3 $\mu$m is, for example, over 10 K. Although drop sizes of 3 $\mu$m (indeed water cloud at all) is unlikely at 400 mb, it does show the importance of $R_e$ to correct modelling of the radiative
transfer.

In figure 3.24 the effect of view zenith angle is shown for clouds at 800 mb and of various optical depth. The expected limb ‘darkening’ of the BTs is present, as a result of both reducing cloud emissivity (the predominant effect in the $\tau = 32$ case) and increasing atmospheric absorption (predominant effect in the $\tau = 1$ case). The problem with RTTOV transmittances for large zenith angles is shown by erratic behaviour of the BTs beyond 60°.

Finally we show in figure 3.25 the rather straightforward effect of cloud fractional coverage. The drop size is 11 µm and the pressure 800 mb. From equation (3) we expect a straightforward linear effect of cloud fraction on radiance and, in the case of the 8.7, 11 and 12 µm channels this linearity is largely preserved in the effect on BTs. This is also the case for the SIR channels for the lower optical depths, but for the essentially opaque case, $\tau = 32$, the strongly non-linear behaviour of the Planck function at these wavelengths becomes apparent and a distinct curvature to the plot can be seen.

The tests presented throughout this section demonstrate the behaviour of BTs calculated using the combined atmosphere-cloud model. The results appear to be physically reasonable and consistant with the exception of the highlighted current limitation of the RTTOV transmittances at higher view angles. This will be investigated and corrected as a matter of urgency. In following sections we will compare model BTs with existing measured values from ATSR-2 (and MODIS AS) to establish the validity of the model in real situations.
Figure 3.24. TOA BTs as a function of view zenith angle for profile #4 and cloud pressure 800 mb and drop size of 8 µm; various optical depths.

Figure 3.25. TOA BTs as a function of cloud fraction for profile #4, cloud pressure 800 mb and drop size of 11 µm; various optical depths.
3.4.3 Model gradient

In this section we derive the equations for the gradient of the infrared model (equations (1)–(3) with respect to the relevant parameters; cloud optical depth, $\tau$, fraction, $f$, drop size $R_c$, cloud pressure, $p_c$ and surface temperature, $T_s$.

Starting with equation (3) for the partly cloudy radiance

$$ R^\uparrow = fR^\uparrow_c + (1-f)R^\uparrow_o $$

we have straightforwardly,

$$ \frac{\partial R^\uparrow}{\partial f} = R^\uparrow_o - R^\uparrow_c $$

The expressions for the gradients of the overcast radiances are follow from equation (2):

$$ \frac{\partial R^\uparrow_c}{\partial \tau} = \tau ac \left[ R^\uparrow_{bc} \frac{\partial \tau_c}{\partial \tau} + B_c \frac{\partial \varepsilon_c}{\partial \tau} + B_{ac} \frac{\partial R_c}{\partial \tau} \right] $$

$$ \frac{\partial R^\uparrow_c}{\partial R_c} = \tau ac \left[ R^\uparrow_{bc} \frac{\partial \tau_c}{\partial R_c} + B_c \frac{\partial \varepsilon_c}{\partial R_c} + \frac{\partial R_{ac}}{\partial R_c} \right] $$

$$ \frac{\partial R^\uparrow_c}{\partial p_c} = \frac{\partial R^\uparrow_{bc}}{\partial p_c} + \frac{\partial \tau_c}{\partial p_c} \left[ R^\uparrow_{bc} \frac{\partial \tau_c}{\partial p_c} + B_c \varepsilon_c + \frac{\partial R_{ac}}{\partial p_c} \right] + \tau ac \left[ \frac{\partial R^\uparrow_{bc}}{\partial p_c} \tau_c + \frac{\partial B_c}{\partial p_c} \varepsilon_c + \frac{\partial R_{bc}}{\partial p_c} \right] $$

$$ \frac{\partial R^\uparrow_c}{\partial T_s} = \tau ac \frac{\partial R^\uparrow_{bc}}{\partial T_s} = (\tau ac \frac{\partial R^\uparrow_{bc}}{\partial T_s}) $$

(For the resolution in parenthesis of the final equation see the expression derived for $\partial R_{bc}/\partial T_s$ given below.) Gradients of the cloud properties $T_c$, $\varepsilon_c$ and $R_c$, are available from the LUT interpolation routines (see next section). Gradients of the radiance and transmittance terms with respect to cloud pressure (they are of course independent of cloud radiative properties) can be made available from RTTOV directly (run in gradient mode). However, here we obtain them from the interpolation of the terms to the cloud pressure $P$ from the RTTOV pressure levels (i.e. by finite differencing the RTTOV levels).

The gradients of $R^\uparrow_{bc}$ can be obtained from equation (1) since this radiance term is not di-
rectly available from RTTOV. Generally, we find

\[ \frac{\partial R_{bc}^\dagger}{\partial X} = \left\{ \tau_{ac} \left[ \frac{\partial R_{bc}^\dagger}{\partial X} - \frac{\partial R_{ac}^\dagger}{\partial X} \right] - \frac{\partial \tau_{ac}}{\partial X} \left[ R_{bc}^\dagger - R_{ac}^\dagger \right] \right\} / \tau_{ac}^2 \]

And therefore, in the case of differentiation wrt \( P \) (although, again this derivative can be and is obtained from the pressure interpolation):

\[ \frac{\partial R_{bc}^\dagger}{\partial p_c} = \left\{ \tau_{ac} \left[ \frac{\partial R_{bc}^\dagger}{\partial p_c} - \frac{\partial R_{ac}^\dagger}{\partial p_c} \right] - \frac{\partial \tau_{ac}}{\partial p_c} \left[ R_{bc}^\dagger - R_{ac}^\dagger \right] \right\} / \tau_{ac}^2 \]

And wrt \( T_s \):

\[ \frac{\partial R_{bc}^\dagger}{\partial T_s} = \left\{ \tau_{ac} \left[ \frac{\partial R_{bc}^\dagger}{\partial T_s} - \frac{\partial R_{ac}^\dagger}{\partial T_s} \right] - \frac{\partial \tau_{ac}}{\partial T_s} \left[ R_{bc}^\dagger - R_{ac}^\dagger \right] \right\} / \tau_{ac}^2 \]

\[ = \frac{1}{\tau_{ac} T_s} \frac{\partial B(T_s)}{\partial T_s} \]

Where \( \tau(p_s \to 0) \) is the total column transmittance. Demonstration and testing of the full gradient model follows, but we firstly show the gradient of the cloud effects from the LUTs. Figure 3.26 shows gradients \( \frac{\partial \epsilon}{\partial \tau}, \frac{\partial \epsilon}{\partial R}, \frac{\partial R}{\partial \tau} \) and \( \frac{\partial R}{\partial R} \) as a function of \( \tau \) for nadir viewing, cloud \( R_c = 8 \mu m \). The plots can be compared to figures 2.1 and 2.2. The top left plot shows cloud emissivity strongly affected in all channels by the optical depth. The lower values in the 3.9 \( \mu m \) channel are due to low emissivity caused by scattering. It becomes higher than the other channels for thicker clouds as the asymptote is delayed (see figure 2.1). The top right plot shows a much weaker dependence on drop size which, except in the case of the 3.9 \( \mu m \) channel, becomes zero for optical depths greater than \( \sim 15 \). The plot shows a significantly stronger dependence in the 11 \( \mu m \) than the 12 \( \mu m \) channel.

Reflectivities gradients are effectively zero for the 8.7, 11 and 12 \( \mu m \) channel. The 3.9 \( \mu m \) channel reflectivity becomes insensitive for clouds optically thicker than 8 but it retains sensitivity to drop size for all the optical depths shown. Figure 3.27 shows the same gradients as a function of \( R_c \). The figures show a general decrease in sensitivity as drop sizes become large except for the 3.9 \( \mu m \) channel sensitivity of emissivity to optical depth.

In both figures the gradients wrt the parameter being varied have a stepped nature and this is a result of the use of differencing two linear interpolations of the LUTs to obtain the gradi-
ent value. This behaviour is acceptable in the gradient model but would not be in the full model; results in figure 2.1 earlier show that it does not occur there. A more sophisticated interpolation of the LUTs might avoid the stepping and produce smoother curves in figure 2.1. Higher resolution tables would be another solution. It is doubtful whether the increased ‘accuracy’ of the bulk properties thus produced would be significant compared to other error sources in cloud parameter retrieval but improved gradient values might lead to faster convergence of iterative schemes.

Figure 3.26. Model gradients as a function of optical depth; wrt $\tau$ (left hand plots) and $R_e$ (right hand plots). $0^\circ$ view angle and $8 \mu m$ $R_e$ throughout.

Figure 3.27. Model gradients as a function of effective radius; wrt $\tau$ (left hand plots) and $R_e$ (right hand plots). $0^\circ$ view angle and $\tau = 4$ throughout.
Results of testing of the gradient of the full model as given by the equations at the start of this section, are presented in the same manner as those for the visible radiative transfer gradient model; i.e as a table of comparisons of finite difference and 'exact' gradient estimations for selected situations.

In the first case, table 3.4.3.1, the cloud is ice phase and the view zenith angle is 10°.

<table>
<thead>
<tr>
<th>Cloud / Atmosphere</th>
<th>Phase</th>
<th>Particle size</th>
<th>Optical depth/ fraction</th>
<th>Pressure</th>
<th>Atmosphere</th>
<th>Surface Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ice</td>
<td>25 µm</td>
<td>1.0 / 1.0</td>
<td>346 mb</td>
<td># 3</td>
<td>287 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gradients $\frac{\partial R}{\partial x}$</th>
<th>3.7 µm</th>
<th>8.7 µm</th>
<th>11 µm</th>
<th>12 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial R}{\partial \tau}$</td>
<td>F.D.:</td>
<td>-6.64e-02</td>
<td>-1.03e+01</td>
<td>-1.59e+01</td>
</tr>
<tr>
<td>Exact:</td>
<td></td>
<td>-6.61e-02</td>
<td>-1.03e+01</td>
<td>-1.59e+01</td>
</tr>
<tr>
<td>$\frac{\partial R}{\partial R_e}$ (µm)</td>
<td>F.D.:</td>
<td>-3.31e-04</td>
<td>-6.89e-01</td>
<td>-8.81e-01</td>
</tr>
<tr>
<td>Exact:</td>
<td></td>
<td>-3.31e-04</td>
<td>-6.89e-01</td>
<td>-8.81e-01</td>
</tr>
<tr>
<td>$\frac{\partial R}{\partial f}$ (0.1)</td>
<td>F.D.:</td>
<td>-5.12e-02</td>
<td>-9.28e+00</td>
<td>-1.62e+01</td>
</tr>
<tr>
<td>Exact:</td>
<td></td>
<td>-5.12e-02</td>
<td>-9.28e+00</td>
<td>-1.62e+01</td>
</tr>
<tr>
<td>$\frac{\partial R}{\partial p_c}$ (100 mb)</td>
<td>F.D.:</td>
<td>1.94e-03</td>
<td>1.72e+00</td>
<td>3.68e+00</td>
</tr>
<tr>
<td>Exact:</td>
<td></td>
<td>1.94e-03</td>
<td>1.72e+00</td>
<td>3.69e+00</td>
</tr>
<tr>
<td>$\frac{\partial R}{\partial T_s}$ (K)</td>
<td>F.D.:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exact:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Radiances mw.st⁻¹.m².cm</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.19e-01</td>
<td>3.44e+01</td>
<td>5.89e+01</td>
<td>6.50e+01</td>
</tr>
</tbody>
</table>

Table 3.4.3.1. Full IR model gradient check for Ice cloud case.

All exact gradient calculations are acceptably close to the finite difference values. Gradient terms are also of an intuitively correct size and sign. That is, radiances fall for increasing optical depth, particle size (~greater absorption) and cloud fraction. Radiances rise for increasing cloud pressure (warmer cloud) and surface temperature.

The second test case for water cloud has the same view angle, a drop size of 8 µm and pressure of 760 mb. Results are in table 3.4.3.2 and again show agreement between finite difference and exact results.
### Table 3.4.3.2. Full IR model gradient check for water cloud case.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Particle size</th>
<th>Optical depth / fraction</th>
<th>Pressure</th>
<th>Atmosphere</th>
<th>Surface Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>8 µm</td>
<td>1.0 / 1.0</td>
<td>760 mb</td>
<td># 4</td>
<td>290 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gradients $\partial R^I/\partial x$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>3.7 µm</td>
</tr>
<tr>
<td>8.7 µm</td>
</tr>
<tr>
<td>11 µm</td>
</tr>
<tr>
<td>12 µm</td>
</tr>
<tr>
<td>$\partial R^I/\partial \tau$ F.D.:</td>
</tr>
<tr>
<td>-1.24e-01</td>
</tr>
<tr>
<td>-3.77e+00</td>
</tr>
<tr>
<td>-4.58e+00</td>
</tr>
<tr>
<td>-3.75e+00</td>
</tr>
<tr>
<td>Exact:</td>
</tr>
<tr>
<td>-1.23e-01</td>
</tr>
<tr>
<td>-3.76e+00</td>
</tr>
<tr>
<td>-4.56e+00</td>
</tr>
<tr>
<td>-3.73e+00</td>
</tr>
<tr>
<td>$\partial R^I/\partial R_e$ (µm) F.D.:</td>
</tr>
<tr>
<td>3.27e-03</td>
</tr>
<tr>
<td>-2.28e-01</td>
</tr>
<tr>
<td>-2.45e-01</td>
</tr>
<tr>
<td>-9.80e-02</td>
</tr>
<tr>
<td>Exact:</td>
</tr>
<tr>
<td>3.27e-03</td>
</tr>
<tr>
<td>-2.28e-01</td>
</tr>
<tr>
<td>-2.44e-01</td>
</tr>
<tr>
<td>-9.79e-02</td>
</tr>
<tr>
<td>$\partial R^I/\partial f$ (/0.1) F.D.:</td>
</tr>
<tr>
<td>-1.03e-01</td>
</tr>
<tr>
<td>-3.51e+00</td>
</tr>
<tr>
<td>-4.69e+00</td>
</tr>
<tr>
<td>-4.37e+00</td>
</tr>
<tr>
<td>Exact:</td>
</tr>
<tr>
<td>-1.03e-01</td>
</tr>
<tr>
<td>-3.51e+00</td>
</tr>
<tr>
<td>-4.69e+00</td>
</tr>
<tr>
<td>-4.37e+00</td>
</tr>
<tr>
<td>$\partial R^I/\partial p_c$ (/100 mb) F.D.:</td>
</tr>
<tr>
<td>2.30e-02</td>
</tr>
<tr>
<td>1.90e+00</td>
</tr>
<tr>
<td>2.96e+00</td>
</tr>
<tr>
<td>3.24e+00</td>
</tr>
<tr>
<td>Exact:</td>
</tr>
<tr>
<td>2.29e-02</td>
</tr>
<tr>
<td>1.89e+00</td>
</tr>
<tr>
<td>2.96e+00</td>
</tr>
<tr>
<td>3.22e+00</td>
</tr>
<tr>
<td>$\partial R^I/\partial T_s$ (K) F.D.:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Exact:</td>
</tr>
</tbody>
</table>

Radiances mw.st⁻¹.m².cm

| 8.01e-01 | 6.50e+01 | 1.03e+02 | 1.12e+02 |

4. **Errors due to aerosol absorption and scattering**

Although molecular scattering is not an issue for the infrared channels, there are certainly significant absorption effects due to atmospheric aerosols. As for the visible channels, WP2.1 §6, we are not in a position to accurately quantify the effect of aerosols at the IR wavelengths for which a dedicated study is required.

5. **Channel co-registration and non-plane-parallel cloud errors**

These effective noise sources on the infrared radiative transfer calculations were dealt with and estimated in WP2.1 §7 under the visible channel description.
1. Introduction

The Along Track Scanning Radiometer (ATSR) instruments, ATSR-1, ATSR-2 and Advanced ATSR (AATSR), are second generation space radiometers which build on the long heritage of the NOAA AVHRR sensors. They exploit the multichannel method pioneered in AVHRR and make use of new technology to improve instrument stability and calibration, and to provide observations of the surface scene at two different angles. These two observations of the same point on the Earth's surface are through differing amounts of atmosphere; the along track view passes through a longer atmospheric path so is more affected by the atmosphere than the nadir view. By combining the data from these two views the ATSR provides a direct measurement of the effect of the atmosphere, thus yielding an improved atmospheric correction and overcoming the limitations inherent in nadir-only viewing instruments.

The ATSR instruments have been designed for exceptional sensitivity and stability of calibration which achieved through the incorporation of several innovative features in the instrument design.

These features are:

- use of low-noise infrared detectors cooled to near-optimum temperatures (i.e., less than 95 K) by a new space-qualified Stirling cycle mechanical cooler;
- continuous on-board radiometric calibration of the infrared is using two stable, high-precision blackbody calibration targets designed by the Mullard Space Science Laboratory, and in the case of ATSR-2 (and AATSR) visible channels using an on-board visible calibration system designed by the Rutherford Appleton Laboratory;
- use of the multichannel approach to SST retrieval previously demonstrated by the AVHRR instruments;
- use of the along-track scanning technique to provide an enhanced atmospheric correction and a further improvement to the accuracy of SST retrievals.

Application of the along track scanning technique is the instruments most innovative development.
The data used in this study is from the ATSR-2 instrument because the combination of visible channel and near-IR data are required.

2. Scientific Objectives of the ATSR Instrument

The primary mission objective of the ATSR series of instruments is the provision of a long-term data-set of consistent and accurate observations of global SST. In particular the following requirements were defined, prior to the launch of ATSR-1.

- The measurement of SST averaged over 50 by 50 km² areas to an absolute accuracy of better than 0.5K (2s) in conditions of up to 80% cloud cover.
- The generation of SST images with a pixel size of order 1km square, and swath width 500km, and relative pixel-to-pixel accuracy of 0.05K (2s).

Key applications for these data include:

- Provision of an SST time series which will help establish if climate change is taking place.
- Provision of high spatial and temporal resolution SSTs for the validation of climate models.
- Comparison with in situ observations of bulk SST, both for validation purposes and to understand the processes at the atmosphere-ocean interface.

To achieve this the ATSR instruments collect brightness temperature images at a spatial resolution of 1 km.

Secondary scientific objectives include the provision of atmospheric parameters associated with aerosol, water vapour and cloud and also the measurement of land and ice surface radiances. With the addition of the vegetation channels on ATSR-2, supplementary objectives include the assessment of the extent and seasonal variation of global vegetation, and evaluation of parameters such as leaf moisture and vegetation stress.

3. ATSR Instrument Design

In order to use the along-track scanning method the ATSR’s optical path is arranged to provide two curved swaths that view the Earth’s surface at different angles as the ERS-1 satellite orbits the Earth (see Figure 1). First, the ATSR views the surface along the direction of the orbit track at an incidence angle of 55° as it flies toward the scene. Then, some 150 seconds later, as the spacecraft passes over at the same point on the Earth’s surface, ATSR re-
cords a second observation of the scene at an angle close to the nadir. This provides two observations of the same scene on the surface through different atmospheric paths.

Figure 1  ATSR viewing geometry showing the forward and nadir swaths of the instrument

From the differences between the radiances measured along these two different atmospheric paths it is possible to infer information about atmospheric attenuation, emission, and scattering between the surface and the spacecraft over and above that obtained by the use of several spectral channels. Thus by using the along-track scanning technique, the ATSR instruments can generate a more precise atmospheric correction than is possible with only a nadir viewing instrument geometry and hence can provide a more accurate SST retrieval.

ATSR’s field of view comprises two 500 km-wide curved swaths, with 555 pixels across the nadir swath and 371 pixels across the forward swath. The nominal instantaneous field of view (IFOV) pixel size is 1 km² at the centre of the nadir swath and 1.5 km by 2 km at the centre of the forward swath. Each pixel is the result of a 75 µs integration of the signal from the scene. This viewing geometry produces 500-km-wide, high-resolution infrared, and the the case of ATSR-2 and AATSR visible, images of the Earth’s surface from which sea surface temperatures maps and other geophysical products can be retrieved through ground processing.

3.1 ATSR-1

The ATSR instrument, launched on the European Space Agency (ESA) ERS-1 satellite on the 17th July 1991, was the original experimental demonstrator for the ATSR concept, and is now known as ATSR-1. It is a dual-view infrared radiometer with channels centered at 1.6, 3.7, 10.8 and 12µm. ATSR-1 is still in operation, and after 4.5 years continuous use the instrument’s detector noise has just degraded to the levels similar to those of the AVHRR channels at launch. The ATSR-1 instrument and its unique features are described in detail elsewhere by Edwards et. al.
The ATSR series of instruments basically have a common specification, although there are some differences in the implementation. In short, original ATSR-1 instrument is a four-channel infrared imaging radiometer with spatially co-registered spectral channels centred at 1.6, 3.7, 10.8, and 12.0 µm.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Wavelength</th>
<th>Bandwidth</th>
<th>Detector Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud Clearing</td>
<td>1.6 µm</td>
<td>0.3 µm</td>
<td>photovoltaic InSb</td>
</tr>
<tr>
<td>SST retrieval</td>
<td>3.7 µm</td>
<td>0.3 µm</td>
<td>photovoltaic InSb</td>
</tr>
<tr>
<td>SST retrieval</td>
<td>10.8 µm</td>
<td>1.0 µm</td>
<td>photoconductive CMT</td>
</tr>
<tr>
<td>SST retrieval</td>
<td>12.0 µm</td>
<td>1.0 µm</td>
<td>photoconductive CMT</td>
</tr>
</tbody>
</table>

Table 3.1 ATSR-1 Spectral Channels

3.2 ATSR-2 and AATSR

The ATSR-2 and Advanced ATSR (AATSR) instruments are developments from the original experimental ATSR-1 instrument which, in addition to the ATSR-1’s infrared channels, carry extra visible channels at 0.55, 0.67 and 0.87 µm for vegetation remote sensing. The ATSR-2 instrument is currently flying as part of the payload of the ESA ERS-2 satellite, and AATSR will be launched towards the end of the decade on ESA’s ENVISAT platform. The ATSR-2 and AATSR channels are given in the following table 3.2.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Wavelength</th>
<th>Bandwidth</th>
<th>ATSR-1</th>
<th>ATSR-2</th>
<th>AATSR</th>
<th>Detector type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorophyll</td>
<td>0.55 µm</td>
<td>20 nm</td>
<td>N</td>
<td>Y</td>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>Vegetation Index</td>
<td>0.67 µm</td>
<td>20 nm</td>
<td>N</td>
<td>Y</td>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>Vegetation Index</td>
<td>0.87 µm</td>
<td>20 nm</td>
<td>N</td>
<td>Y</td>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>Cloud Clearing</td>
<td>1.6 µm</td>
<td>0.3 µm</td>
<td>Y</td>
<td>Y</td>
<td>PV InSb</td>
<td></td>
</tr>
<tr>
<td>SST retrieval</td>
<td>3.7 µm</td>
<td>0.3 µm</td>
<td>Y</td>
<td>Y</td>
<td>PV InSb</td>
<td></td>
</tr>
<tr>
<td>SST retrieval</td>
<td>10.8 µm</td>
<td>1.0 µm</td>
<td>Y</td>
<td>Y</td>
<td>PC CMT</td>
<td></td>
</tr>
<tr>
<td>SST retrieval</td>
<td>12.0 µm</td>
<td>1.0 µm</td>
<td>Y</td>
<td>Y</td>
<td>PC CMT</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2 ATSR-2 and AATSR Channels

The major purpose of ATSR-2 and AATSR is to provide continuity of the crucial sea surface temperature data sets which have been produced by ATSR-1. Therefore, the key scientific parameters of which were optimised for ATSR, are retained for both the new instruments. The ATSR-2 instrument flies on the ESA ERS-2 satellite and is largely the same as ATSR-1 except for the inclusion of 3 extra spectral bands in the visible (primarily for vegetation monitoring) and an on-board visible calibration system for these channels. The AATSR instrument is functionally the same as the ATSR-2, but the structure and some of the other components have been re-worked to match the environment of the ENVISAT platform, which is somewhat different to the ERS satellites. The major advantage AATSR has over ATSR-2 is the telemetry bandwidth available on ENVISAT. For ATSR-2 the limited
telemetry available on ERS-2 imposed severe limitations on the collection of visible channel
data; on ENVISAT there are no such restrictions so AATSR can telemeter all the visible
channel data it can collect.

This study is primarily concerned with the use of ATSR-2 data as a proxy for SEVIRI chan-
nels; details of filter passbands for the ATSR-2 and SEVIRI visible / NIR channels are
given in figure 5.6, 5.7 and 5.8 of WP 2.1 and figures 3.1, 3.2 and 3.3 of WP 2.2 for the
infrared channels.

3.3 Calibration of the thermal channels

By using a two blackbody calibration approach, rather than a single hot calibration and a
space view, we can determine the radiometric gain and offset of each of the ATSR chan-
nels, in a way that allows us to achieve the highest accuracy in SST with minimal correction
for signal channel non-linearity.

In reality the situation is slightly more complex than stated above. This is because, firstly,
the blackbody targets used for calibration cannot be made perfectly black so they also reflect
radiation and this component of the signal must be included in the calibration. Secondly, de-
spite the care taken in designing the signal channel electronics in ATSR there is still some
non-linearity in the response of the detectors to variations in scene radiance. The way these
are handled in the ATSR programme is discussed below.

For each of the ATSR instruments the reflected signal was measured during the pre-flight
calibration and characterisation of the instrument by checking the calibration procedure
against measurements of external targets over the temperature range cover LN$_2$ (liquid ni-
trogen) to 310 K. This characterisation was also repeated for a range of thermal conditions
within the instrument designed to simulate beginning-of-life, end-of-life and the normal or-
normal orbital excursions of temperature the. This reflected term is included in the instrument’s cali-
bration look-up tables (LUTs).

The infrared focal plane of the ATSR instruments use two different types of infrared detec-
tors. The 1.6 and 3.7 µm channels employ photovoltaic indium antimonide (InSb), and the
10.8 and 12.0 mm channels use photoconductive cadmium mercury telluride (CdHgTe or
CMT) detectors. The response of the InSb detectors is fairly well behaved and linear over
the range of temperatures from LN$_2$ to 310 K, however the same is not true of the CMT
detectors, which show a marked non-linear behavior because of "Auger recombination". In
this process the probability of a electron-hole pair recombining without contributing to the
photocurrent from the detector increases with the number density of electrons and holes
(i.e., as the photon flux on the detectors increases). This causes a reduction in the measured
detector signal, compared to that predicted assuming a linear detector response, at high pho-
ton fluxes. The size of this reduction depends on the temperature and decreased as the detec-
tor temperature increases. The non-linear detector responses are corrected using the meas-
ured radiances from the pre-flight calibration and characterisation, and are included in the
LUTs used for calibration in the ground processing scheme.

3.4 Calibration of Visible and near-infrared channels

Visible channel calibration is achieved in a similar way to the infrared channels. Careful
pre-flight calibration and characterisation of the visible channels were performed and this is
supplemented by continuous in-flight calibration of the channels with an on-board visible calibration system.

The radiometric offset for the visible channels is determined by viewing the ATSR-2 cold blackbody, the signal measured while viewing this target is assumed to be the "dark signal" for the channels (i.e., the signal observed by a “blinded” detector). The radiometric gain is determined once each orbit when the instrument’s visible calibrator views the Sun as the satellite moves away from the pole. At this point, as the satellite move into eclipse, sunlight enters the VISCAL baffle through a protective window and is directed onto a Russian opal diffusing plate which is viewed by the instrument scan mirror as a bright patch at the edge of the hot blackbody during each scan.

The VISCAL provides a radiance equivalent to a 25% signal from a Lambertian scatterer; the performance and degradation of the VISCAL is monitored by a photodiode. With a-priori knowledge of each channel offset from the “dark signal", the gain of the visible channels can be obtained from this calibrated VISCAL signal.

In the ATSR-2 instrument, there was a problem with the build-up of condensation on the relay lens in the visible focal plane assembly. This film acted like an interference filter and amplitude modulated the signals observed by the visible channels, such that the sensitivity of the channels varies with time in a periodic fashion. Consequently ATSR-2 visible channel data had to be calibrated at regular intervals using contemporaneous calibration signals. Calibration data older than a fews days was no longer applicable because of the time varying nature of the signal channel responses. This point should be noted, as the same is likely to be true for AATSR; the calibration scheme for the AATSR visible channels must allow for this effect.

Degradation in the opal efficiency or window transmission will compromise the visible calibration. This effect is monitored by an unfiltered radiation-hardened silicon photo diode which samples a portion of the sunlight before it reaches the scan mirror. In situ measurements from areas of uniform sand or snow are also used to calibrate the visible data.

4. ATSR-2 - SEVIRI channel intercomparison

4.1 Atmospheric

For a discussion and illustration of the intercomparison of the SEVIRI and ATSR−2 VIS and NIR channels refer to WP 2.1 sections 5.2, 5.3 and particularly figure 5.8.

We make an intercomparison of the proposed SEVIRI IR channels and the ATSR-2 counterparts using the transmittance spectra generated for the fast model coefficients in WP 2.1 section 3.2. The following section presented some of the statistics shown here graphically.

For each channel pair we show profiles of the mean and standard deviation of the transmit-
tance to space for both the constant mixed gases and water components.

Scales in all figures through this section (and following sections on HIRS and MODIS) are fixed to facilitate intercomparisons. Figure 4.1.1 shows transmittance profiles for the 3.7 / 3.9 µm channels. There are significant differences in the mean profiles with the SEVIRI channel more strongly absorbed by the mixed gas and less by water. The standard deviation plots show corresponding behaviour although the mixed gas values are naturally quite low. Such differences (in the water transmittances) are likely to be large enough to lead to different capabilities, at least in subtle respects, of the two instruments for cloud parameter retrieval although, compared to the other IR channels, both are less affected by the atmosphere. The high SEVIRI water transmittances are a particularly good feature as the mixed gas variances are so low.

For the 11 and 12 µm channels, shown in figures 4.1.2 and 4.1.2 respectively, the differences in channel transmittances are negligible and the simulation of SEVIRI capability in
this case quite accurate.

Figure 4.1.2. As figure 4.1.1 but for the 11 µm channels

Figure 4.1.3. As figure 4.1.1 but for the 12 µm channels
4.2 Cloud

No significant differences are expected in the VIS channels. In the NIR, some small differences in drop size dependency due to shifted wavelength and slightly different solar constant are expected. In the SIR channel there will be significantly different drop size dependencies and solar constants and therefore a different balance between emission and reflection terms although in both instruments the solar reflection component will be large. No significant differences are expected in the IR channels.
1. Introduction

To simulate the 8.7 µm channel data from the MSG SEVIRI instrument data from the Tiros Operational Vertical Sounder (TOVS) carried aboard the current NOAA Polar orbiting satellites are being used. The TOVS package of sensors is described in the literature by Smith et. al. 1979. TOVS is actually three separate instruments: (1) the High resolution Infrared Sounder (HIRS/2), (2) the Microwave Sounding Unit (MSU), and (3) the Stratospheric Sounding Unit (SSU). Each of these instruments complements the others in the payload, and offers operational meteorologists an "all-weather capability" for temperature sounding the atmosphere throughout the troposphere and lower stratosphere. For our work we will however only be concerned with the data from the HIRS/2 instrument for the purposes of its application to testing a scheme for cloud parameter retrieval from SEVIRI, therefore the following text will confine itself to only the detail of the HIRS/2 part of the TOVS package.

2. Instrument characteristics

The HIRS/2 instrument measures incident radiation in the IR (15µm) and SIR (3.7µm) regions, but it also has a visible channel at 0.7µm for cloud detection. The 20 channels of the HIRS/2 instrument are detailed the table 1.
<table>
<thead>
<tr>
<th>Channel</th>
<th>Wavelength µm</th>
<th>Principal absorber</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.00</td>
<td>CO₂</td>
</tr>
<tr>
<td>2</td>
<td>14.70</td>
<td>CO₂</td>
</tr>
<tr>
<td>3</td>
<td>14.50</td>
<td>CO₂</td>
</tr>
<tr>
<td>4</td>
<td>14.20</td>
<td>CO₂</td>
</tr>
<tr>
<td>5</td>
<td>14.00</td>
<td>CO₂</td>
</tr>
<tr>
<td>6</td>
<td>13.70</td>
<td>CO₂/H₂O</td>
</tr>
<tr>
<td>7</td>
<td>13.40</td>
<td>CO₂/H₂O</td>
</tr>
<tr>
<td>8</td>
<td>11.10</td>
<td>Window - SST and cloud detection</td>
</tr>
<tr>
<td>9</td>
<td>9.70</td>
<td>O₃</td>
</tr>
<tr>
<td>10</td>
<td>8.30</td>
<td>H₂O Sounding</td>
</tr>
<tr>
<td>11</td>
<td>7.30</td>
<td>H₂O Sounding</td>
</tr>
<tr>
<td>12</td>
<td>6.70</td>
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<td>4.52</td>
<td>N₂O</td>
</tr>
<tr>
<td>15</td>
<td>4.46</td>
<td>CO₂/N₂O</td>
</tr>
<tr>
<td>16</td>
<td>4.40</td>
<td>CO₂/N₂O</td>
</tr>
<tr>
<td>17</td>
<td>4.24</td>
<td>CO₂</td>
</tr>
<tr>
<td>18</td>
<td>4.00</td>
<td>Window - Surface Temperature</td>
</tr>
<tr>
<td>19</td>
<td>3.70</td>
<td>Window - Surface Temperarure</td>
</tr>
<tr>
<td>20</td>
<td>0.70</td>
<td>Window - Cloud</td>
</tr>
</tbody>
</table>

Table 1  The HIRS/2 channel numbers, wavelengths and principal absorbing gas(es) in the bandpass

The IFOV of the HIRS/2 channels are stepped across the satellite track by use of a rotating mirror. This across-track scan, combined with the satellite’s motion in orbit, provides coverage of a major portion of the Earth’s surface each day. The width of the across-track scan is 99° (equivalent to 2240 km) and consists of 56 steps. The mirror is stepped from home position in 55 steps of 1.8°. At the end of the scan (at position 56) the mirror rapidly returns to the home position and repeats the scanning pattern. Each scan takes 6.4 seconds to complete (100ms per step) and there are 42 km between IFOVs along the sub-satellite track. The optical FOV is 1.25° which gives a ground IFOV of 17.4 km diameter at the nadir. At the end of the scan, the ground IFOV is 58.5 km across-track by 29.9 km along-track.
### Table 2. Key HIRS/2 instrument parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration method</td>
<td>Two stable blackbodies and space view</td>
</tr>
<tr>
<td>Across-track scan angle</td>
<td>±49.5° from nadir</td>
</tr>
<tr>
<td>Scan time</td>
<td>6.4 seconds</td>
</tr>
<tr>
<td>Number of scan steps</td>
<td>56</td>
</tr>
<tr>
<td>Angular FOV</td>
<td>1.25°</td>
</tr>
<tr>
<td>Step angle</td>
<td>1.8°</td>
</tr>
<tr>
<td>Step time</td>
<td>0.1 seconds</td>
</tr>
<tr>
<td>Ground IFOV diameter (at nadir)</td>
<td>17.4 km</td>
</tr>
<tr>
<td>Ground IFOV size at end of scan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>across-track</td>
</tr>
<tr>
<td></td>
<td>along-track</td>
</tr>
<tr>
<td>Along-track Distance between IFOV centres</td>
<td>42.0 km</td>
</tr>
<tr>
<td>Swath width</td>
<td>±1120 km</td>
</tr>
<tr>
<td>Data rate</td>
<td>2880 bits per second</td>
</tr>
<tr>
<td>Data precision</td>
<td>13-bits</td>
</tr>
<tr>
<td>Time between start of each scan line</td>
<td>6.4 seconds</td>
</tr>
<tr>
<td>Step and dwell time</td>
<td>0.1 seconds</td>
</tr>
<tr>
<td>Time</td>
<td>0.5 seconds</td>
</tr>
</tbody>
</table>

3. **Instrument calibration**

HIRS/2 can be commanded to automatically enter a calibration mode every 256 seconds. When the instrument is in the calibration mode, the mirror (starting from the beginning of a scan line) rapidly slews to a space view and samples all channels for the equivalent time of one complete scan line of 56 scan steps. Next, the mirror is moved to a position where it views a cold calibration target and data is taken for the equivalent of 56 scan steps. The mirror is then stepped to view an internal warm target for another 56 scan steps. (Further details of the instruments in the TOVS package can be found at the NOAA WWW pages at URL http://pegasus.nesdis.noaa.gov/tovs.html.)

Upon completion of the calibration mode, the mirror continues its motion to the home position where it begins the normal Earth scan. The total calibration sequence is equivalent to three scan lines (no Earth data are obtained during this period). The analogue data output from the HIRS/2 sensor is digitised onboard the satellite at a rate of 2880 bits per second. At this rate, there are 288 bits per step (step time = 100ms) which includes all 20 channels. The data is digitised to 13-bits precision.

The HIRS/2 forms part of the payload of the the TIROS-N series of Earth observing satellites which have provided a near continuous record of operational vertical sounder radiance data from 19 October, 1978 to the present. The TIROS platforms, designed to operate in a near-polar, sun-synchronous orbit with an orbital period of approximately 102 minutes, produce 14.1 orbits per day. Because the number of orbits per day is not an integer, the sub-
orbital tracks do not repeat on a daily basis. The local solar time of the satellite’s passage, however, is essentially unchanged for any given latitude.

This study will make use of data from the HIRS/2 Channel-10 centred at a wavelength of 8.30 µm, the filter function for this channel is shown in figure 3.1 of WP 2.2.

**4. HIRS - SEVIRI channel intercomparison**

**4.1 Atmosphere**

Here we discuss only the 8.3 and 8.7 µm channel combination since HIRS data will potentially be used for study of this wavelength. The other candidate is the MODIS AS (see WP 2.4a) 8.6 / 8.8 µm. Depending on the degree to which we eventually use the HIRS data (it has the disadvantage of a large pixel size (>18 Km), it may become desirable to intercompare also the HIRS 11,12 and 3.9 µm channels.

As with the ATSR–2 comparison, WP 2.3 section 4.1, we show statistics of the transmittances calculated over many profiles for the RTTOV coefficients.

![Figure 4.1.1 Statistics of SEVIRI and HIRS 8.7/8.3 µm transmittances.](image)

Figure 4.1.1 shows that the HIRS 8.3 µm and the proposed SEVIRI 8.7 µm are quite poorly matched. The 8.3 µm has more absorption by both the mixed gases and by water; and consequently it will be a harder channel to interpret than the 8.7 µm. It is unlikely that such differences will make the HIRS channel of little use in simulating the SEVIRI channel especially as quantification of cirrus is likely to be its main role. The match between the MODIS AS channels is better (see WP 2.4a section 4.1) and the imagery available of much higher resolution. However, HIRS data can be acquired for any geographic area and time unlike the limited campaign dat of MODIS AS.

**4.2 Clouds**
No info on this as yet. However, unlikely to be very significant differences between 8.3 and 8.7 µm in their optical properties.

References:

1. Introduction

The MODIS Airborne Simulator (MAS) is a modified Daedalus Wildfire scanning spectrometer which flies on a NASA ER-2 and provides spectral information similar to that which will be provided by the Moderate Resolution Imaging Spectroradiometer (MODIS), scheduled to be launched on the EOS-AM platform in 1998 (King et al. 1992).

The Wildfire Spectrometer was delivered to NASA Ames Research Center in April 1991, and has been subsequently modified several times. Initially a single visible channel was added and several spectral channels in the infrared port were altered to configure the instrument for the FIRE Cirrus-II experiment. In January 1992 the modified Wildfire was then further modified to become MAS. Beginning in June of 1992, the MAS has been flown in a series of experiments that lasted on average 2 to 4 weeks and have been held approximately every 6 months since.

2. Spectrometer campaign details

The MAS spectrometer acquires high spatial resolution imagery in the wavelength range 0.55 to 14.3 μm. A total of 50 spectral bands are available in this range, and at the time of the campaign data to be used in the digitiser is configured before each mission to record any 12 of these bands during flight. For all pre-1994 MAS missions the 12-channel digitizer was configured with four 10-bit channels and seven 8-bit channels. A list of all the MAS bands is provided in table 1.

The MAS spectrometer is mated to a scanner sub-assembly which collects image data with an IFOV of 2.5 mrad, giving a ground resolution of 50 metres from 20 km altitude, and an across track scan width of 85.92°. More details on the MAS sensor and scanner characteristics are shown in table 2.

A 50-channel digitizer which will record all 50 spectral bands at 12 bit resolution is currently under development and is expected to be completed in mid 1994. Prior to 1995, the MAS data system was capable of recording only 12 spectral bands at 8-bit resolution. This required unique instrument configurations for each Field Experiment.

In November/December 1991, the modified Wildfire instrument was flown in the FIRE Cirrus-II experiment onboard a NASA ER-2 in coordination with other aircraft and satellites over the Coffeyville KS field site as well as the TX/LA Gulf coast. In January 1992, the modified Wildfire was converted to MAS configuration. In June 1992 the MAS was flown over portions of the Atlantic Ocean in the region of the Azores during the ASTEX experi-
ment. During early 1993 the MAS was flown in the southwestern Pacific Ocean during the TOGA/COARE and CEPEX experiments.

<table>
<thead>
<tr>
<th>MAS Band</th>
<th>Left Peak Right</th>
<th>MAS Band</th>
<th>Left Peak Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50% 100% 50%</td>
<td></td>
<td>50% 100% 50%</td>
</tr>
<tr>
<td>01</td>
<td>0.523 0.546 0.569</td>
<td>26</td>
<td>2.875 2.959 3.039</td>
</tr>
<tr>
<td>02</td>
<td>0.627 0.653 0.680</td>
<td>27</td>
<td>3.031 3.110 3.195</td>
</tr>
<tr>
<td>03</td>
<td>0.679 0.700 0.721</td>
<td>28</td>
<td>3.202 3.276 3.358</td>
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<tr>
<td>04</td>
<td>0.720 0.741 0.762</td>
<td>29</td>
<td>3.338 3.422 3.507</td>
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<tr>
<td>05</td>
<td>0.761 0.781 0.802</td>
<td>30</td>
<td>3.511 3.588 3.668</td>
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<tr>
<td>06</td>
<td>0.802 0.823 0.844</td>
<td>31</td>
<td>3.669 3.743 3.819</td>
</tr>
<tr>
<td>07</td>
<td>0.844 0.865 0.886</td>
<td>32</td>
<td>3.819 3.901 3.986</td>
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<tr>
<td>08</td>
<td>0.888 0.906 0.922</td>
<td>33</td>
<td>3.976 4.054 4.132</td>
</tr>
<tr>
<td>09</td>
<td>0.921 0.945 0.967</td>
<td>34</td>
<td>4.126 4.208 4.288</td>
</tr>
<tr>
<td>10</td>
<td>1.595 1.622 1.650</td>
<td>35</td>
<td>4.288 4.363 4.435</td>
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<td>1.652 1.678 1.705</td>
<td>36</td>
<td>4.439 4.516 4.594</td>
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<td>12</td>
<td>1.706 1.732 1.757</td>
<td>37</td>
<td>4.585 4.667 4.748</td>
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<td>1.759 1.786 1.812</td>
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<td>4.745 4.823 4.901</td>
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<td>1.813 1.838 1.863</td>
<td>39</td>
<td>4.897 4.974 5.047</td>
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<td>1.863 1.889 1.914</td>
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<td>5.046 5.124 5.203</td>
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<td>1.914 1.939 1.963</td>
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<td>5.205 5.281 5.362</td>
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<td>1.964 1.989 2.013</td>
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<td>2.066 2.090 2.113</td>
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<td>5.662 5.736 5.810</td>
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<td>2.114 2.138 2.162</td>
<td>45</td>
<td>5.810 5.884 5.958</td>
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<td>2.163 2.187 2.210</td>
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<td>5.958 6.032 6.106</td>
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<td>22</td>
<td>2.211 2.237 2.261</td>
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<td>6.106 6.179 6.253</td>
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<td>23</td>
<td>2.262 2.287 2.310</td>
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<td>6.253 6.327 6.400</td>
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<td>24</td>
<td>2.312 2.337 2.360</td>
<td>49</td>
<td>6.400 6.472 6.545</td>
</tr>
<tr>
<td>25</td>
<td>2.361 2.386 2.410</td>
<td>50</td>
<td>6.545 6.618 6.691</td>
</tr>
</tbody>
</table>

Table 1 List of MAS Spectral Bands

Although the MAS instrument is a 50 band spectrometer, the data system used until mid-1994 only had the capability to record 12 channels (at 8 bit resolution). This required unique instrument configurations for each Field Experiment, below in table 3 are the configurations of the instrument for the campaign data presently acquired for use in this study.
### Modis Airborne Simulator Characteristics

<table>
<thead>
<tr>
<th>Platform:</th>
<th>NASA ER-2 aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Speed:</td>
<td>400 knts (206 m/second)</td>
</tr>
<tr>
<td>Altitude:</td>
<td>20 kilometres (nominal)</td>
</tr>
<tr>
<td>Pixel Spatial Resolution:</td>
<td>50 metres (at 20 kilometres altitude)</td>
</tr>
<tr>
<td>Pixels per Scan Line:</td>
<td>716 (roll corrected)</td>
</tr>
<tr>
<td>Scan Rate:</td>
<td>6.25 scans/second</td>
</tr>
<tr>
<td>Swath width:</td>
<td>37.25 km or 22.9 milliradians (at 20 km altitude)</td>
</tr>
<tr>
<td>Total Field of View:</td>
<td>85.92°</td>
</tr>
<tr>
<td>Instantaneous Field of View:</td>
<td>2.5 milliradians</td>
</tr>
<tr>
<td>Roll Correction:</td>
<td>±3.5 degrees (approx)</td>
</tr>
<tr>
<td>Data Channels:</td>
<td>50 (pre-1995 was 12 selected from 50 spectral bands)</td>
</tr>
<tr>
<td>Spectral Bands:</td>
<td>50 (digitised to 16-bit resolution)</td>
</tr>
<tr>
<td></td>
<td>Port 1: 09 bands from 0.529 - 0.969 microns</td>
</tr>
<tr>
<td></td>
<td>Port 2: 16 bands from 1.595 - 2.405 microns</td>
</tr>
<tr>
<td></td>
<td>Port 3: 15 bands from 2.925 - 5.325 microns</td>
</tr>
<tr>
<td></td>
<td>Port 4: 09 bands from 8.342 - 14.521 microns</td>
</tr>
<tr>
<td>Bits per Channel:</td>
<td>12 bits (pre-1995: 8 bits, configured to have 4 channels @ 10 bits, 7 channels @ 8 bits)</td>
</tr>
<tr>
<td>Data Rate:</td>
<td>246 Megabytes/hour</td>
</tr>
<tr>
<td>Visible Calibration:</td>
<td>Integrating sphere on the ground</td>
</tr>
<tr>
<td>Infrared Calibration:</td>
<td>Two blackbodies on board</td>
</tr>
</tbody>
</table>

Table 2. MAS Sensor Characteristics

<table>
<thead>
<tr>
<th>FIRE Cirrus-II (First ISCCP Regional Experiment Cirrus IFO II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA CHANNEL</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>01</td>
</tr>
<tr>
<td>02</td>
</tr>
<tr>
<td>03</td>
</tr>
<tr>
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<td>09</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12</td>
</tr>
</tbody>
</table>

Table 3. MAS Configurations for FIRE Cirrus-II and CEPEX
### Table 3 cont. MAS Configurations for FIRE Cirrus-II and CEPEX

The data is provided by NASA in HDF format, as calibrated and geolocated radiances. Details of the calibration and geolocation can be found at the Modis Airborne Simulator WWW site at the URL http://ltpsun.gsfc.nasa.gov/MAS/masdug.html. The calibration includes a correction for the temperature of the instrument while it is in-flight.

### 3. MAS Data Calibration

#### 3.1 Visible/Near-Infrared Band Calibration

Calibration coefficients for the MAS visible (~< 0.7 µm) and near-infrared (0.7 µm < ~ 3.7 µm) bands are derived from integrating spheres used pre and post launch. The transformation from digital count to radiance is defined by

\[
Radiance = (\text{Count} - (\text{Gain} \cdot \text{CBBavg})) \cdot \text{Slope}
\]

where *Radiance* is the computed radiance, *Count* is the recorded count, *Gain* is the channel gain, *CBBavg* is the running average of 30 previous cold blackbody counts, and *Slope* is slope coefficient, determined for each band.

The radiance units are Watts per square metre per steradian per micron (W m\(^{-2}\)sr\(^{-1}\)µm\(^{-1}\)). Integrating sphere calibrations may be carried out several times during a MAS flight experiment. There may be several sets of calibration slopes, each applied to data from a discrete time period, during a single experiment.

#### 3.2 Temperature Correction of Visible/Near-Infrared Bands
MAS testing in a cold chamber at NASA Ames Research Center has shown that some MAS VIS/NIR bands are subject to sensitivity changes as a function of temperature. This is important, since at cruise altitude (20 km) the MAS instrument environmental temperature is typically around -35°C. The cold chamber data is used to develop equations which predict the sensitivity of the VIS/NIR channels at given temperatures. Temperature sensors mounted on the MAS in-flight are then used as a reference for computing the sensitivity correction. For example in ASTEX data it was found that only channels 5 and 6 were sensitive to this phenomenon. For these two channels Count = \( C_{\text{eff}} \) for all other VIS/NIR channels Count = \( C_{\text{rec}} \). The form of the equation for \( C_{\text{eff}} \) during ASTEX was:

\[
\text{Count} = C_{\text{eff}} = GC_{\text{cbb}} + \frac{(C_{\text{rec}} - (G * C_{\text{cbb}}))}{(a_1 T_{\text{mas}} + b_1)}
\]

where \( C_{\text{eff}} \) is the temperature corrected effective digital count, \( G \) is the channel gain, \( C_{\text{cbb}} \) is the recorded in-flight digital count for cold black body, \( C_{\text{rec}} \) is the recorded original in-flight digital count, \( a_1 \) and \( b_1 \) are the coefficients determined for each band, \( T_{\text{mas}} \) is the temperature of cold blackbody in °C. The coefficients \( a_1 \) and \( b_1 \) are determined for each temperature sensitive channel in each MAS experiment. This correction is applied before the linear transformation to radiance units.

### 3.3 Infrared Band Calibration

Calibration data for the MAS infrared (IR) bands (~> 3.7 µm) are obtained during flight from two blackbody sources which are viewed during every mirror scan. The first (cool) blackbody is usually left to float at ambient temperature, although it can be temperature controlled. The second (warm) blackbody is maintained at a higher temperature than the cool blackbody, and the temperature level is set depending on the desired scene temperature range. Thermistors measure the temperature of the blackbodies during flight. The equivalent Planck radiances for the blackbodies (assuming unit emissivity) are computed using a sensor weighted integral of the Planck function over the wavelength range of the spectral band:

\[
\text{B}(l, T) = \frac{C_1}{l^5} \text{exp} \left( \frac{C_2}{lT} \right) - 1
\]

where \( C_1 = 2hc^2 = 1.1910439 \times 10^{-16} \text{ W m}^{-2} \) and \( C_2 = (hc/k) = 1.4387686 \times 10^{-2} \text{ mK} \), \( l \) is the wavelength in metres, and \( T \) is the temperature in Kelvin.

Once the equivalent Planck radiances for the blackbodies are known, the calibration slope and intercept are computed by the relationships:

\[
\text{Slope} = \frac{(R(l, T_{bb2}) - R(l, T_{bb1})) / (C_{bb2} - C_{bb1})}{(C_{bb2} - C_{bb1})}
\]

\[
\text{Intercept} = \left( (R(l, T_{bb1}) C_{bb2}) - (R(l, T_{bb2}) C_{bb1}) / (C_{bb2} - C_{bb1}) \right)
\]

where \( R(l, T_{bb1}) \) and \( R(l, T_{bb2}) \) are the equivalent Planck radiances for the cool and warm blackbodies respectively, \( C_{bb1} \) and \( C_{bb2} \) are the digital radiance counts for the cool and
warm blackbodies, respectively. The calibration from digital counts to radiance is then a linear transformation of the form

\[ \text{Radiance} = \text{Slope} \times \text{Count} + \text{Intercept} \]

The radiance units are Wm\(^{-2}\)sr\(^{-1}\)µm\(^{-1}\). This procedure is performed for every IR channel on every scanline. No averaging of MAS blackbody data is done. Conversion from IR radiance to Planck equivalent temperature or “brightness temperature” may be done by inverting the Planck equation. The inverse equation is of the form:

\[ T(l,B) = \frac{C_2}{l \log_e \left( \frac{C_1}{(l^5 B(l,T) \times 10^6) + 1} \right) + 1} \]

where \( T(l,B) \) is the brightness temperature in Kelvin, and the others are as described above.

4. MODIS - SEVIRI channel intercomparison

4.1 Atmosphere

Following the discussion in WP 2.3 section 4.1 we restrict ourselves here to analysis of the match between SEVIRI 8.7 and MODIS AS 8.6-8 µm channels. As in the previous analyses, the transmittance profiles from the fast model coefficient generation are used as an indicator of the match between channels. A general caveat on this section is, as mentioned earlier, the MODIS filters are approximated by gaussians fitted to the given central wavenumbers and half power widths and may therefore be somewhat wider or narrower than the true filters. Figure 4.1.1 shows the results for the MODIS 8.6 µm channel (present in the CEPEX campaign data) compared to the SEVIRI 8.7 µm.

![Figure 4.1.1 Statistics of SEVIRI and MODIS AS 8.6 µm transmittances](image)

Figure 4.1.1 Statistics of SEVIRI and MODIS AS 8.6 µm transmittances
Some differences in transmission are apparent in both the mixed gas and the water components although they may not be significant. The figure resembles that for the SEVIRI-HIRS comparison in WP 2.4 section 4.1 except that the longer wavelength of the MODIS channel leads to higher transmittances and a better comparison. The comparison with the MODIS

![Figure 4.1.2. As figure 4.1.1 but for the MODIS 8.8 µm channel](image)

8.8 µm channel (present in the FIRE-II campaign data) shown in figure 4.1.2 is clearly much closer and the channels are very well matched.

### 4.2 Cloud

No significant differences are expected in the cloud optical properties between MODIS and SEVIRI wavelengths.
1. Overview

This workpackage deals with the principles and practicalities of the proposed and implemented retrieval scheme. Section §2 briefly reiterates the physical basis for the retrieval of cloud parameters from the SEVIRI radiance measurements about. This has been discussed in previous workpackages. Section §3 explains the general principles behind the proposed retrieval method and discusses the practical considerations of statistical constraints. The section on simulated error analysis presents expressions for the various terms in the error budget of the retrieval and then examines how these behave under various situations. Section §3.5 describes the method of finding the solution when presented with real data and suggests techniques for dealing with hard constraints and a particular feature of cloud retrievals: the phase change. Section §3.6 addresses the important subject of quality control of retrievals and §3.7 clarifies the requirements of data that are to be used as either a priori and ‘first guess’ constraints.
2. Origin of physical information

This section is intentionally brief since most aspects of the discussion are already dealt with elsewhere in the Report. In WP 1.3 we recommended a combined infrared-visible product definition and we can use this here to explain the origin of the information.

τ – *visible optical depth*. This is only ‘visible’ in the sense that a visible (0.55 µm) wavelength is used as a reference against which to refer optical depths at all channel wavelengths. τ has a strong influence on measurements in all channels. At VIS wavelengths the total reflected radiance is related directly and strongly to the total number of scattering objects in the scene. Thus the strength of the reflection is in the simplest case directly related to τ. The VIS reflectance continues to rise even for substantially large τ. There is a small drop size dependence however, and the presence of surface reflection and atmospheric effects. τ also determines very strongly the transmission and emission of IR radiance but ‘saturation’ is reached for quite low values; i.e. the transmission reaches zero and the emission its maximum value. In the IR case, the effect of τ on the measurements is principally through absorption and not scattering.

re – *Particle size*. We use the phrase ‘particle size’ to cover the cases for water (where a well defined effective radius is available) as well as for ice. re affects the measurements by changing the effectiveness with which an ensemble of particles scatters radiation. This arises because the interaction of radiation with the particle is partly through external diffractive and reflective effects (which tend to change as the surface area) and partly through internal absorption effects (which tend to change by volume). In the case of the VIS channels where there is practically no internal absorption, re has only a small effect for a given τ. This is similarly true for those IR channels where absorption dominates. For the NIR, SIR and 8 µm channels where both scattering and absorption are important, then the change in the balance between the two leads to a sensitivity to re. In the reflectance channels (1.6 and 3.9 µm) there is higher reflectance for a lower re. In the thermal channels (3.9 and 8.7 µm) the response is an enhancement of transmission and decrease in emission.

pc – *Pressure*. Pressure affects the measurements principally because it determines the temperature of the cloud. Thus the IR thermal emission has a strong dependence on pc as well as a strong dependence on optical depth and fraction. The VIS reflectances depend on pc through absorption in the atmosphere above (and sometimes below) the cloud. Thus, in principle, there will be information on pc from the pure reflectance channels although this dependence will be weak for all but the wettest atmospheres and the lowest clouds.

f – *fraction*. The cloud fraction dominates the signal in all of the channels since their response to cloud-covered and cloud-free atmospheres are generally very different. There are only a few exceptional circumstances e.g., thin cloud over highly reflective land in the VIS, low cloud with a similar temperature to the land/sea surface in the IR.

*Phase – cloud phase*. The effect of the phase of the cloud, water or ice, is due to two effects. Firstly, for the 1.6, 8.7 µm and SIR channels the refractive index difference of liquid and solid leads to a change in particle absorption (for a given re) and thus a different range of reflectance and emission. Secondly, the shape of the particle has important effects. At the short wavelengths (VIS, NIR, SIR) the bi-directional reflectance pattern differs between spherical water and irregular or hexagonal ice particles. At longer wavelengths, the shape influences the ability of a particle of similar size to ‘capture’ (i.e. absorb) radiation. Irregular
particle shapes are less efficient at photon capture than the spherical shape, thus cloud transmis­
sions for ice are higher than water clouds with the same given optical depth and particle
size. Phase information from the SEVIRI system is likely to be largely derived (in the day­
time at least) by change of absorption characteristics in the 1.6 and 3.7 µm channels since
the bi-directional reflection effects are more subtle and also consistent between channels.

\( T_s \) – **Surface temperature.** Although not a cloud parameter, the surface temperature has been
included in the retrieval system because it may prove that, particularly over land, the value
supplied by the NWP model data is of insufficient accuracy. The effect of \( T_s \) on the measure­
ments is restricted (but not small) to the IR channels.

3. Retrieval methodology

3.1 Principles and the error budget

As we stated in WP 1.4 we have recommended and EUMETSAT have (1st PM) agreed for
us to pursue a methodology based on optimal estimation. The notation is largely that of
Rogers 1976 and 1990 which should be referred to for a thorough description of optimal es­
timation directed towards remote sounding problems. Rogers 1990 in particular describes
the analysis of errors used in this section.

As outlined in section §2 above, the basic ‘state’ that is to be retrieved is that of \( \tau, r_e, p_e, f, \)
and \( T_s \). For the purposes of the theoretical discussion, this is defined as a state vector \( x \):

\[
x = [ \tau, r_e, p_e, f, T_s ]
\]

(1)

All the other elements of the radiative transfer are assumed to come from *a priori* information. The state vector units used in this study are \[ \log_{10}(\tau) \ \text{(no units),} \mu\text{m, mb, (no units), K} \] but see section §3.5.4 on the scaling of parameters.

We have a set of measurements available which we define as a vector \( y \):

\[
y = [0.6, 0.8, 1.6, 3.7, 8.7, 11, 12]
\]

(2)

where a certain shorthand has been used to describe the channel information. In all the fol­
lowing the 0.6, 0.8, 1.6 µm channel measurements will be assumed to be expressed in terms of
\% reflectance \( R = 100 \times I / F_o \), where \( I \) is the measured radiance, and \( F_o \) is the solar irradi­
ance (taken from LOWTRAN). The 3.7, 8.7, 11 and 12 µm channels are assumed to be ex­
pressed as brightness temperatures, \( T_B = B^{-1}(R, \nu) \) where \( B^{-1} \) is the inverse Planck function,
\( R \) is the measured radiance and \( \nu \) is the effective central wavenumber of the channel. A par­
ticular vector \( y \) that is of actual measurements (rather than calculations at a particular state
\( y(x) \)) will be referred to as \( y_m \).

The basic principle of optimal estimation is to maximise the probability of the retrieved
state conditional on the value of the measurements and any *a priori*. Formally, it is required
to maximise \( P(x \mid y, x_p, b) \) where \( x_p \) is the *a priori* value of \( x \) and \( b \) are all the other elements
of the radiative transfer, called forward model parameters. \( b \) includes the NWP temperature
and humidity profiles, surface reflectance / emissivity and theoretically, although we do not
consider them further here, spectroscopic information (for gaseous transmission), refractive
index information (for scattering properties). $b$ is formally given as

$$ b = [T(z), H(z), R_s, \varepsilon] $$

(3)

where $T(z)$ is the atmospheric temperature profile obtained from NWP and specified here on the 40 RTTOV IR model pressure levels from 1000–0.1 mb, $H(z)$ is similarly the humidity profile specified on 15 levels from 1000–300 mb. $R_s$ is a vector (4) of surface reflectances at 0.6, 0.8, 1.6 and 3.7/9 µm and $\varepsilon$ is a vector (4) of surface emissivities at 3.7/9, 8.7, 11 and 12 µm.

The principle of maximising $P$ is a fairly general one. Here we take the usual approach and assume that errors in the contributing components are normally distributed and are described by covariance matrices. Thus we have;

$S_y$ – error covariance of the measurements ($ny \times ny$) where $ny$ is the length of $y$.
$S_x$ – error covariance of the a priori state ($nx \times nx$) where $nx$ is the length of $x$.
$S_b$ – error covariance of the forward model parameters ($nb \times nb$) where $nb$ is the length of $b$.

For discussion on the values of $S_y$, $S_x$ and $S_b$ see section §3.3.

The ability of the measurement system $y$ to retrieve $x$ depends on the sensitivity of the measurements to the various parameters. This sensitivity is formally defined by the gradient terms;

$K_x = \partial y / \partial x$ – gradient of measurements with state - often known as ‘weighting functions’.
$K_b = \partial y / \partial b$ – gradient of measurements with forward model parameters.

For the system to successfully estimate $x$, it is clear that either $K_x$ must be $>> K_b$ or the values of $b$ must be well known, i.e. that $S_b$ be small. (The system can also estimate $x$ if $K_x$ and $K_b$ are orthogonal, but this is unlikely in practice.) $K_x$ are the gradients described and tested in WP 2.1 and 2.2. Examples of $K_b$ for temperature and humidity are given in figures A1 to A5 for which a description is given below. However, this is somewhat of an aside to the main argument so we advise the reader skip over this section unless details of the behaviour of $K_b$ are required.

Figure A1 shows $K_b$ for the LOWTRAN tropical model, ‘land’ surface reflectance and zero cloud cover; the effects are just atmospheric in this case. The upper plots show $K_b$ for the reflectance channels, the lower plots for the IR channels. Left-hand plots show $K_b$ with respect to the temperature profile and right-hand plots show $K_b$ with respect to the humidity. Note the different scales for the temperature and humidity parts of the reflectance channels. An increased temperature has a very small positive effect on the reflectance (possibly through a negative temperature dependence of continuum absorption). Increased absorption by humidity gives a negative $K_b$ and since in the reflectance channels the atmosphere is only absorbing, this effect continues to the surface. The large difference between the effects at 0.6 and 0.8/1.6 µm is partly due to the different atmospheric transmissions but mainly due to the surface reflectance assumed: 5, 25 and 15% reflectance respectively. In the IR channels both temperature and humidity have significant and opposite effects: an increased temperature gives a higher radiance as does a decreased humidity. Because there is emission by the atmosphere as well as absorption, both parts of $K_b$ for the IR channels tend to small values near the surface where the surface and air temperatures are roughly the same and any increased absorption is largely cancelled by in-
creased emission. Finally, the F=5 refers to a magnification factor applied to avoid numerical precision problems with small perturbations; the actual perturbations applied to obtain the figure are 5 K and 50% (whereas the values 1 K and 10% are used in the calculation of the retrieval errors due to uncertainties in b (equation (6)). Figure A2 shows $K_b$ if a water cloud of $\tau=4$, $R_c=8$ micron, $p_c=500$ mb and fractional cover 0.5 is added to the atmosphere used in A1. There is a detectable but hardly significant increase in the sensitivities of the reflectance channels to the atmosphere, caused by the multiple reflections between cloud and surface. The clearest difference is seen in the IR channels where a large ‘spike’ at 500 mb in the temperature profile is caused by the cloud layer; the low spike value for the 3.7 µm channel is because a large part of the signal in this channel is from reflected solar radiation. Atmospheric effects below the cloud are reduced compared to figure A1 because this part of the atmosphere is now partly ‘screened’ by the cloud cover.

In figure A3 the cloud and atmosphere are specified as for A2 but the solar and viewing zenith angles are increased from 30° and 10° to 60° and 40° respectively. The increased slant paths do give rise to slightly larger sensitivities in the IR but slightly lower sensitivities in the reflectance channels. The balance is presumably between higher sensitivity and lower signal due to the higher atmospheric opacity.

In figure A4 the surface reflectance used is that typical of ‘ocean’, i.e. very low. The cloud parameters are $\tau=1$, $R_c=8$ micron, $p_c=800$ mb and fractional cover 1.0. The reflectance channel $K_b$ values are now very low because of the lack of signal from the surface. In the IR, the peak response for temperature is again at cloud level although it now merges with the broader atmospheric (humidity) effects. The 3.7 µm humidity sensitivity is higher in the atmosphere than the other IR channels because there is a strong solar component from the cloud and a weaker atmospheric absorption in the lower levels.

Finally, in figure A5 there is an optically thick ($\tau=16$) cloud, full cloud cover and at 700 mb. The surface reflectance is typical of land so that the reflectance channel sensitivities are now significant and show a discontinuity due to absorption of directly reflected radiation (above 700 mb) and that due to absorption of the cloud-surface multiple reflected radiation (throughout the profile). VIS wavelength radiation is transmitted by this cloud cover but the IR plots show zero response below the cloud for both humidity and temperature. The exception is a small humidity effect on the 3.7 µm where the cloud is still significantly transmitting (by virtue of the high scattering at this wavelength).

A final definition required here is the function $D_y$ (the ‘contribution function’ or ‘inversion operator’) which describes the response of the retrieval estimator (the ‘inverse model’) to a change in measurements. Thus $D_y = \partial x'/\partial y$ where $x'$ is the estimated value of $x$. This is a general definition at present to illustrate that the error analysis method is not dependent on the retrieval estimation method, it only assumes that $D_y$ can be defined. The expression for $D_y$ actually used in this study makes use of the assumption of normally distributed errors and is given below. Note that $D_y$ is the system response in the region of the solution – it may be quite different at the start of an iterative process far from the solution.

Leaving aside the question of techniques for finding the maximum of $P$ until section 3.5 we can now investigate the theoretical errors in the solution for $x$ assuming that this maximum has been found. Following Rogers 1990, we can identify the error sources as a) ‘null space’ or a priori smoothing error, b) measurement error and c) model parameter error. These are expressed as covariances $S_N$, $S_M$ and $S_S$ respectively, thus:

1) ‘Null space error’

$$S_N = (D_y K_x - I) S_x (D_y K_x - I)^T$$

where $I$ is the unit matrix and $^T$ implies matrix transpose.

1The slightly erratic nature of the responses in $K_b$ in the near-surface levels is due to the uneven spacing of the radiative transfer model levels so that equal perturbations in temperature for example result in uneven perturbations in opacity.
expresses the error that arises from a basic lack of information in the measurement system, hence the term ‘null space’ error. To clarify using an example; in the case of thick cloud, overcast conditions it is clear there is no information in the SEVIRI measurements on surface temperature - the ‘null space’ error on \( T_s \) in this case will be large (it will essentially be the \textit{a priori} error). This can be intuitively seen from the equation since both \( D_y \) and \( K_x \) will be effectively zero and \( S_N = S_x \).

2) Measurement error

\[
S_M = D_y S_y D_y^T
\]  

(5)

\( S_M \) expresses the mapping of the errors in the measurements onto the solution. Clearly zero errors will give a zero contribution.

3) Model parameter errors

\[
S_S = (D_y K_b) S_b (D_y K_b)^T
\]  

(6)

\( S_S \) expresses the mapping of the errors in the forward model parameters onto the solution. This term is frequently neglected from error analyses on the grounds perhaps that \( S_b \) is either small (all parameters are well known) or that all uncertain parameters are included in the state vector \( x \), and are therefore manifest through \( S_N \) and \( S_M \). In the present case with relatively few measurements (maximum 7) and a large number of unknowns we have taken the view that the inversion problem is more tractable and more likely to succeed with the state vector comprised of only the principle cloud (and surface temperature) components. thus there are important model parameters that are not in the state (as described above) and it is therefore vital to estimate their effect on the error budget.

The behaviour of the three error terms are explored in some detail in section §3.4. They are, as indicated, error \textit{covariances} and therefore contain information on the correlation of solution errors. However, it is normal to examine only the square root of the diagonal elements; i.e. the standard deviation of the error. The off-diagonal elements can be useful though since they indicate how two or more parameters may not be separately estimable.

3.2 The inversion operator \( D_y \)

As stated, the problem is to maximise \( P(x \mid y, x_b, b) \) for a given \( y, x_b \) and \( b \). With the assumption of independent and normally distributed errors, \( P \) can be expressed in the quadratic form;

\[
P \propto \exp[-(y(x) - y_m)S_y^{-1}(y(x) - y_m)^T] \times \exp[-(x - x_b)S_x^{-1}(x - x_b)^T] \times \exp[-(b_t - b)S_b^{-1}(b_t - b)^T]
\]  

(7)

where the three terms represent weighted deviations from measurements, the \textit{a priori} state and the model parameters respectively. We have written \( b_t \) for the (unknown) true values of the model parameters. Maximising probability is equivalent to minimising the negative logarithm, so that we essentially wish to minimise \( J \) where:
\[ J = (y(x) - y_m)S_y^{-1}(y(x) - y_m)^T + (x - x_b)S_x^{-1}(x - x_b)^T + (b_t - b)S_b^{-1}(b_t - b)^T \]  

(8)

Notice we are minimising with respect to the state variable \( x \), so that the derivative of \( J \) is independent of the third term and \( b \) therefore cannot be part of the solution. It can be shown (see Rogers 1976) that the minimum of this function (assuming \( x_b \) is near enough the solution for the system to be linear) is given when

\[ x' = (S_x^{-1} + K_x^T S_y^{-1} K_y)^{-1} \cdot (S_x^{-1} x_b + K_x^T S_y^{-1} y_m) \]  

(9)

In this form it is clear that the solution is a weighted average of the measurements, \( y_m \), and the a priori state \( x_0 \). The solution can be written in a different form to express it as a deviation from the a priori state:

\[ x' - x_b = S_x K_x^T (K_x S_x K_x^T + S_y)^{-1} (y_m - K_x x_b) \]  

(10)

However, it is the first version, which differentiated with respect to \( y_m \) mostly clearly gives the sought inversion operator:

\[ D_y = (S_x^{-1} + K_x^T S_y^{-1} K_y)^{-1} K_x^T S_y^{-1} \]  

(11)

Finally we should note that the error analysis presented in the previous section and the expression for \( D_y \) given here are correct and appropriate in the vicinity of the solution \( x' \), i.e. they are linearised expressions for the system and the implication is that \( K_x = K_x(x') \). With a value of \( x \) that is far from the solution, \( K_x \neq K_x(x') \) and although the value of \( D_y \) is still the correct expression for the behaviour of the inversion model, the expressions for retrieval errors are not correct. In general starting from an arbitrary \( x_0 \) (‘first guess’) far from the solution, an iterative approach is required to continually update \( x \) until the solution is \( x' \) reached. This is the subject of section §3.5.

### 3.3 Defining statistical constraints

The statistical constraints on the solution \( x' \) are the error covariance matrices \( S_x \) and \( S_y \), i.e. the quality of the measurements and a priori values of the state. The error covariance matrix \( S_b \) defines the contribution of the model parameter error to the retrieval error and does not affect the behaviour of the retrieval (but see section §3.3.3 on inclusion of model parameter equivalent measurement errors).

#### 3.3.1 a priori \( S_x \)

For \( S_x \) we take the individual state elements separately. Firstly a general comment on errors for what are bounded quantities. In the case that there is no a priori information on a value the error should be set effectively to \( \infty \). In the case of a bounded quantity, e.g. cloud fraction which must lie between 0 and 1, it may be tempting to suggest that the error on the a priori value (e.g. 0.5) should be of order 0.5 since its expected value is always within 0.5 of the a priori. However, this will ultimately bias results to the value 0.5 and away from the true bounds. Since the probability distribution function is flat within the bounded region and zero elsewhere the best approximation as a gaussian distribution is for the error to be \( \infty \). See section §3.5.2 for a discussion of the behaviour of an iterative scheme at boundaries.
a) \( \mathbf{x}(0) = \tau - \text{cloud optical depth} \). Generally there will be no significant \textit{a priori} and \( \mathbf{S}_\mathbf{x}(0,0) = \infty \). In the case of MSG and rapidly repeating measurements over the same area it is possible that a previous retrieval can supply useful information and \( \mathbf{S}_\mathbf{x}(0,0) \) will be finite. The value in this case should be of order of the expected error in the previous retrieval plus an increment to allow for genuine change in the optical depth with time. Some care has to be taken to prevent \( \mathbf{S}_\mathbf{x}(0,0) \) rapidly decreasing and effectively locking the optical depth to a single value regardless of the measurements.

b) \( \mathbf{x}(1) = \rho - \text{cloud drop size} \). Similar comments apply to those above. There is no real \textit{a priori} but time sequence sequential estimation may prove very useful.

c) \( \mathbf{x}(2) = \rho_c - \text{cloud pressure} \). In the case of a pure independent pixel retrieval, there is again no real \textit{a priori} unless sequential estimation is employed. With cloud pressure however, there definite possibilities arise for deriving regional values from ensemble characteristics, using spatial coherence and thresholding techniques. The value of an \textit{a priori} value of \( \rho_c \) from this sort of source should be assessed carefully and, as a general rule, the error estimate should be on the high side. In this study we perform retrievals with \( \mathbf{S}_\mathbf{x}(2,2) = (50 \text{ mb})^2 \) to simulate the effect of good \textit{a priori} values of \( \rho_c \).

d) \( \mathbf{x}(3) = f - \text{cloud fraction} \). The quality of the \textit{a priori} value of \( f \) is highly dependent on the situation. During daytime ocean measurements away from sunglint, the HRV channel with 1 km resolution may be capable of defining \( f \) within the larger channel footprint to quite high accuracy. In the study we have assumed a value of \( \mathbf{S}_\mathbf{x}(3,3) = (0.1)^2 \) for this sort of case. Over land during the day, the single wavelength HRV channel will give much less reliable estimates of \( f \) and \( \mathbf{S}_\mathbf{x}(3,3) \) should be increased accordingly. We have used \( \mathbf{S}_\mathbf{x}(3,3) = (0.3)^2 \) to simulate these cases. At night, without the benefit of the HRV channel there is no real \textit{a priori} information and \( \mathbf{S}_\mathbf{x}(3,3) = \infty \).

There may be a case for using previously measured values as an \textit{a priori} values as in the case of the previous state elements. However, it would have to be carefully treated since clouds definitely move and the 15 minutes between observations will require a significant increment to be added to the previous retrieval error. It would also be dependent on the actual retrieved fraction and the ensemble characteristics of the previously retrieved scene. For example, if the previous retrieved \( f \) were 1.0 amongst a field of values all around 1.0, then some confidence could be attached to an \textit{a priori} of 1.0 for the latest retrieval. With \( f<1 \) and inhomogeneous cloud fields the error attached to the \textit{a priori} would have to increase rapidly. Again, we stress that, if there is doubt, it is better to overestimate \textit{a priori} errors to permit the latest measurements to dominate the state estimation.

e) \( \mathbf{x}(4) = T_s - \text{Surface skin temperature} \). This, being the only non-cloud state parameter is also the only parameter with significant \textit{a priori} information. The value is supplied through NWP and the basic value should be set to the reasonably well characterised NWP errors. Thus in this study we use \( \mathbf{S}_\mathbf{x}(4,4) = (1.0)^2 \) for ocean scenes and \( \mathbf{S}_\mathbf{x}(4,4) = (3.0)^2 \) for land scenes where the rapid diurnal changes can make the NWP values poor. Especially over land, the sequential estimation of \( T_s \) may be very useful, a previously observed cloud-free area can potentially supply a good \( T_s \) estimate; again, the error treatment should be cautious. Similarly, the ensemble analysis methods could provide good information on local surface temperatures (although what they actually produce is a local ‘clear’ radiance which would need to be adjusted for atmospheric attenuation for \( T_s \)).
Correlations between errors in each parameter are harder to specify. These determine the off-diagonal elements of \( S_x \). In the case of straightforward independent pixel retrievals with no sequential estimation or ensemble techniques it is hard to suggest reasons why errors in the \textit{a priori} state values should be correlated and \( S_x \) should be diagonal. In the case of sequential estimation, \textit{a priori} derived from the previous retrieval, the value \( S_x = S_M + S_N + S_S + S_+ \) can be used where \( S_+ \) is the increment to allow for change in the time interval. Such a value would naturally include the appropriate correlations. Finally, in the case of ensemble derived values the case for correlations would have to be considered on the basis of the technique used. It is likely that errors in values of \( p_c \) and \( T_s \) so derived would be uncorrelated.

3.3.2 Model parameters - \( S_b \)

The model parameters \( b = [T(z),H(z),R_s,\epsilon] \) are derived from disparate sources and so are treated separately here.

\( T(z),H(z) \) are obtained from ECMWF NWP analysis fields and the errors associated are reasonably well characterised through comparisons of 6 hour forecasts with the radiosonde network. The error covariance currently in use for studies within ECMWF was obtained (A.P. McNally, pers comm.) and is shown in figure 1 as a surface plot to give an idea of correlations between levels. The near part of the covariance (levels 1-40) are the temperature errors 1000–0.1 mb and the far part (levels 41-55) are humidity errors 1000–300 mb. The zero correlations between temperature and humidity are almost certainly unrealistic, but are set this way because of difficulties with their estimation. Figure 2 shows the standard deviations by level (i.e. the square root of the diagonal elements). It is likely that this covariance, derived from global data, will overestimate humidity errors at high (dry) latitudes and underestimate at low (wet) latitudes. Similarly it will probably underestimate errors in regions far from conventional data sources since the comparisons it is based on are of necessity biased to data-rich regions.

![Figure 1. ECMWF temperature and humidity error covariance matrix](image)

\( S_b \) for \( R_s \) has been set in this study reasonably, but somewhat arbitrarily, since the source of climatological information and its likely error therefore has not been identified. Nevertheless, it should be sufficiently accurate to indicate the likely effect of surface reflection. We
set values as \( S_b(i,i) = (R(i,i) \times e_{rs})^2 \) where \( e_{rs} \) is the fractional error in the surface reflectance. Off-diagonal elements are set assuming a correlation of 0.4 between channels. \( e_{rs} \) is specified according to the experiment in progress, but a value of 0.1 is used by default in actual data retrievals.

\( S_b \) for \( \varepsilon \) is again a difficult quantity to assign accurate values in the absence of information regarding to the climatological source that will be used. Certainly for moderate \((<50^\circ)\) view zenith angles over ocean (and in the absence of high whitecap cover), the emissivity can be specified with high accuracy (probably \(<0.1\% \) absolute value). The real interest in the effects of emissivity are over land surfaces where knowledge is far less advanced. We have obtained a crude but perhaps realistic account of the uncertainty in emissivity from a recent conference paper (Recovering surface temperature and emissivity from thermal infrared multispectral data, Schmugge, Coll and Hook; Physical measurements and signatures in remote sensing, ed Guyot & Phulpin 1997, Balkema Rotterdam). The paper analysed Thermal Infrared Multispectral Scanner data over the Sahel and surrounding regions and we extract the following precis. Over vegetated soil the average emissivity was around 0.97 with very little spectral variation over the 8 - 12.5 \( \mu \)m range; plots in the paper suggested a variation in time of order 0.01-0.02. For bare soils the 11 - 12.5 \( \mu \)m emissivities were still high and with similar variations but emissivities in the 8 \( \mu \)m region were around 0.77 and with a variation of order 0.03-0.05. From this we adopt the following two values of \( S_b \) for \( \varepsilon \): a ‘vegetated land’ version where we assume a 1 \% error in emissivity in all channels, and a ‘bare soil’ version where we assume a 4\% error in the 3.7 and 8.7 \( \mu \)m channels and 2\% at 11 and 12 \( \mu \)m. The vegetated land version can be seen as a ‘best case’ and the bare soils as a worst case scenario.

![Figure 2. ECMWF temperature and humidity error profiles](image)

\[ \text{3.3.3 measurement - } S_y \]

The measurement error covariance can be considered to consist of basic instrumental radiometric noise plus any errors arising from the radiative transfer model.

The basic instrumental noise is specified by MSG documentation in terms of noise equivalent delta radiances (NEdR) for the reflectance channels (0.6 through 1.6 \( \mu \)m) and NEdT_B for the thermal channels. The NEdT_B for the thermal channels can be directly used in \( S_y \) but the reflectance channel NEdR are converted to equivalent \% reflection \( S_y(i,i) = (100 \times \text{NEdR}_i/F_{io})^2 \) for the ith channel.
We have considered forward model noise as a result of both inadequacies in the plane-parallel cloud model and as a result of errors in the co-registration of the channels. In both cases there is a case for setting noise levels appropriate to the scene type, information on which must come from ensemble algorithm information. Errors from assuming plane-parallel clouds are almost certainly correlated between channels but lacking good information on this (see WP 2.1, 2.2) we assume they are uncorrelated. Co-registration errors are likely to be uncorrelated.

Finally we consider here the addition of what we may call ‘equivalent model parameter measurement noise’ or EQMPN for brevity. The rationale here is to map errors in the model parameters, \( \mathbf{b} \), into measurement space and thus to adjust the weight the measurements receive in the inversion operator \( \mathbf{D}_y \). The model parameter errors \( \mathbf{S}_b \) map into measurement errors as,

\[
\mathbf{S}_{yb} = \mathbf{K}_b \mathbf{S}_b \mathbf{K}_b^T
\]

(12)

and can be directly added to \( \mathbf{S}_y \) to include the EQMPN.

An example is appropriate. Vegetated land has say 20% \( R_s \) (surface reflectance) in the 0.8 \( \mu \)m channel and 5% in the 0.6 \( \mu \)m and an uncertainty of 15% of \( R_s \) in both. With thin cloud or partial cloud cover the radiative transfer model response to \( R_s \) will be similar, i.e. \( \mathbf{K}_b = \partial \mathbf{y} / \partial \mathbf{R}_s \) will be roughly the same for each channel. However, the mapped EQMPN error will be significantly higher for the 0.8 \( \mu \)m channel because of its higher \( R_s \) value. If the EQPMN error is included in \( \mathbf{S}_y \) and thus into \( \mathbf{D}_y \) the effect will be to downweight the 0.8 \( \mu \)m channel relative to the 0.6 \( \mu \)m – a desirable feature. A blunter approach (see e.g. MODIS algorithm desc.) is to remove the 0.8 \( \mu \)m channel over land and use just the 0.6 \( \mu \)m. However, with thicker cloud, full cover, there may be no need to remove the 0.8 \( \mu \)m channel and the potential advantage of the EQMPN approach is that it is more naturally flexible: the weights are adjusted appropriately to the situation. Similar automatic channel weighting can be expected for errors due to the other elements of \( \mathbf{b} \). Section §3.4 includes many examples of \( \mathbf{S}_{yb} \).

It should be noted that if the EQMPN is included in \( \mathbf{S}_y \) then the expression for the total retrieval error becomes \( \mathbf{S}_M + \mathbf{S}_N \), i.e. the \( \mathbf{S}_S \) is omitted since effects of \( \mathbf{S}_b \) are now implicit in \( \mathbf{S}_M \).

This automatic weighting of channels because of expected errors from \( \mathbf{b} \) can also be achieved by including \( \mathbf{b} \) in \( \mathbf{x} \), i.e. extending the state vector to include the full set of significant variables. However, this approach implies estimation of around 60 variables from a maximum of 7 measurements and a consequent heavy reliance on a priori constraints - accurate specification of \( \mathbf{x}_b \) and \( \mathbf{S}_x \) - and a much larger inversion problem. Although perhaps theoretically expected to give the same ultimate results, we feel the reduced state vector and EQPMN error method to be a sensible and probably more practical and robust methodology.

3.4 Simulated error analysis

In this section we apply the results of section §3.1 to study the theoretical errors in the measurement of cloud parameters under various conditions. We restrict the analysis to the standard errors defined by the square root diagonal elements of \( \mathbf{S}_M \), \( \mathbf{S}_N \) and \( \mathbf{S}_S \) on the grounds
that it is these errors which inform most about the system retrieval skill. The correlations defined by the off-diagonal elements may be informative and of interest but they are not considered further here. In addition we show the equivalent model parameter noise, EQMPN, since it highlights where $S_S$ originates and allows us to see what level of noise is imposed by inaccurate model parameters. EQMPN is shown separately for the profile $(T(z), H(z))$ and surface reflectance $(R_s)$ parts of $b$.

There are of course many combinations of conditions to consider, variations in all five state parameters, surface types, viewing and solar geometry, atmospheres etc; and we cannot hope to treat them all. The studied scenarios are intended to cover the major categories and provide information from which to determine the important aspects of the retrieval and against which to interpret results obtained from real data.

Each principal simulation has a table summarising the actual state, the measurements used, the geometry etc and indicates the figure number where the results are presented. Often a small change will be made (e.g.) remove a channel; in which case the table or figure may be omitted for brevity, the text will explain the change and the effect on the retrieval.

A key to the table entries is required as some are not self-explanatory:

- $a priori$ - $S_x$ refers to the accuracy to which the $a priori$ state variable is known and a $\infty$ indicates there is no practical constraint.
- A ✓ in the Meas’ column indicates the channel was included in the simulation, $LWT Trop$ shows that the LOWTRAN tropical atmosphere was used, $ECMWF$ that the ECMWF profile error covariance was assumed, $Ocean$ that a surface reflectance vector of $[0.01, 0.01, 0.01, 0.01]$ or $Land$ that a vector $[0.05, 0.25, 0.15, 0.01]$ was used for $R_s$.
- A ✗ in the Co-reg and Homog boxes indicates the measurement noise level assumed according to the discussion in WP 2.1, 2.1 on co-registration and homogeneity noise.

The following discussion will make use of the shorthand symbols previously defined for the various error terms etc. We do apologise for this, but without it the discussion would become very verbose.

### 3.4.1 Daytime, water cloud.

<table>
<thead>
<tr>
<th>A6</th>
<th>State - $x$</th>
<th>Meas’ - $y$</th>
<th>Model parameters - $b$</th>
<th>Geometry</th>
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<tr>
<td></td>
<td>Value</td>
<td>$a priori$ - $S_x$</td>
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<td>Value</td>
</tr>
<tr>
<td>$\tau$</td>
<td>4</td>
<td>$\infty$</td>
<td>0.8 µm</td>
<td>✓</td>
</tr>
<tr>
<td>$r_e$</td>
<td>8 µm</td>
<td>$\infty$</td>
<td>1.6 µm</td>
<td>✓</td>
</tr>
<tr>
<td>$p_e$</td>
<td>500 mb</td>
<td>$\infty$</td>
<td>3.7 µm</td>
<td>✓</td>
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<tr>
<td>$f$</td>
<td>variable</td>
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<td>8.7 µm</td>
<td>✓</td>
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<tr>
<td>$T_s$</td>
<td>299.7</td>
<td>1 K</td>
<td>11 µm</td>
<td>✓</td>
</tr>
</tbody>
</table>

*Phase: water* 12 µm ✓
As indicated, figure A6 shows the simulated retrieval errors for this situation. Before describing its characteristics we should clarify the contents of this and the following figures.

The five larger plots are the retrieval errors for each state element. There may be less than five plots in later simulations since if a parameter is ‘removed’ from the state vector it is not retrieved. Errors in $\tau$ are most sensibly given as a percentage: $100 \times \delta \tau / \tau$. All other errors are given in straightforward units; $\mu$m, mb, (no units), K.

All the error terms discussed above are shown as functions of the state parameter that is variable; in this case the fraction, $f$. Both the measurement, $S_M$, and null space, $S_N$, errors are shown as is the total of these (note that they are properly added in a mean square sense; $S_T = [S_N^2 + S_M^2]^{1/2}$). Thus the solid line shows the total conventional retrieval error with the dotted and single dashed lines showing the measurement and null space contributions respectively. The distinction is worth making: if the null space error is close to the total then it is unlikely that any improvement in measurement noise characteristics can improve the result. On the contrary, a total with a high measurement contribution should be improved with less noisy measurements. The remaining two lines show the error contributions of the model parameters. That due to errors in the temperature and humidity profiles (the ‘atmosphere’), $S_b(T/H(z))$, is shown by the long dash, single dotted line. That due to errors in surface reflectance, $S_b(R_s)$, are shown by the long dash, triple dotted line. Finally, for the state parameters where there is significant *a priori*, the dotted line with + symbols shows the error assumed. Because these are simulated results, the total retrieval error cannot be greater than the *a priori*. However, there is no such restriction on the model parameter error contribution.

The two small plots to the bottom right show the EQMPN values for interest. For reasons of space they are not annotated, but the reflectance channels (0.6, 0.8 and 1.6 $\mu$m) are shown as dotted lines, the 3.7 $\mu$m as a dot-dash and the thermal channels (8.7, 11 and 12 $\mu$m) are shown dashed. (Generally, given the land surface reflectance used, the 0.8 $\mu$m has the highest EQMPN($R_s$) value; and the 12 $\mu$m channel the largest EQMPN($T/H(z)$) value.

Returning to the interpretation of figure A6. The most obvious feature is the strong dependence of retrieval errors on the cloud fraction for $\tau$, $R_s$ and $p_c$; errors reducing as the fraction approaches unity. As expected, retrieval errors for these parameters become very large as the fraction tends to zero. Both $S_N$ and $S_M$ contribute but with $S_M$ the smaller, particularly in the $R_s$ case. $S_b(T/H(z))$ is appreciable for $\tau$ and, particularly, $p_c$ when there is not high cloud cover. $S_b(R_s)$ is not significant for any of the parameters because of the low reflectance ocean surface in this simulation. This also explains the lack of significant EQMPN($R_s$) in the reflectance channels.

The retrieval errors for $f$ and $T_s$ are dominated by the assumed *a priori* (i.e. good estimates of fraction from the HRV channel and low NWP errors over the ocean) and little extra information is gained from the measurements. The $T_s$ error, as would be expected, approaches the *a priori* error for complete cloud cover. EQMPN($T/H(z)$) for the thermal channels is reasonably high, up to 3 K depending on channel and for cloud-free atmosphere. Since the NWP temperature errors are of order 1 K throughout the atmosphere, the high values can be attributed mostly to the NWP humidity. Note that EQMPN($T/H(z)$) for 8.7, 11 and 12 $\mu$m approaches 1 K as the fraction reaches unity, it then being almost totally a response to the 1 K NWP temperature error. The 3.7 $\mu$m value is lower presumably because the ($\tau = 4$) cloud is reasonably transmissive at this wavelength.
Changing *only* the surface type to *Land*, we get the results shown in *figure A7*. This is a very interesting result if a little unrealistic because of the continued assumption that $R_s$ is known to 1% and accuracy. It is interesting because, compared to A6 we see that the basic retrieval errors have reduced for all parameters except $T_s$ (which does marginally improve). It would need a detailed investigation of error correlations to understand certainly why a significant surface reflectance aids the retrieval, however, we can hypothesise the following to make it seem not unreasonable. In the ocean case the background against which the cloud is observed is uniform (spectrally) in the reflectance and thermal channel sets. It is likely then that the state parameters $p_c$ and $\tau$ can trade off against each other in the thermal channels without rapidly increasing the overall cost. Similarly, the parameters $f$ and $\tau$ can trade off against each other in the reflectance channels. With the strong spectral variation of land reflectance (5% at 0.6 µm and 25% at 0.8 µm) the second trade-off causes a more rapid increase in cost and hence the improved definition of the state. By imposing the land surface reflectance we have decoupled the 0.6 and 0.8 µm channels, which over the ocean are essentially redundant, and effectively gained a extra measurement. This hypothesis could perhaps be tested using a ‘desert’ reflectance where the surface reflectance is high but roughly spectrally invariant. We might expect the additional skill to disappear in this case.

We also note from A7 the increase in $S_b(T/H(z))$ and $S_b(R_s)$ compared to A6. This almost certainly arises because the improved ability of the system leads to larger elements in $D_\gamma$, and, in the case of the $\tau$ and $p_c$ retrieval, $S_b(T/H(z))$ becomes the dominant error. Notice also that $EQMPN(R_s)$ in the reflectance channels is now finite, albeit small, as is $EQMPN(T/H(z))$ which is larger (~1 %).

A7 was an unrealistic scenario in that a 1% error in $R_s$ is very optimistic. With a more appropriate value of 10% (see e.g. MSG MPEF Doc.) we get the result in *figure A8*. $S_b(R_s)$ errors now dominate all the state parameters and practically invalidate the overall retrieval except for the near total cloud cover. However, we should remember that this is a fairly highly reflecting surface and a relatively optically thin cloud (4); the situation will improve as these conditions improve. As we have discussed previously (section §3.3.3) there are two strategies which can be adopted to improve this situation (apart from the obvious one of ensuring the most accurately possible $R_s$ values). Firstly the blunt method of removing the channel which undoubtedly is responsible for most of the error, the 0.8 µm. Secondly, our recommended strategy which is to include the $EQMPN(R_s)$ noise in $S_\gamma$, thus weighting the channels appropriately to their noise levels. In *figure A9* this has been done and the strategy can be seen to be very effective. The normal retrieval errors $S_M+S_N$ have risen somewhat because of the decreased information available, but the overwhelming $S_b(R_s)$ errors are reduced to being almost insignificant. In this case, the blunt approach of removing the 0.8 µm channel has almost the same effect (not shown) and might appear an equally valid strategy. However, to reiterate, the method of including EQMPN noise will deal appropriately with all situations; with thicker cloud or lower land reflectance the 0.8 µm channel will start to contribute effectively and to have removed it simply because the scene is a land one will be to lose information. The only caveat to this argument is that the estimation of EQMPN noise does depend on estimation of $S_b$ which may be poorly defined. In any case the safe option is to assume a high $S_b$ (poor model parameters) if there is doubt, in which case the channel weight (0.8 µm in this example) will be low rather than high.

Similar arguments of course apply to the inclusion of $EQMPN(T/H(z))$ noise in $S_\gamma$, although
for brevity we do not show results here. In this case the effect is probably less dramatic
since the thermal channels are less different in their response to the atmosphere than the re­
fectance channels to $R_s$. There should however, be an increased reliance on the 3.7 µm
channel if EQMPN($T/H(z)$) is included.

We now briefly examine the system with different subsets of the measurement set available.
We return to the ocean surface example but with only 0.6, 0.8 and 1.6 µm channels avail­
able. As a reminder:

<table>
<thead>
<tr>
<th>$\text{A10}$</th>
<th>State - $x$</th>
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<th>Model parameters - $b$</th>
<th>Geometry</th>
</tr>
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<tr>
<td>Value</td>
<td>$a \text{ priori}$ - $S_x$</td>
<td>0.6 µm</td>
<td>✓</td>
<td>Value</td>
</tr>
<tr>
<td>$\tau$</td>
<td>4</td>
<td>✓</td>
<td>0.8 µm</td>
<td>✓</td>
</tr>
<tr>
<td>$r_c$</td>
<td>8 µm</td>
<td>✓</td>
<td>1.6 µm</td>
<td>✓</td>
</tr>
<tr>
<td>$p_c$</td>
<td>500 mb</td>
<td>✓</td>
<td>3.7 µm</td>
<td>✓</td>
</tr>
<tr>
<td>$f$</td>
<td>variable</td>
<td>10%</td>
<td>8.7 µm</td>
<td>✓</td>
</tr>
<tr>
<td>$T_s$</td>
<td>299.7 K</td>
<td>✓</td>
<td>11 µm</td>
<td>✓</td>
</tr>
<tr>
<td>Phase: water</td>
<td>12 µm</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this case results (not shown) indicate only skill of retrieval with $\tau$; $R_s$ has large errors
($\sim$ 15 µm) and the other parameters are not suprisingly at or around their $a \text{ priori}$ levels. The $R_s$ result is suprising since $f$ is still constrained by a 10% $a \text{ priori}$ and the atmospheric ef­
fects on the included channels is not large. We suggest that this is a somewhat pessimistic
prediction resulting from an underconstrained system with infinite $a \text{ priori}$ errors on several
parameters, particularly $p_c$. ‘Infinite’ $a \text{ priori}$ are used so as to obtain flat probabilities
within the acceptable range of the parameter and therefore not to bias results towards to middle of the range. In this case, since we expect no real measurement information on $p_c$ it is ‘safe’ to assume an $a \text{ priori}$ on $p_c$ of at worst 500 mb. If we do this we get retrieval errors
given in figure A10. $\tau$ and $R_s$ are estimated but clearly there is no information on $p_c$, $f$ or $T_s$.
If we further contrain the $a \text{ priori}$ on $p_c$ to 50 mb we see from figure A11 a much reduced
error on $R_s$. In A11 $p_c$ has effectively been removed as degree of freedom. This is con­
firmed by figure A12 where the state vector is the reduced [$\tau, R_s, f, T_s$] showing retrieval
errors in $\tau, R_s$ that are almost identical to A11. These results suggest that in the case of re­
duced channel information, the $a \text{ priori}$ errors assumed should be carefully considered. It is
not clear whether a practical inversion scheme that had ‘infinite’ $a \text{ priori}$ on $p_c$ would ‘chase’ $p_c$ at the expense of $R_s$, but given the possibility it would be safer to apply non-
infinite $a \text{ priori}$ on the relevant variables or remove them from the state vector.

We now examine the relative contributions in this case of the 1.6 and 3.7 µm channels. The
results in Figure A13 are with the 3.7 µm channel omitted and can be compared to figure A7
where the full channel set is used. A significant increase in $R_s$ error is apparant, both in $S_M + S_N$ and in the $S_b(T/H(z))$ component, although interestingly a large $S_b(T/H(z))$ effect in
A7 for low cloud amounts disappears in A13. Other parameters are only slightly affected if
at all. Figure A14 shows the effect of removing just the 1.6 µm channel and again is to be
compared with A7 and A13. This time, there is little noticable degradation in $R_s$ accuracy; it
appears from this that the 3.7 µm channel is contributing mostly to the $R_s$ estimation.
4.4.2 of WP 2.1 provides an explanation as it shows the sensitivity to drop size is retained at much lower optical depths than the 1.6 µm channel. The \( \tau = 4 \) in this case is quite a low value. For thicker clouds over the ocean we may expect more weight to be given to the 1.6 µm channel.

The effect of co-registration and homogeneity noise is now examined. Using the example above, now with the full channel set and assuming both types of added noise for the worst case (cumulus) we get retrieval characteristics shown by figure A15. Again, we can compare to A7 which is with only instrumental noise assumed. There are two effects. Firstly, \( S_M + S_N \) errors in all the unconstrained parameters rise significantly as the information content is reduced. However, the second effect is a significant reduction in \( S_b(T/H(z)) \) errors; by increasing measurement noise the retrieval demands a less stringent fit to the measurements and therefore there is less amplification of errors in the atmospheric profile. This perhaps illustrate a general point which is well known in inverse sounding problems; noise amplification by retrieval ‘coefficients’ which are derived assuming too low a measurement error suggest it is best to overestimate this error.

An important consideration is the availability of a significant *a priori* for fractional cover, \( f \). We have assumed up to now that the MSG HRV channel will provide daytime estimates of \( f \) in the larger pixel to around 0.1 accuracy. Figure A16 shows expected retrieval errors for the ocean surface if the *a priori* \( f \) error is set infinite, i.e. no estimate available. A16 can be compared to A6. There is a significant increase in errors, but essentially the full measurement system is capable of full state retrieval without an *a priori* \( f \). In the land case, the robustness against lack of *a priori* \( f \) is even greater (not shown) which is consistent with the comments regarding comparison of A6 and A7 above.

We show two results to illustrate the effect of the atmosphere on the expected retrieval accuracy. Figure A17 can be compared to A7 with the single difference that the LOWTRAN midlatitude profile has been used. Little difference is apparent in the \( S_M + S_N \) errors but some significant reduction can been seen as expected in the \( S_b(T/H(z)) \).

Figure A18 shows the error behaviour for an optically thick cloud (\( \tau = 16 \)) at increasing pressure and with cloud fraction 1. Other parameters are as in the table. All parameters are estimated (except \( T_s \)) with good accuracy with a slight increase in error as the cloud approaches the surface. The \( S_b(T/H(z)) \) contribution becomes significant as the pressure becomes greater than around 600 mb as the atmospheric transmission becomes significant. The \( E Q M P N(T/H(z)) \) behave as might be expected except for the 3.7 µm channel which appears to be unaffected by temperature errors for high cloud in the way the other IR channels are. The 8.7, 11 and 12 µm channel errors follow almost exactly the NWP temperature profile errors when the atmospheric transmission is high, i.e. when the cloud is higher than 700 mb. The 3.7 µm error behaves much more like the reflectance channel errors, i.e. as a pure transmission effect and therein lies the explanation – the cloud is highly reflecting (\( R_c = 8 \) µm) and with a low solar angle the 3.7 µm signal is dominated by reflection and not emission.

3.4.2 Night-time, water cloud.

The basic night time water cloud situation studied here is defined in the table below. Clearly
only the four thermally emitting channels are available and the good \textit{a priori} \( f \) from the
HRV channel is absent. This leads to an underconstrained inversion problem and simulations
with the full state vector and all \textit{a priori} except \( T_s \) unconstrained lead to high errors in
all parameters (not shown). It is necessary then, to add \textit{a priori} information, remove degrees
of freedom or add measurements in order to make the problem soluble (see WP 1.4 section
on infrared product estimation for more discussion on this subject).

<table>
<thead>
<tr>
<th>Model parameters - ( b )</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
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<td>Value ( a \ priori ) - ( S_x )</td>
<td>( \theta_o )</td>
</tr>
<tr>
<td>( \tau )</td>
<td>4</td>
</tr>
<tr>
<td>( r_e )</td>
<td>8 ( \mu m )</td>
</tr>
<tr>
<td>( p_c )</td>
<td>700 mb</td>
</tr>
<tr>
<td>( f )</td>
<td>( variable )</td>
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<td>( T_s )</td>
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<tr>
<td>( Phase: ) water</td>
<td></td>
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<tr>
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</table>

Additional useful information may be available from the MSG CLA products where cluster
analysis and threshold tests have been applied. The CLA definition acknowledges the fundamental
lack of information by grouping, i.e. not distinguishing the \textit{semi-transparant} and \textit{fractional}
cover results for a pixel. However, cluster techniques should be able to produce
estimates of \( p_c \) and \textit{figure A19} shows expected errors with an \textit{a priori} \( p_c \) with error 200 mb.
There is now some retrieval skill in the system but it is debatable whether it is useful. Errors
in \( \tau \) are around the 100% level, in \( f \) from 0.1 to 1.0 and in \( r_e \) around 4 \( \mu m \); there is no improvement in the \textit{a priori} \( p_c \). Assuming an improved \textit{a priori} \( p_c \) with error 100 mb gives the
result in \textit{figure A20} showing that with this accuracy there is possibly useful information in the
retrieval. Notice that in both A19 and A20 the errors are mostly dominated by \( S_x \): it is
not a question of measurement noise or errors in the NWP profiles, there is a simple lack of
information.

A second class of additional information from cluster analysis and thresholding is the identi-
fication of fully cloudy (\( f=1 \)) pixels. Returning to an \textit{a priori} \( p_c \) with error 400 mb but now
with \( f \) removed from the state vector, we get results in \textit{figure A21}. This shows (and only the
results at \( f=1 \) are strictly relevant) that good retrieval errors can be expected for fully cloudy
pixels \textit{if} they really can be identified as such. The result with \( f \) reinstated with an \textit{a priori}
error of 0.1 is shown in \textit{figure A22}. This simulates the situation where \( f=1 \) case are identi-
fied but allows for a 10% error in the \( f=1 \) classification. Again the results are only really
meaningful at the \( f=1 \) level. Compared to A21 retrieval errors are significantly higher showing
the sensitivity to the \textit{a priori}, but the results are nevertheless encouraging.

We digress briefly here to show \textit{figure A23} which compares to A22 except that the 3.7 \( \mu m \)
measurement is removed. It demonstrates the crucial role that this channel plays in constrain-
ing the retrieval in this situation; there is no any retrieval skill without the 3.7 \( \mu m \) measure-
ment since there is no longer any significant response to \( R_e \). Removing just the 8.7 \( \mu m \) channel
has little effect (not shown) and reinstating the 3.7 \( \mu m \) measurement without the 8.7 \( \mu m \)
gives errors almost identical to the full four channel system (also not shown).
The second option for obtaining a constrained nighttime system (again, see WP 1.4) is to reduce the degrees of freedom; i.e. to remove state variables. We have already done this in the case of removal of $f$ above where it was assumed an accurate fully cloudy pixel identification was possible. But generally, one can recast the inversion into one which is soluble. By, for example, removing $R_e$ from the state we obtain results in figure A24 showing an apparently reasonably accurate retrieval of $\tau$, $p_c$ and $f$ (although as usual poor errors arise for low $f$). This is strictly ‘cheating’ in that we are hiding the effect of $R_e$; essentially these are the results that would be obtained if all water clouds had $R_e = 8 \mu m$, the effect of the real $R_e$ is not shown. However, it is potentially a valid approach in the sense that this caveat is recognised and the retrieved parameters can be defined as ‘effective’, that is they are state parameters at a reference cloud with $R_e = 8 \mu m$. It is not certain that such parameters are useful quantities. In WP 1.4 we discussed the possibilities of reduced state vectors and, in the infrared remote sensing community, it is common to use ‘effective’ parameters. A particular example is cloud ‘effective emissivity’ which is essentially $f \varepsilon(\tau, R_e)$ and is used where $\varepsilon(\tau, R_e)$ can be assumed to be the same function for all measurements (e.g. within the 13 $\mu$m sounding waveband). Here we have measurements widely spread (3.7 – 12 $\mu$m) and this assumption cannot be made. By omitting the 3.7 $\mu$m measurement the approximation would probably be valid between 8.7 and 12 $\mu$m and it is possible that a reasonable estimation of $f \varepsilon(\tau, R_e)$ and $p_c$ could be made. The similarity of the 8.7, 11 and 12 $\mu$m atmospheric responses however would probably preclude any good accuracy. Such retrievals are usually made with closely spaced ‘sounding’ channels where the atmospheric response varies strongly and the emissivity function is channel independent. Unfortunately, we are not in a position to simulate such a retrieval at the present time.

The above discussion does lead to the third possibility to improve the situation which is to add measurements. The obvious choice from the SEVIRI channel set is the 13.4 $\mu$m measurement which is a CO$_2$ absorption band. It will have significantly different absorption characteristics to the 8.7, 11 and 12 and therefore its use may provide enough extra information to permit a night-time retrieval of the full state. Failing that it should at least significantly aid a $[f \varepsilon(\tau, R_e), p_c]$. The remaining SEVIRI channels (6.2, 7.3 and 9.7 $\mu$m), although predominantly sensing variable gases (H$_2$O and O$_3$); may provide useful additional constraints on pressure and fraction when used in conjunction with the other channels. They would have to be treated with care since the uncertainty in H$_2$O and O$_3$ concentrations would be a large effect; here the use of $EQMPN(T/H(z))$ noise addition would be very beneficial.

Again, we are unfortunately not in a position to simulate retrievals made with these extra channels. In view of the underconstrained nature of the nighttime situation determined by the above experiments this is unfortunate, and was not anticipated at the study outset. We recommend, however, that the usefulness of the extra channels, particularly the 13.4 $\mu$m, should be investigated.
### 3.4.3 Daytime, ice cloud.

<table>
<thead>
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<th>A25</th>
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<th>Meas’ - y</th>
<th>Model parameters - b</th>
<th>Geometry</th>
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<td>Value</td>
</tr>
<tr>
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<td>∞</td>
<td>0.8 ( \mu \text{m} )</td>
<td>✓</td>
</tr>
<tr>
<td>D/( r_e )</td>
<td>60 ( \mu \text{m} )</td>
<td>∞</td>
<td>1.6 ( \mu \text{m} )</td>
<td>✓</td>
</tr>
<tr>
<td>( P_c )</td>
<td>300 mb</td>
<td>∞</td>
<td>3.7 ( \mu \text{m} )</td>
<td>✓</td>
</tr>
<tr>
<td>( f )</td>
<td>variable</td>
<td>10%</td>
<td>8.7 ( \mu \text{m} )</td>
<td>✓</td>
</tr>
<tr>
<td>( T_s )</td>
<td>299.7</td>
<td>1 K</td>
<td>11 ( \mu \text{m} )</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Phase: ice**

The basic ice cloud state for simulations is shown in the above table and we can compare retrieval error simulations, figure A26, with figure A6 which is the analogous water cloud case. Note that the value of \( r_e \) is 60 \( \mu \text{m} \) and that this is the ‘proxy’ value used to maintain a regular grid spacing in the LUTs (see WP2.1). The characteristics noted for figure A6 generally apply in the ice cloud case with the noted exception of higher errors in \( R_e \) (note the scale difference between plots). \( S_b(T/H(z)) \) values are lower in the ice cloud case, presumably because there is less absorbing atmosphere above the cloud. Figure A27 is the situation with a land surface reflectance underlying the cloud and compares to A8 in the water case. The effect on retrieval accuracy through \( S_b(R_s) \) is comparable, and just as significant as in the water case since this contribution arises through cloud-surface interactions.

It is interesting to examine the relative merits of the three ‘particle sizing’ channels, 1.6, 3.7 and 8.7 \( \mu \text{m} \). Figures A27, 28 and 29 show the retrieval errors for measurement sets [0.6, 0.8, 1.6, 11, 12 \( \mu \text{m} \], [0.6, 0.8, 3.7, 11, 12 \( \mu \text{m} \] and [0.6, 0.8, 8.7, 11, 12 \( \mu \text{m} \] respectively. In comparison to figure A26, figure A27 shows that with only the 1.6 \( \mu \text{m} \) channel, there are no real changes to the basic retrieval error, \( S_N + S_M \), but there are higher contributions from \( S_b(R_s) \) and also from \( S_b(T/H(z)) \) perhaps due to the loss of the atmospherically ‘clean’ 3.7 \( \mu \text{m} \) channel. In figure A28, with only the 3.7 \( \mu \text{m} \) channel, there are only small differences in comparison to figure A26. There is a small loss of skill in estimating \( T_s \), and the \( R_e \) estimation errors, \( S_N + S_M \), are more dominated by null space errors. In figure A29, with only the 8.7 \( \mu \text{m} \) channel, the basic estimation of all parameters except \( T_s \) remains good with only slight increases in \( S_N + S_M \) compared to the full channel set. However, there are significantly higher contributions from \( S_b(T/H(z)) \) in all except (strangely) the \( R_e \) parameter. In summary, it appears that, in these circumstances, the full state can be retrieved with reasonable accuracy, albeit with increasing susceptibility to model parameter errors, when ‘particle sizing’ channels are removed from the system. In fact, simulations (not shown) suggest that even the measurement set [0.6, 0.8, 11, 12 \( \mu \text{m} \] is reasonably capable although [0.6, 0.8, 12 \( \mu \text{m} \] definitely is not. These conclusions may change under different circumstances, e.g. optically thicker cloud where the 1.6 \( \mu \text{m} \) and 3.7 \( \mu \text{m} \) measurements might become more important for \( R_e \) estimation, or in the case of higher assumed noise levels etc.

Figure A30 shows results for the basic land reflectance case in the absence of a good \( a \text{ priori} f \) estimate from the HRV channel. As in the water cloud case, the measurements are shown to be capable of retrieving the full state although there is a clear increase (compared to figure A26) in the contribution of \( S_b(R_s) \) to most parameters.
Optically thin ice clouds, particularly cirrus, occur frequently and figure A31 shows retrieval errors as a function of $\tau$, with $f = 1$ and an ocean surface. The errors are consistently low because of the $f=1$ conditions (see previous figures) and the slightly erratic nature of the results occurs because conditions ($\tau$) are stepping across LUT indices (suggesting a more sophisticated LUT interpolation might be useful). The results are intuitively reasonable: errors decrease with $\tau$ for the cloud parameters (except $\tau$ itself since this is expressed as a fractional error) and increase for the non-cloud parameter, $T_s$. Similarly, contributions $S_b(T/H(z))$ and $S_b(R_s)$, and the EQMPN($T/H(z)$), decrease as the surface and absorbing atmosphere and effectively blocked by the increasingly thick cloud.

Figure A32 shows the effect of increasing particle size, again for the ocean surface, $\tau$=3 and $f=1$. Again, the results are reasonable if even less dramatic than figure A31. The IR absorption increases with particle size decreasing the sensitivity to the atmosphere and allowing more accurate retrievals of $f$ and $p_c$. Less information is available for $T_s$ and a lower sensitivity to $R_e$ means higher errors for the larger particles.

### 3.4.4 Nighttime, ice cloud.

<table>
<thead>
<tr>
<th>A33</th>
<th>State - $x$</th>
<th>Meas’ - $y$</th>
<th>Model parameters - $b$</th>
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</tr>
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<tbody>
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<tr>
<td>$\tau$</td>
<td>3</td>
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<td>0.8 $\mu$m</td>
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</tr>
<tr>
<td>$D/R_e$</td>
<td>60 $\mu$m</td>
<td>$\infty$</td>
<td>1.6 $\mu$m</td>
<td>✓</td>
</tr>
<tr>
<td>$p_c$</td>
<td>300 mb</td>
<td>$\infty$</td>
<td>3.7 $\mu$m</td>
<td>✓</td>
</tr>
<tr>
<td>$f$</td>
<td>variable</td>
<td>10%</td>
<td>8.7 $\mu$m</td>
<td>✓</td>
</tr>
<tr>
<td>$T_s$</td>
<td>299.7</td>
<td>1 K</td>
<td>11 $\mu$m</td>
<td>✓</td>
</tr>
<tr>
<td>Phase: ice</td>
<td></td>
<td></td>
<td>12 $\mu$m</td>
<td>✓</td>
</tr>
</tbody>
</table>

The situation for nighttime ice clouds is similar to that found for nighttime water - there is not enough information to constrain a retrieval of the full state parameter set. As with the water case, we can add information in the form of an $a$ priori $p_c$ estimate. In this case we find an estimate with error as low as 100 mb still does not produce a viable retrieval. Constraint by removing $f$ from the state vector does give a retrieval with useful errors, see figure A33. As before, the errors are only relevant for $f=1$ and do rely on some method of identifying such pixels. Assuming this can be done, we examine the relative utility of the particle sizing channels through simulations in figures A34 and A35 where the channel sets are [3.7, 11, 12 $\mu$m] and [8.7, 11, 12 $\mu$m] respectively. Figure A34 shows retrieval errors that are very similar to those with all (nighttime) channels (figure A33) whilst figure A35 implies a measurement system lacking sufficient information.

Further discussion on the nighttime retrieval of ice cloud is redundant in the sense that it follows that in section 3.4.2 for water cloud. The measurement system is severely limited at night and will rely on either a reformulation of the problem in terms of fewer ‘effective’ variables, a significant input of $a$ priori information or extra measurement information from SEVIRI channels not used in this study.
3.4.5 The effect of surface emissivity

Errors in the assumed values of surface emissivity for the infra-red channels are evaluated in precisely the same way as other model parameter errors (§3.1 (6)). That is, the expected errors in the emissivity are mapped onto the solution error by the product of the gradient of the measurements with respect to the emissivity and the inversion operator. Figures A6 through A33 could therefore have included an extra diagnostic on each error plot; in addition to \( S_b:R_s \) and \( S_b:T/H(z) \) we could have included \( S_b:E_s \). This would have made the plots unduly complicated for what is probably and usually a small error contribution. However, this conclusion does depend on the assumed error in the emissivity value. In §3.3.2 we discussed the value of the uncertainty in emissivity and, based on only a limited survey of the situation, derived ‘best’ and ‘worst’ case scenarios correspondingly to vegetated and bare soil type land cover.

Figure 3 shows \( \boldsymbol{K_b} \) for emissivity\(^1 \) (\( \partial y/\partial \varepsilon \), K/\%) as a function of optical depth with \( R_e = 8 \mu m \), \( p_c = 500 \text{ mb} \), \( f=1 \), view zenith 30° and a LOWTRAN tropical atmosphere. As expected, the sensitivity to emissivity is rapidly lost as the cloud transmission decreases. Of the channels, the 3.9 µm is the least sensitive (barely visible at the bottom of the plot) because of a large solar reflectance contribution and the sensitivities of the other channels correspond to their atmospheric transmissions. We may expect sensitivities to increase for lower cloud fraction and less humid atmospheres, and to decrease for higher view angles.

![Figure 3. \( \boldsymbol{K_b} \) for emissivity for IR channels. Conditions given in text.](image)

In figure 4 we present the results of the error contribution \( S_b:E_s \) for the daytime / ocean water cloud case described at the beginning of §3.4.1. The figure can be compared to figure A6 except that it includes emissivity effects as long dash lines marked with *; EQMPN(E\(_s\)) figures are conveniently shown in the same (lower right) plot as the EQMPN(R\(_s\)) as the effects are mutually exclusive between the reflectance and thermal channels. The assumed

1 The IR RTM used in the study does not exactly account for surface emissivity (see WP2.2 §3.4) as the reflection (implied by \( \varepsilon \neq 1 \)) term uses the downwelling radiance \( a \) from a clear atmosphere rather than the cloudy one. Hence it predicts a larger effect of non-unit emissivity than is correct and consequently an over-estimate of the cloud parameter retrieval errors. Emissivity and reflection for the 3.7 µm channel are treated separately in this study but are, of course, closely linked.
emissivity error in this case corresponds to the ‘best’ case scenario. The effective noise on the IR channels in this case (i.e. the EQMPN(Es)) is quite low, of order 0.1-0.2 K, and apparently quite insignificant compared to the effects of profile errors (EQMPN(T/H(z))). The corresponding effect on the cloud retrievals are also low and insignificant compared to the other terms (except the Sb:Rs for this low ocean reflectance case).

Figure 5 shows the ‘worst’ case scenario results for the same cloud and viewing conditions. In this case EQMPN(Rs) values are around 0.5 K and, although this is significantly lower than the EQMPN(T/H(z)) values of around 2 K, the emissivity effect now gives rise to cloud parameter errors which are comparable to Sb:T/H(z) except in the case of p_c. The reason for this disproportionately strong effect probably lies in error correlations. The profile induced errors will be highly correlated (an error in humidity gives rise to roughly the same error in all channels) and as such are not as ‘damaging’ to the retrieval as errors of the same size but which are uncorrelated. We have assumed uncorrelated errors in the emissivity.

Given the results of this ‘worst’ case scenario, we consider the emissivity effect to be reasonably small compared to other sources of error in the system. That is not to say it should be ignored. Clearly the best available surface emissivity estimates should be used in the retrieval and the uncertainty in these values assessed. The uncertainty will depend strongly on the geographic (i.e. the surface type) location and can be conveniently incorporated into the retrieval by including EQMPN(Es) in the S_y as with the other model parameter error sources.

Figure 4. Retrieval error characterisation for water cloud case including the effects of ‘best’ case scenario emissivity uncertainties marked as ‘*’.
3.4.5 The effect of surface reflectance

We have presented some results on the effect of surface reflection on the retrieval accuracy in sections §3.4.1 and §3.4.3. There, it was found that, over ‘vegetated’ land ($R_s = \{0.05, 0.25, 0.15, 0.05\}$) $S_b(R_s)$ errors from a 10% uncertainty in $R_s$ would dominate retrieval errors with $\tau=4$ in all parameters even for complete cloud cover (see figure A8 for example). The situation could be much improved by using the EQMPN method to effectively down-weight the 0.8 µm channel.

Discussion following the final presentation led to a recommendation to examine further the effect of surface reflectance errors, particularly the behaviour with cloud optical depth and assumed reflectance error. To this end we present simulated errors for a range of optical depths (1 to 128) with a range of surface reflectance errors (2, 5 and 10% of absolute value as defined in §3.3.2). The cloud, atmosphere and viewing geometry are as given in the following table. Note that the results are for $f=1$ and therefore represent the lowest effects of $R_s$ uncertainty (figure A8 etc can be referred to for the effect at lower $f$ values). Figures A36, A37 and A38 show retrieval errors for 2, 5 and 10% surface reflectance error respectively. A36 shows that a 2% reflectance error does not lead to significant increased errors for any optical depth although $S_b(R_s)$ does become somewhat larger than $S_{SN+SM}$ for $\tau<10$ for some of the state parameters ($T_s$ being the principle exception). Figure A37 shows that a 5% error in $R_s$ does lead to significant errors (compared to $S_{SN+SM}$) for $\tau<15$ in all parameters, again with the exception of $T_s$. It might be considered that the retrieval errors caused are acceptably low (~15% in $\tau$, 1 µm in $R_s$, 50 mb in $p_c$, 0.15 in $f$); but they nevertheless dominate the basic retrieval error at these optical depths. The effect decreases very suddenly with increasing $\tau$, the threshold being, as mentioned, around $\tau = 15$; this continues to be the case shown in figure A38 where a 10% error in $R_s$ is used. $S_b(R_s)$ errors for $\tau<15$ are now very domi-
nant, which was the conclusion stated in §3.4.1 regarding the results in figure A8.

<table>
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</tr>
<tr>
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</tr>
<tr>
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<td>1.6 µm</td>
<td>✓</td>
</tr>
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<td></td>
</tr>
</tbody>
</table>

It is a little surprising that the effects so suddenly reduce around $\tau=15$ since, although IR transmissions fall quickly (see WP2.1 §2 figure 2.1), VIS transmissions are slower to decrease (hence the ability to retrieve $\tau$ for optically thick clouds); note the somewhat more smoothly decreasing equivalent measurement errors for $R_s$ on figure A38. These latter do show, however, that the noise effect of the $R_s$ error has significantly decreased by $\tau=15$.

We include two further figures as caveats to the above results. Firstly figure A39 shows the result of assuming homogeneity noise (equivalent to stratocumulus scene, see WP2.1 §7) and can be compared to figure A37; the 5% error in $R_s$ case. The general result is the same but the basic $S_N+S_M$ retrieval errors are higher (less information in the measurements) and the $S_b(R_s)$ are lower (smaller $D_y$ values and therefore less sensitivity). In this case it perhaps cannot be claimed that $S_b(R_s)$ are significant for any but the most optically thin cloud, $\tau<4$.

Finally we show figure A40 where the EQMPN($R_s$) noise has been added to $S_y$, again there is a 5% error in $R_s$ assumed. Basic $S_N+S_M$ retrieval errors are again slightly higher but the $S_b(R_s)$ contribution is now almost negligible.

In summary, 5% errors in $R_s$ for a typical land reflectance can give rise to significant errors in retrieved parameters in the fully cloudy case if only instrumental measurement noise is assumed. Including moderate (and more realistic) amounts of noise from additional source(s) (co-registration etc) is likely to de-sensitise the retrieval to the $R_s$ error and at the 5% level it becomes only significant for clouds $\tau<4$. Including EQMPN($R_s$) noise almost completely de-sensitises the retrieval to 5% errors in $R_s$.

3.4.7 The effect of calibration errors

Calibration errors may be considered to be effectively systematic measurement errors as far as the effect on the retrieval accuracy is concerned. We have already made some examination of the sensitivity to measurement errors (§3.4.1 figure A15 compared to A7 for example) where the effect of co-registration errors was tested. Here we compute the effect on the retrieval errors of systematic calibration errors of levels 2, 5 and 10% of signal (in reflectivity for the 0.6-1.6 µm channels, and in radiance for the 3.7-12 µm channels). The effect, as usual, is dependent on both the cloud/atmosphere/geometry prevailing and also on the assumed noise levels etc, so we are bound to restrict the analysis to a few cases.

A calibration error, $C_y$, in the measurements is mapped into a retrieval error, $S_e$, by the fol-
lowing relation:

$$S_e = D_y C_y$$

Note the similarity of this equation to the random error case (equation (5)), $$S_M = D_y S_y D_y^T$$. There, the errors are assumed mean zero with covariance $$S_y$$ and the retrieval error resulting similarly mean zero and with a finite covariance. Here, the measurement errors and resulting retrieval error have zero variance but finite mean. The two are otherwise comparable; similar size measurement error should give similar size retrieval errors.

A problem with estimating the effect is how to define the calibration error itself. Here we assume a simple fractional error, $$f_c$$, the same size and sign in all channels. Thus for the reflectance channels the calibration error is given by $$C_{y} = f_c \times y$$ where $$y$$ is as usual the measured reflectance. For the infrared channels the calibration error in brightness temperature (the form used in the study) is given by $$C_{y} = \frac{\partial T}{\partial B} (f_c \times B(y))$$ where $$B()$$ is the Planck function for the channel. We should stress that a different formulation of calibration errors will cause different retrieval errors; thus if we assume negative errors in the reflectance channels, positive in the IR, we will obtain a different result to the all positive errors assumed here.

The results presented therefore only give a guide to the sensitivity and some compensating effects may occur. Two results are shown for ocean and land cases; calibration error in all channels and calibration error only in the reflectance channels.

Figure 6 shows the calibration error effect for the ocean water cloud case considered in §3.4.1 and figure A6; error present in all channels.

Figure 6. Effect of 2, 5 and 10% calibration errors (all channels) on the ocean water cloud case.

Note the sign of the effect can be negative. As in the random error results, the effects are generally largest for low fractional cover. Calibration errors of 10% lead to large retrieval errors in particle size, pressure. The skin temperature and fraction retrievals are mostly unaffected because of the a priori available (1.0 K and 0.1 respectively) for these parameters. It is surprising that the optical depth retrieval is also insensitive to even 10% errors, but the rea-
son may lie in compensating effects. A positive calibration error in the IR channels will lead to a low value of \( \tau \), whereas a positive calibration error in the reflectance channels will lead to a high value. Figure 6a shows the result when there is calibration error only in the reflectance channels.

![Graphs showing the effect of calibration error on optical depth, particle size, and pressure.](image)

**Figure 6a.** As figure 6 but calibration error only applied to reflectance channels.

Errors are only significant for optical depth and are surprisingly a weak function of fraction. The IR channels are clearly quite highly weighted in the retrieval of most of the parameters. Results from the equivalent land case (see also figure A8) are shown in figure 7 for calibration error in all channels.

![Graphs showing the effect of calibration error on optical depth, particle size, and pressure.](image)

**Figure 7.** Effect of 2, 5 and 10% calibration errors on the land water cloud case.
This time there are significant optical depth and fraction errors for high calibration error and low actual fraction. Skin temperature errors are also higher because of the poorer \textit{a priori} (3 K) over land. It is interesting that the particle size error has changed sign from the ocean case, but not necessarily surprising considering the combined effect of all the parameters on the measurements: the elements of $D_y$ compensate for all effects. Figure 7a is the result considering only reflectance channel calibration error.

![Figure 7a](image)

Figure 7a. As figure 7 but calibration error only applied to reflectance channels.

It shows a similar error structure to figure 7 but with somewhat lower values except in the drop size retrieval.

Figure 8 corresponds to a cloud, $p_c=800$ mb, $f=1$, over land with $\tau=1–128$, calibration error in all channels. Most of the errors decrease with increasing optical depth. Although the fractional calibration error means that the reflectance channel errors increase with $\tau$, the IR channel error will reduce. The retrieval error for $T_s$ drops rapidly to zero, partly as a result of this, but more because the there is no information on $T_s$ for high $\tau$ ($f=1$). The $\tau$ error is again remarkably insensitive to the calibration error and again it seems likely that this is a result of compensating effects. Figure 9 shows the result with a reduced measurement set (0.6, 0.87 and 1.6 $\mu$m only) and a reduced state vector ($\tau$, $R_e$ and $f$ only) and now we see much larger errors (in $\tau$ and $R_e$ at least) which persist at high optical depths. This lends support to the idea that the VIS and IR effects were compensating in the full measurement / full state cases. Even if this is the case, it should not be thought that system is insensitive to calibration errors since any compensation will be entirely dependent on the sizes and signs of the calibration errors themselves and the particular error structure used here could be misleading. A further caveat is that these error analyses are linear about the solution and assume the solution can be found (see §3.5). Calibration errors of 10% may well be large enough to both invalidate the linear approximation (in which case actual errors resulting may be over or under-estimated) and also prevent the adopted inversion method from finding the solution.
Optical depth

Particle size m

Pressure mb

Optical depth

Particle size m

Pressure mb

Figure 8. Effect of 2, 5 and 10% calibration errors with variable $\tau$ over land, $R_c=8 \mu m$, $p_e=800$.

Figure 9. As figure 8 but with a reduced measurement set (0.6, 0.87 and 16 $\mu m$) and reduced state.
3.5 Data inversion: minimising J

Up to this point we have assumed the maximum probability solution can be found and have studied the errors implied by the characteristics of $J$ at the solution. This section addresses the problem of finding the solution. This is an area where many techniques and methods can be employed and where tuning of the adopted scheme can turn out to be as important as the scheme itself. Essentially any method of finding the minimum is acceptable in sense, except that it must be reasonably robust and reasonably fast. The particular characteristics of this problem are that:

a) first and second derivatives of $J$ (w.r.t $x$) are available and continuous,
b) multiple minima are unlikely,
c) $J$ is likely to be approximately quadratic in the region of the solution, far from quadratic elsewhere.

Characteristic a) implies descent algorithms that make use of the local gradient are possible and these are generally faster than methods that do not. b) implies that extravagant domain searches to avoid minor minima are probably not required. c) is a result of the reasonably strongly non-linear nature of the forward (radiative transfer) problem. It means that quick convergence from a poor starting position is unlikely.

We do not claim to be experts in this area and can only recommend methods on the basis of our experience and the general consensus of the remote sensing community. This is therefore only a suggested approach and the one implemented in our study.

The cost function to be minimised is a reduced form of (8) since there is no explicit dependence on $b$:

$$J = (y(x) - y_m)S_y^{-1}(y(x) - y_m)^T + (x-x_b)S_x^{-1}(x-x_b)^T$$

From (13) we get the first and second derivatives of $J$ with respect to $x$:

$$J' = K_x^T S_y^{-1}(y(x) - y_m) + S_x^{-1}(x-x_b)$$

$$J'' = K_x^T S_y^{-1}K_x + S_x^{-1}$$

(15) is a commonly used approximation in that $K_x$ is assumed to be independent of $x$, i.e the radiative transfer is linear in $x$. This is only strictly true near the solution (in the region where $J$ is quadratic) but (see section §3.5.1) since $J''$ is only employed near the solution the approximation is acceptable.

3.5.1 Steepest descent – Newton – Marquardt

Characteristic a) is certainly true, b) is largely hypothesis based on experience but could be tested by simulation experiments or a brute force calculation of $J$ overall state phase space; c) is almost certainly true since even a two-channel / two variable state version demonstrates string non-linearities. The lack of multiple minima means that expensive domain searching methods are not required and the available gradient information suggests use of Newton and steepest descent methods.
To find the minimum we start at some ‘first guess’ state $x_0$ (which in the absence of other information is usually set equal to the a priori value $x_n$, but could equally be set to the previous retrieved state, see section §3.7) and proceed to make steps in $x$ based on some algorithmic theory. Assuming the value of $J$ decreases at each step we are heading for the minimum. The iteration can be stopped when either the step size becomes so small as to be negligible or the value of $J$ is acceptably small (see section §3.5.6); these conditions should coincide.

The steepest descent (SD) algorithm is intuitively the simplest. A vector $-J'$ defines the ‘downward’ direction – the local steepest gradient. A move $\delta x = -J'$ must be at least vaguely in the direction of the minimum although it may be too far or barely far enough. The step is therefore usually scaled, $\delta x = -\alpha J'$ where $\alpha$ is variable. If $J$ is found to be decreasing $\alpha$ can be increased to move faster; if $J$ increases then $\alpha$ is reduced until $J$ decreases. $J$ must eventually decrease with this method otherwise something is wrong with the calculation of $\partial J/\partial x$. The problem with SD is that it can be very slow to converge, especially near the solution where the gradient necessarily becomes small. It is however, very robust.

Newtonian descent on the other hand is very fast near the solution because it will find it in one iteration if $J$ is quadratic. Newton’s method finds the root of an equation and is therefore applied here in the form to find the root of $J' = 0$. The Newton step is therefore defined as $\delta x = -J'/J''$. The problem with Newtonian descent is that, away from the solution, $J$ can be very non-quadratic; the $J''$ can easily be the ‘wrong’ sign and the step is taken away from the solution. No amount of scaling can cure this problem.

The combined use of SD and Newtonian methods constitutes the method of Marquardt. The Marquardt method (MM) essentially tests before each step is taken to check whether the resulting $J$ will decrease. If so the step is taken and an adjustment is made to make the next step ‘more Newtonian’. If an increase in $J$ is detected then the step is not taken and an adjustment is made towards more steepest descent. In this way, MM adopts SD away from the solution and makes use of Newton near the solution. Formally the increment in MM is:

$$\delta x = -(J'' + \alpha I)^{-1}J'$$ (16)

Where $I$ is the unit vector ($nx\times nx$) and $\alpha$ is the control variable described. When $\alpha$ is large (compared to the ‘average’ size $J''$) the step tends to SD; when small the step approximates Newtonian. The comparison with $J''$ ($\alpha$ is set to the average of the diagonals) is made at the start of the algorithm to obtain a reasonable value. Typically the factor by which $\alpha$ changes each iteration is 10. This appears to work in practice and the large value ensures that the method can quickly switch between descent methods.

3.5.2 Physical boundaries

The state space in which the solution is to be found is bounded ‘physically’. $\tau$ is bounded at least on the low end at zero, although the logarithmic scaling of $\tau$ means that this is strictly avoided. $p_c$ is certainly bounded at the high end by the surface pressure and practically at the low end around 100 – 200 mb. $f$ is strictly bounded at 0 and 1. Only $T_s$ is not practically bounded in this system. $R_c$ is a special case in that the lower bound in the ice phase implies water phase and the converse is true in the water phase. Section §3.5.3 discusses the treatment of phase.
The question arises of how to deal with an iteration step $\delta \mathbf{x}$ which attempts to cross a boundary. It is not possible if $\mathbf{J}$ would rise as a result since the step would not be taken. However, it certainly is possible that $\mathbf{J}$ may continue to fall even with a parameter out of bounds (e.g. with $p_c=200$ mb and $f$ too low, a lower cost is found for a $p_c$ less than 200 mb). At least two strategies are possible. In the first strategy the step is not taken and the control parameter adjust towards SD and a more robust step. The second strategy allows the step but limits the offending parameter to the boundary value it is attempting to cross.

We find the second method more likely to result in successful convergence of the scheme. The reason possibly lies in the nature of the boundary for the cloud fraction. Unlike the other parameters, the boundary values are highly likely for $f$; overcast and clear conditions are quite possible. The other parameters limits are more physically unreasonable. Therefore the cloud fraction frequently and correctly attempts to be near its limiting value. The first strategy then fails because the step size is constantly reduced as $f$ attempts to become $>1$; eventually the step size in all parameters is so small that the convergence criteria declare a successful retrieval. The second method allows the step size to remain reasonable. Whilst the parameter remains on the boundary the optimisation problem simply becomes one in one fewer variables.

3.5.3 Phase change

Phase change in the scheme is achieved through switching when the $R_e$ parameter attempts to cross a boundary. If the phase is water and the step implies $R_e$ crossing the upper boundary ($>23 \mu m$) then phase is switched to ice and the inversion process restarted. Similarly if the phase is ice and $R_e$ becomes too small ($<40 \mu m$ proxy size) then the phase is switched to water. The other boundary crossings (water and $R_e < 1 \mu m$, ice and $R_e > 100 \mu m$ proxy size) are treated in the way described in section §3.5.2. This phase identification is likely to be driven largely by the 1.6 $\mu m$ channel during daytime because the large change in absorption with phase means that reflectance from all reasonable sized ice particles are lower than all reflectances from from reasonable sized water particles. Whether the scheme will work at night will be tested. If there is a lack of discrimination then other information can be brought bear; cloud temperatures implied by $p_c$ could be used to force phase change although the appropriate temperatures might be difficult to guage.

3.5.4 Parameter scaling

The sensitivity of the radiative transfer to the state parameters varies strongly. $p_c$ only weakly affects affects VIS reflectances compared to the large effect of $f$. As an example, for a unit (1 mb) change in $p_c$, $\delta R$ might be 0.01%; for unit (=1) change in $f$ $\delta R$ might be as large as 60%. Thus $K_x$ will contain elements of widely varying orders of magnitude. This is not theoretically a problem, it simply reflects the true physical situation. However, such disparate values can lead to problems of ill-conditioning of the matrices that are inverted. Consequently, some scaling of parameters is advisable to remove the largest effects. It is difficult to always ensure similar size elements since $K_x$ is strongly dependent on the cloud conditions. Nevertheless, we find scaling the fraction term by 100 (i.e. to make it a % cover) to help convergence of the iteration to some extent. Note that a linear scaling like this does not change the location or the ‘shape’ of the minimum. From (14), (15) and (16) one can see that the step size will not change in a pure Newtonian iteration but will in a SD iteration.
Non-linear scaling strictly does not change the location of the minimum either, but it may do so subtly since it will probably imply different *a priori* errors at different parameter values if the problem is not very carefully considered. It can change the ‘shape’ of the minimum though and thus may aid convergence. In the scheme demonstrated in this study we use logarithmic scaling on τ since the basic measurement response of (certainly the VIS reflectances) is more linear with τ expressed in this way.

3.5.5 Convergence

An iterative search for the solution must be stopped at some suitable point and this is usually done when the calculated step is less than a pre-determined criterion. This is more or less an arbitrary decision, but clearly the convergence criteria should not be so lax as to stop the iteration before all the information has been extracted, and not so tight as to prevent convergence. The criteria adopted for this study are:

\[ \delta x = [0.05, 0.3, 30.0, 0.02, 0.25] \] for water phase and
\[ \delta x = [0.05, 2.5, 30.0, 0.02, 0.25] \] for ice phase;

the only difference being for particle size where the much larger range of sizes for ice requires a larger convergence criterion. The iteration must be stopped at some point even if convergence according to the above criteria is not being reached; thus an iteration limit is set. In this study we use a limit of 20 iterations although tuning of inversion parameters and improved first guess estimates should allow lower values to be used.

3.6 Quality control

This is a very important part of any retrieval scheme since if there is no effective way of checking the validity of the result, there is really no value in any of the results. Fortunately, the optimal estimation method provides diagnostics which should allow a reasonably strict quality control to be applied. There are three principle diagnostics directly available from the inversion method. The first, a check of the ‘goodness of fit’ of the solution to its constraints, should principally detect situations where the scene is not modelled by the radiative transfer – mixed layer cloud, large errors in surface reflectance etc. Secondly, situations that are modelled successfully but imply large errors due to the nature of the scene – low fractional cover, insufficient channels (e.g. nighttime) etc. Thirdly, and less usefully, the number of iterations taken to convergence can be an indicator of ‘difficult’ scenes.

3.6.1 Solution \( J - \chi^2 \)

The value of \( J \) at the solution indicates via a single number whether the solution is good to within the statistical accuracies assumed for the measurements and the *a priori*. If, at the solution, none of the measurements deviate from the calculated values (i.e. \( y(x) - y_m \)) by significantly more than their expected noise values (given by \( S_y \)) or, and no state variables deviates from their *a priori* values (i.e. \( x - x_b \)) by significantly more than the *a priori* error (given by \( S_x \)) then \( J \) will be of order \( (ny+nx) \). Because of the general lack of *a priori* and the bounded state variables there are actually less degrees of freedom than \( (ny+nx) \). A bounded fraction \( (0-1) \) cannot contribute anywhere near its expected \( S_x \) value \((\sim \infty)\) to \( J \). Therefore we can say that if there are nb state variables that are bounded but without significant *a pri-
ori then an acceptable solution will have $J$ of order $(ny+nx-nb)$. This is essentially a $\chi^2$ test on the solution.

In the present context, it is the measurement term which will mostly contribute to $J$ and indeed it is the final $y(x)-y_m$ that will most often indicate a problem with the solution. We actually keep account separately of $J_x$ and $J_y$ where $J = J_x + J_y$. In examination of retrieval results there are various levels of checks depending on the level of post-mortem required: firstly check $J$ for a general retrieval OK or NOT. Then check $J_x$ and $J_y$ for measurement or $a$ priori misfit and finally either $y(x)-y_m$ or $x-x_b$ for the offending measurement or state variable.

Because the value of $J$ depends on the somewhat tricky estimation of values for $S_y$ and $S_x$ it is likely that $J$ will not initially be of order $(ny+nx-nb)$ as expected. Values too low imply an overestimation of (probably) measurement noise; values too large imply either underestimation of noise levels or convergence criteria that are too loose.

### 3.6.2 Solution expected error

There are situations where there is theoretically little information (section §3.4) and consequently a high expected error in at least some of the retrieved state parameters. As we stated in the introduction, these situations can produce a low value of $J$ because they conform properly to the model. The theoretical solution error is given by the sum $S_N + S_M + S_S$, from equations (4), (5) and (6), and the $\sqrt{\text{diagonal values are used to give the parameter expected error. Unlike the previous method quality control from this source applies to each parameter individually. A theoretically poor estimate of one parameter does not necessarily imply a poor estimate of another.}$

### 3.6.3 Convergence rate

A further, but less powerful diagnostic is the convergence speed of the retrieval, i.e. the number of iterations. A poor retrieval is unlikely to converge quickly, and conversely a good retrieval should not take many iterations to converge. However, these are not hard and fast rules, but the number of iterations does often coincide with scenes that are expected to be unsuitable.

### 3.7 Use of $a$ priori and ‘first guess’ information

It is important to discuss the nature and application of $a$ priori and ‘first guess’ information because of their subtle but important differences and because the MSG SEVIRI system should benefit significantly from both.

Firstly we stress that $a$ priori information acts as a constraint on the retrieval – it is weighted through $S_x$. It should not therefore originate directly from (i.e. should be independent of) the measurement data that is being used in the inversion. For example, to extract a cloud pressure value from a particular SEVIRI 11 µm measurement, place it in $x_b$ and attribute some error $S_x(2,2)$ to it, and perform the simultaneous retrieval (including cloud pressure and the 11 µm channel) for the same measurement is clearly wrong. The 11 µm information is being used twice. What is acceptable, and often useful, is to use the estimate, without an error at-
tached, as a ‘first guess’ value - part of the starting state \( x_0 \). This is because the final retrieved state \( x' \) is independent of \( x_0 \) but not of \( x_b \).

‘First guess’ information helps to speed convergence and may prevent erroneous solutions from difficult situations where a poor start can give an incorrect result. However, it is not strictly independent information and should not be used as such.

The reason that these distinctions are important is that there are many opportunities to supply both types of information in the MSG system and we can broadly identify the following:

1) **Pixel-based information from the ‘current’ retrieval pixel.** That is to say, information derived from one or more SEVIRI channel measurements at the observation currently being used for the retrieval (as in the example above). In this case the nature of the information is clear – it is not independent of the measurements to be used and is ‘first guess’ information – \( x_0 \). Other examples (which we use in data retrievals WP4) are phase from the 11 \( \mu \)m temperature and \( \tau \) from the 0.8 \( \mu \)m reflectance.

2) **Pixel-based information from a previous retrieval pixel.** ‘Previous’ could mean either at the same location but at an earlier time, or at the same time but a nearby (adjacent) location. In either case, the information more independent of the current measurements and may be used as \( x_b \). The caveat is required because the ‘previous’ retrieval almost certainly will have relied on information (e.g NWP) that has errors strongly correlated to similar information being used in the current pixel. For example, the \( p_c \) value obtained previously or adjacent will have an error due to NWP profile errors that will exist almost unchanged in the current location. However, the measurements are strictly independent and it is probably ‘safe’ to use the value as \( a \ priori \) assuming suitable (safe) errors are attributed to it.

3) **Ensemble-based information from current or previously.** By which we mean parameters derived from strictly ensemble characteristics of the data. There are many examples of this which are described in detail in the MSG MPEF document. Cloud type information could be used to set noise levels or decide on phase. Cloud top temperature (and hence pressure) may be derived from local low standard deviation areas, surface temperatures similarly. This type of information, although originating from the same SEVIRI measurement, set is derived in a substantially different way and can be regarded as being independent of the current pixel measurement set; it can therefore be used as \( a \ priori \).

Many of the parameters that are available from the Scenes Analysis products of the MSG MPEF fall into the category 3) above. Many of the pixel based cloud parameters from the Cloud Analysis fall into category 1). In general: if there is any doubt that the information is independent it should be restricted to use as first guess information; if it is used as \( a \ priori \) then it should be attributed generous errors.
1. Introduction

The results of WP4 are demonstrations of the suggested retrieval methodology using various existing remotely sensed data sources. We concentrate on the use of ATSR-2 data because it has available most of the channels included in the study and at a resolution (~1 km) that allows simulation of both the SEVIRI image data and the HRV channel that will be used for initial cloud fraction estimation during the day. Additionally there is a large archive of ATSR-2 data available from which to select scenes and areas of diverse interest. MODIS AS data is used to study the particular contribution of the 8.7 µm channel since this is not available from ATSR-2. MODIS AS data is certainly of high enough resolution (~metres) to simulate SEVIRI measurements but the scene selection is relatively limited.

Section §2 describes the implementation of the retrieval methodology somewhat theoretically described in WP2.5. Retrieval results and analysis are are presented from selected scenes of ATSR-2 data in Section §3 and from selected MODIS scenes in section §4.
2. Implementation details

2.1 Overview

Figure 2.1 shows the overall processing chain adopted for these experimental retrieval studies.

![Processing chain for experimental retrieval studies](image)

**Notes:**

1 Cloud flagging is an attempt to roughly simulate the initial flagging that might be achieved
using the SEVIRI HRV channel during the day. No flagging is possible during the night. The method used was developed for ATSR-2 data and is relatively crude. However, it does make use of two channels: the 0.67 and 0.87 µm rather than the single HRV wavelength that will be available to SEVIRI processing. The method works by analysing the histogram of the quantity \((R_{0.87} - R_{0.67})/R_{0.87}\) which is similar to some definitions of NDVI. Figure 2.2 shows the histogram over an area (especially chosen) containing cloud filled ATSR-2 pixels, clear pixels over land and sea and a partially filled pixels.

![Figure 2.2. \((R_{0.87} - R_{0.67})/R_{0.87}\) used for cloud flagging over a mixed scene](image)

The strong peak at just below zero contain the opaque cloud filled pixels. The smaller peaks at −2 and +0.5 contain clear pixels over ocean and land respectively. The negative value over ocean is because of rayleigh scattering in the 0.67 µm channel and the otherwise very low background reflectance. The positive land values are due to the higher 0.87 µm reflectance over vegetated land. Pixels that lie in none of the peaks contain either optically thin cloud or are partially covered. The decision as to whether a pixel is cloudy or not relies on determination of reasonable thresholds away from the central peak.

Although this technique relies on two channels, there is no external input in the form of land reflectance data or other data sources and it has not been developed beyond that shown. (It will not work over low vegetation terrain for example.) The scenes analysis used for MSG will use time series data and will be a far more sophisticated algorithm. Therefore it is likely that the method used here is a fair approximation of the reliability of the MSG cloud detection product.

2 NWP fields of temperature and humidity were obtained for the dates of the sample data from the ECMWF operational and re-analysis products stored on the British Atmospheric Data Centre at RAL. The products obtained are on a 2.5° grid and at every 6 hours. The spatial resolution is inadequate in the sense that land / sea boundaries are poorly resolved, but otherwise should be adequate. It would be straightforward to time-interpolate the fields to the data time, but this was not done. It is unlikely that a 3 hour discrepancy (the maximum possible) would cause significant errors to most variables, but the skin temperature is one important exception. Note that the NWP data is extracted before the retrieval loop. This is because the model resolution is poor compared to the for the small areas processed (~500 km for ATSR-2). Normally this step would be inside the data loop.

3 Equivalent SEVIRI measurements are extracted from the test data simply by averaging to the appropriate ground resolution. In the case of ATSR-2 data, resolutions of 8x8 and 10x10
Surface reflectance is set according according to whether the scene is land or sea. Sea reflectance is always considered to be 0.01. For land, two options were allowed; a default reflectance of [0.05, 0.25, 0.15, 0.01] for the [0.67, 0.87, 1.6 and 3.7 µm] channels or a specified reflectance vector obtained by manual analysis of the scene.

The background value of cloud fraction, f, was obtained by default (and therefore only during the day) from the cloud flag high resolution (~1 km) image. An option exists to constrain the a priori f to a specified value (normally 1.0). In the case of no flag available and no value specified, a value of 0.5 was used.

The a priori error covariance is set according to whether the scene is land or sea (the T_s part depends on this) and according to whether a cloud flag is available. Any value can also be set by a specified value. The defaults are; \( \tau - 1 \times 10^8 (\infty); R_e - 1 \times 10^8; p_c - 1 \times 10^8; f - 1 \times 10^8 \) if no a priori available, 0.1 if cloud flag used; T_s - 1 K over ocean, 3 K over land. All correlations are assumed to be zero.

The measurement error covariance includes firstly the NEdT/R values as given in the MSG documentation, although they would perhaps be more appropriately set to values determined by the test instruments. Switches allow for the inclusion of additional (and generally much larger) noise sources: any or all of co-registration, cloud homogeneity and EQMPN.

A priori \( (x_b) \) values for the state parameters are set by default to \([ \log_{10}(4.0), 8 \text{ µm (water)}/60 \text{ µm (ice)}, 500 \text{ mb}, T_s] \) where T_s is the NWP value. Note the different \( R_e \) a prioris depending on the phase; the a priori for \( R_e \) can also be changed during the iterative process. Values can also be set by specified values. First guess \( (x_o) \) values are set equal to the a priori, but see 9.

First guess values for \( \tau \) and \( p_c \) can be set (during the day) from crude estimates inferred from the a priori \( f \) and the measured values of the reflectance in the 0.87 µm channel, \( R_{87} \), and the radiance from the 11 µm channel, \( R_{11} \), respectively. An approximate expression for the overcast 0.87 µm reflectance with an overhead sun (effectively an albedo), \( A_{87} \), is,

\[
A_{87} = \frac{R_{87} - R_s(1 - f)}{f \cos(\theta_o)}
\]

and this is related to a log10 optical depth using the following simple relation:

\[
i = \text{nint}(R_{87} / 10)
\]

\[
x_o(0) = \text{LT}(i)
\]

where

\[
\text{LT} = [0.1, 0.3, 0.65, 0.8, 1.0, 1.15, 1.3, 1.5, 1.7, 2.0, 2.4]
\]

The values of LT are obtained from the LUTs described in WP 2.1.

Similarly, for the pressure, an approximate expression for the overcast radiance at 11 µm, \( R_{11} \), is,

\[
R_{11} = \frac{R_{11} - R^f(1 - f)}{f}
\]

where \( R^f \) is the upwelling clear radiance (an estimate of which is available from the thermal radiative transfer model, see WP 2.2). \( R_{11} \) is then compared to \( B^{-1}(T(p),11\mu m) \), i.e. the Planck radiance of the temperature profile at 11 µm, to obtain an estimate of \( p_c \).
The Marquardt inversion scheme is detailed in the next section.

2.2 The Marquardt inversion scheme

Figure 2.3 shows the logic structure of the version of the Marquardt data inversion scheme used. The notation \( y(x) \) implies a radiative transfer calculation using the state vector \( x \). \( x_n \) refers to the current iterative state of \( x \); given a successful inversion after \( n=m \) iterations, \( x_m \) is the solution state.

[Figure 2.2 Marquardt inversion flow diagram]
Notes:

1 A phase change implies a switch to cloud properties from a different set of look-up tables.

2 The Marquardt starting and step parameters decide on the relative weight given to steepest descent (SD) and Newton’s method (see WP2.5 §3.5.1 for details). To initialise the start parameter the average values of the Hessian matrix, $J''(x_0)$, are calculated. This gives an estimate of the local cost function ‘curvature’ to which Newton’s method is sensitive. The step parameter is fixed at a single value (normally 10).

3 The prospective step is examined to check whether any of the fixed bounds would be passed. The action taken is to limit the offending parameter to the boundary value but to continue with the full step in all other parameters.

4 A prospective step that does not decrease the solution cost is not taken and the scheme adjusted towards more SD and less Newton by increasing the Marquardt parameter.

5 Setting the measurement error covariance, $S_y$, at every iteration is only required if it depends on the current state vector, i.e. if EQMPN noise is being included. If this is not the case, it can be set once only for each retrieval as it depends only on the scene reflectance / brightness temperature.

3 Retrievals from ATSR-2 data (WP4.1)

Several orbits of ATSR-2 data from July 22 to July 25 1996 were processed to level 1b. These dates were chosen because the instrument was operating in ‘high rate’ mode meaning that all of its measurements were transmitted at full bit-rate and pixel resolution. This gave an archive of 550 scenes (one scene = 512×512 pixels or therefore about 512×512 km), roughly half of which were night and half daytime. From these, a 10 scenes were selected to give a wide range of conditions and cloud types.

In the following sections we present results and analysis of the application of the retrieval algorithm described above to the selected scenes. Figures are presented in three ways for ease of use.

Annex A contains the ATSR-2 full image at 1 pixel resolution and presented in ‘true-colour’ for the daytime images, and greyscale (normally the 3.7 µm channel) for the nighttime images. The ‘true-colour’ representation (red - 1.6 µm, green - 0.87 µm, blue - 0.67 µm) allows easy identification of land and sea and strikingly, although qualitively, highlights ice and ice phase cloud as a cyan colour due to the low 1.6 µm reflectances. Also shown on the annex A figures are the location of the scene on the earth. A table gives the date, the solar and sensor geometry, the authors assessment of the scene contents, the channel availability and the case number referred to in the text. The box marked on the image shows the reduced area over which retrievals were performed. Annex A figures are referred to as A1 for case #1 etc

Annex B contains colour figures of retrievals and retrieval diagnostics for the different experiments described below. Further black and white and smaller figures are included in the text. Annex B figures are referred to as B4.1.1 etc. At the back of Annex B is a sheet of colour scales so that quantitative assessment of the colour contoured plots can be made if

1 The normal operational rate over land is ‘low rate’ because of conflicting demands of the ERS-2 SAR instrument. In this mode the 1.6 µm and 3.7 µm channels are toggled between day and night respectively and ‘along track’ data is either in a narrow swath (~250 pixels) or dithered every other line / pixel.
required. Some figures carry labelled contours in addition to the filled contours but generally these reduce clarity and are omitted.

3.1 Case #1: Daytime, marine stratocumulus

The first case was chosen because the cloud type is one which approximates well to the idealised plane-parallel model on which the radiative transfer and therefore the retrieval is based. We show results from this case reasonably comprehensively to demonstrate many aspects of the retrieval and its quality control. Space forbids us to treat the other cases in the same way and only points of particular interest are illustrated. Figure A1 shows a broad swath of cloud across the retrieval area with some large scale structure. At the bottom of the area the cloud deck has a reasonably well defined edge; towards the top it is more broken.

Figure B4.1.1 shows the full state vector retrieved from the area using a ‘SEVIRI’ averaging length of 8 pixels, the ‘across’ and ‘along’ track axis labels are SEVIRI pixels. The titles for each plot give the state element title and indicate whether it was ‘actively’ included in the retrieval or fixed at an a priori value. (In the daytime cases, all state variables are always active; in nighttime cases some are inactive.) We use a table for each retrieval to summarise the presence or otherwise of state variable, the a priori and the error assumed for it and additionally to indicate any measurement noise source assumed over and above the ‘instrument’ noise which is always included.

<table>
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<th>B4.1.1</th>
<th>$\tau$</th>
<th>$R_c$</th>
<th>$p_c$</th>
<th>$f$</th>
<th>$T_s$</th>
<th>$S_y$</th>
</tr>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>a priori value?</td>
<td>$\log_{10}(4)$</td>
<td>8/60 µm</td>
<td>500 mb</td>
<td>1km Flag</td>
<td>NWP</td>
<td>Coreg</td>
</tr>
<tr>
<td>a priori error</td>
<td>∞</td>
<td>∞</td>
<td>1000 mb</td>
<td>1.0</td>
<td>1 K</td>
<td>1</td>
</tr>
</tbody>
</table>

From B4.1.1 we see the fraction retrieval appears to be reasonably in agreement with the image in A1. The $\tau$ field is plausible and consistent with the image in the main cloud area but becomes highly variable towards the edges where unrealistically high values appear. The same is true for the $R_c$ field which shows values around 12 µm in the main cloud area but indicates a false change of phase at the edges and elsewhere. The $p_c$ differs in that it is consistently around 660 mb in the main cloud but relaxes back to the a priori of 500 mb elsewhere. Finally the $T_s$ field only sporadically moves from the a priori value since it is quite heavily constrained.

Figure B4.1.2 shows the fields of solution cost and the number of iterations taken in the retrieval. The cost is shown as that due to deviations from the measurements and that due to deviations from the a priori. Histograms of each are shown under the contour plots. The measurement cost, $J_m$, is generally low in the main cloud area and generally high elsewhere. There are sporadic retrievals with very high $J_m$ within the cloud but not many. The histogram of $J_m$ confirms that in the cloud area retrievals have converged with a final cost of around 1-2. It appears then, that in this case, the estimate of measurement error (instrument+coreg=1) is roughly consistent with the resulting measurement fit although values 0-1 are expected. Although the theory predicts that given correct error estimates the final cost should be of order 1 for a successful retrieval, this is affected to some degree by the convergence criteria. It is not therefore suprising that values are a little higher. A priori cost, $J_a$, is always low in the cloud area and occasionally high outside. Given the lack of a priori constraints in this case the low $J_a$ values are not suprising. The number of iterations taken does
not appear to correlate particularly with features in the image, high and low values appear in both consistently cloudy and clear areas. The histogram indicates a modal convergence rate of around 11 iterations. The scheme is stopped at 20 iterations and the peak there probably includes cases that are not retrievable.

The other major diagnostic of the quality control is the state expected error, $S_M + S_N$, and this is shown in figure B4.1.3 for the five state parameters. Histograms are shown in figure B4.1.4. As expected from the simulation studies, there is a strong dependency of the expected error in $\tau$, $R_e$ and $p_c$ on the retrieved fraction, with very large errors outside the main cloud field. Note that the expected error for $\tau$ and $R_e$ can get very large in this case because of the complete lack of a priori whereas the moderate constraint on $p_c$ means that the maximum expected error can be 500 mb. The expected error in $f$ is lowest in the low fraction and higher optical depth areas and that in $T_s$ only marginally deviates from the 1 K a priori in the clear areas; clearly seen in the histograms, figure B4.1.4.

Figure B4.1.5 shows the fields of $y_m - y(x)$; the residual differences in actual measurements and calculated values at the solution. The $J_m$ field shown in B4.1.2 is a weighted sum of the residuals but the individual channel fields can indicate why there is a high cost in a particular area. In this case there are not any obviously high residuals. Histograms (not shown) confirm that the mean fit in the reflectance channels is around 0.2% reflectance with a standard deviation of around 0.75%. The thermal channels have a mean residual around 0.2 K with standard deviations around 0.8 K. There is a suggestion that the moderate $J_m$ values outside the main cloud area result from a conflict between the 3.7 and the 12 µm channels; probably due to errors in the NWP profile. Within the cloud, the only area where there is any suggestion of poor fit to measurements is the small region around pixel [30,12] where the calculated 0.6 and 1.6 µm values are high and low compared to the measurements respectively.

The retrievals described above were obtained with a poor confidence attached to the a priori fraction estimate from the cloud flag. With a more realistic error estimate of 0.1 we get the results shown in figure B4.1.6.

<table>
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<td>✓</td>
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<tr>
<td>a priori value?</td>
<td>$\log_{10}(4)$</td>
<td>8/60 µm</td>
<td>500 mb</td>
<td>1 km Flag</td>
<td>NWP</td>
<td>Coreg</td>
</tr>
<tr>
<td>a priori error</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>1000 mb</td>
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</tbody>
</table>

All the gross features of the previous retrieval are present but there are clear differences in the fields. The fraction has been kept more nearly 1.0 in the main cloud area and this has resulted in a more uniform $p_c$ field. Both the $R_e$ and $\tau$ fields also appear qualitatively more consistent although it is of not clear that these fields should be uniform in the way $p_c$ should be for stratocumulus. This demonstrates the benefit of the a priori fraction estimate and the importance of using it with the appropriate error. Figure 3.1 shows a cross section at $y=16$ of the $f$, $p_c$ and $J_m$ values for the two experiments. The left hand plot is for the first experiment with $S_x(3) = 1.0$ (assumption of poor cloud flag) and shows clearly the fraction and pressure trading against each other - a lower fraction and lower pressure result in approximately the same thermal channel radiances. A similar trade-off is occurring between frac-
tion and optical depth to maintain similar reflectance values.

Although these compensations are occurring, the value of $J_m$ rises significantly where they occur – the solution is definitively poorer in a technical sense. It is possible that an improved descent algorithm could avoid such solutions. In any case, the addition of a suitable constraint in the form of $S_x(3) = 0.1$ (assumption of a good cloud flag) appears to largely remove the problem as shown in the right hand plot of figure 3.1. Both the compensating effects and the solution costs are lower.

These results are interesting in that they show the importance of *a priori* information and the way it is weighted. It is, of course, not necessarily easy to estimate the error in a piece of *a priori* information. How good is the fraction estimate from the cloud flag? A reasonable guess can be made but the retrieval scheme itself can lend supporting information. For example; a further experiment was run with the assumption that $S_x(3) = 0.01$, i.e. that the error in the *a priori* fraction was only 1%. This sounds implausibly small since, even with a perfect decision process over the cloudyness of the HRV pixels, there must be errors from HRV pixels that are themselves partly cloudy. Figure 3.2 compares the same cross section for the cases of $S_x(3) = 0.1$ (left) and $S_x(3) = 0.01$ (right). The fraction field for the highly constrained case is maintained at a uniform 1.0 and the pressure field is largely unchanged. There is a suggestion that the $J_m$ values in this case are becoming higher than those for $S_x(3) = 0.1$ and that the fraction is now overconstrained, although it is perhaps not convincing. However, the mean values of $J_m$ in the lower half of the retrieval area (where the fraction is < 1) are 7.08, 6.09 and 102.8 for the three cases $S_x(3) = 1.0, 0.1$ and 0.01 respectively lending support to the conjecture that the fraction is underconstrained in the first case and very much overconstrained in the third.

This has been only a preliminary look at this issue but it does demonstrate the general principle that the error assumed for information (and this applies to measurements as well as *a

\[1\] The error in the cloud flag estimated by counting contaminated pixels should actually depend on the cloud fraction. There are more ‘opportunities’ for error when the fraction is intermediate than when it is either 0 or 1.
priori) can be assessed by examining the effect of the assumed error on the solution cost.

We now turn to the implementation of quality control to the retrievals of B4.1.6. As discussed in WP 2.5 §3.6 there are two principal indicators; the overall solution cost \( J_m + J_a \) and the state expected error, \( S_M + S_N \). We may abbreviate quality control by the first as QC:J and by the second as QC:S. As a general point, QC:J is an indicator that the whole inversion is in error - a fit could not be found to the measurements and a priori with the given plane-parallel cloud model and supporting model parameters. QC:S is an indicator that, even with a good fit, the information content of the system does not allow for accurate measurement of a particular state parameter. Note the difference that QC:J applies to all state parameters and may be best used to remove a retrieval from further consideration; QC:S applies individually and perhaps is best used as a quality flag or confidence level attached to a retrieval. Both indicators are, however, best demonstrated by removing values from plots where the QC value exceeds a permitted value.

Figure B4.1.7 shows the results of B4.1.6 with QC:S applied at the level: \( S_{\text{max}} = [30\%, 3 \mu m, 100 \text{ mb}, 0.1 (f), 3.0] \). In this case, QC:S is very effective and removes all the areas outside the main cloud band in the case of \( \tau \), \( R_c \) and \( p_c \). The remaining fields contain no obvious errors. The fraction and \( T_s \) fields are unaffected in this case since the QC levels are at or above the a priori levels. Figure B4.1.8 shows the results of B4.1.6 with QC:J applied with a threshold \( J_{\text{max}} = 10.0 \). Note this time the quality control applies to all parameters similarly and that some retrievals are now eliminated from the main cloud area. This is a high level of threshold (see discussion in WP 2.5 §3.6.1) and many clearly erroneous retrievals outside the main cloud area are passed. Tightening the threshold removes more retrievals and this is demonstrated in figure 3.3 where the resulting optical depth fields for \( J_{\text{max}} = 10, 5, 2.5 \) and 1 are shown. The two extremes, 10 and 1, appear too relaxed and too severe respectively whereas the intermediate values, 5 and 2.5, produce the most plausible fields.

As we have discussed previously, resulting values of J depend quite strongly on the assumed measurement error \( S_y \) since J contains the real measurements. The expected error \( S_M + S_N \) is less sensitive because it contains no direct reference to the actual measurements and is self-
The result is that until the measurement errors (including, that is, co-registration, model parameter etc) are well characterised, levels for QC:J will have to be set somewhat empirically in order not to be too slack or too tight.

Before moving on to a second case we show in figure B4.1.9 the retrieved state for one further experiment on case #1 where only the reflectance channels, 0.67, 0.87 and 1.6 µm have been used in the inversion. QC:S has been applied as before but with the $R_e$ threshold set to 5 µm as the expected error without the thermal channels is substantially higher. Compared to figure B4.1.7 there appears to be less coherency in the $R_e$ and $\tau$ fields. The $p_c$ and $T_s$ fields do not appear to have moved from their *a priori* values and the $f$ field appears to have moved less from the *a priori* flag value. All of these features are consistant with simulations performed in WP2.5 §3.4.1 and, judging by those results, the rather noisy $R_e$ field is due to leaving the system seriously underconstrained. Figure 3.4 shows the line 16 cross section for retrievals with (dashed line) and without (solid line) the thermal channels. It highlights the unstable nature of the $\tau$ $R_e$ retrieval in the reflectance only channel case. It would be informative to see the result of the reflectance-only channel case where at least $p_c$ was removed from the retrieval state, but this has not been done here. It is reassuring at least to see that retrieval fields are not disimilar despite the difference in measurement systems used. The joint use of thermal and reflectance channels does appear to be the most stable and even where the two results basically agree, there are subtle differences that are presum-
ably a result of appropriate ‘atmospheric corrections’ supplied by full measurement set.

Figure 3.4 Cross sections at line 16 of $R_c$, $\tau$ and $p_c$ for the reflectance channel-only (−) and for the full measurement set (−−−)

3.2 Case #2: Daytime, coastal stratus

The second ATSR-2 case shown in figure A2 is again principally stratocumulus cloud but this time rather more broken and with both land and sea underlying surfaces. The retrieval parameters are essentially as before and are given in the following table.

<table>
<thead>
<tr>
<th>B4.1.10</th>
<th>$\tau$</th>
<th>$R_c$</th>
<th>$p_c$</th>
<th>$f$</th>
<th>$T_s$</th>
<th>$S_y$ +</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active?</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$a priori$ value?</td>
<td>$\log_{10}(4)$</td>
<td>8/60 μm</td>
<td>500 mb</td>
<td>1km Flag</td>
<td>NWP</td>
<td>Coreg</td>
</tr>
<tr>
<td>$a priori$ error</td>
<td>∞</td>
<td>∞</td>
<td>1000 mb</td>
<td>0.1</td>
<td>1 / 3 K</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure B4.1.10 shows the retrieved state for this case with QC:S added with levels $S_{\text{max}} = [40\%, 2\, \mu\text{m}, 50\, \text{mb}, 0.1\, (f), 2.5\, ]$. In this experiment, the surface reflectance was set to the crude ‘vegetated land’ default values $R_s = [0.05, 0.25, 0.15, 0.01]$. A qualitative assessment of the $f$ field shows a retrieval consistent with the image and the $\tau$ and $p_c$ fields are reasonable. The $R_c$ retrieval appears plausible except that quite low values (~4 μm) occur in some regions where optical depth and $f$ are low. High optical depths are found in the denser cloud patch towards the top left image and $p_c$ is relatively flat everywhere except near the cloud edges. Again, because it is a stratocumulus field we can reason-
ably expect a near common cloud pressure across the area. The retrievals are not obviously sensitive to the land sea boundary as the cross section at line 23 in figure 3.5 shows. The boundary around pixel #7 is indicated by a sudden increase in the expected error for $T_s$ (*a priori* changes from 1 K to 3 K at this point). None of the retrieved quantities show any kind of jump at the same point; the explanation lies in the cloud being reasonably thick at this point and errors due to the surface reflection relatively small.

![Figure 3.5 Cross sections at line 23 of $\tau (-)$, $R_s (-)$ and $p_e (-.-.)$ (/100+10) showing a land/sea boundary at pixel #7 where $S(T_s)$ (...) rises abruptly.](image)

The QC:S appears to be effective at the levels given, however, applying QC:J with a threshold $J_{\text{max}} = 5$ eliminates around 90% of retrievals. In a second experiment we took values for $R_s$ from an analysis of local clear pixels - a better simulation of the situation to be expected for SEVIRI where updated surface reflectance maps will be available. The local $R_s$ was found to be $[0.05, 0.16, 0.13, 0.02]$. We also use better local estimates of $T_s$ as the ECMWF model fields could not be expected to resolve the rather detailed coastline of the area.

The retrieved state for this experiment is shown in figure B4.1.11. The differences in the fields in B4.1.10 and B4.1.11 are subtle, but certainly the $p_e$ field in the latter is smoother in the centre region where the cloud is thin and broken and similar, but even less obvious, comments can be made regarding the $R_s$ field. The most distinct change is in the fraction field; in the latter case the fraction is generally higher. It is difficult to comment on whether the ‘good’ local parameters ($R_s$ and $T_s$) have had a positive impact on the retrievals without a very detailed study. Certainly if we repeat the cross section of figure 3.5 in the new experiment, there are only minor differences.

There are strong indications that the retrieved state is improved from the change in the overall cost of solution, $J_m$ in particular. Figure 3.6 shows the cost and iteration fields and histograms for the original case with ‘poor’ local parameters. The high $J_m$ are found as usual in the low / thin cloud areas. The histogram of $J_m$ shows why 90% of retrievals were rejected using a $J_{\text{max}} = 5$ threshold. High $J_m$ are found over the clear sea where the retrieval attempted to change a poor NWP value. Figure 3.7 shows the same for the second case where ‘good’

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1 The 3.7 µm reflectance was crudely estimated by calculating the reflected component given expected atmospheric deficits from the radiative transfer model and using the 11 µm channel to define the surface temperature.
local estimates were used. $J_m$ are significantly lower than for figure 3.6, particularly in the areas of thin and broken cloud, but a $J_{\text{max}} = 5$ threshold still eliminates many retrievals. $J_a$ are substantially better over the sea area showing that the NWP $T_s$ was indeed a problem there.

The convergence rate, given by the number of iterations, also improves in the ‘good’ local estimate experiment. Very high $J_m$ and iterations are now mostly restricted to the sea and cloud-free coastal regions.

A third experiment was run using the technique described in WP2.5 §3.3.3 to add EQMPN
noise to $S_{\gamma}$. We are restricted to adding only the $\text{EQMPN}(R_s)$ because the forward model cannot calculate the gradient with respect to atmospheric transmission except by a perturbation method which is too slow for this application. Nevertheless, in this case (high latitude, land surface) it is probably the $\text{EQMPN}(R_s)$ which is the important term and, anyway, it serves as a good example. We do not show the retrieval fields because without validation they are uninformative, only subtle differences are apparent. Figure 3.8 show the cost fields for the run with $\text{EQMPN}(R_s)$ added.

Figure 3.8 Cost fields for the retrieval experiment with ‘good’ local estimates of $R_s$ and $T_s$ and $\text{EQMPN}(R_s)$ added to $S_{\gamma}$

$J_m$ values are now substantially lower in all areas except the strip of cloud-free sea. Iterations also are significantly down on the run not using $\text{EQMPN}(R_s)$. It could be argued that neither of these diagnostics really prove anything in this case without further detailed analysis as the addition of $\text{EQMPN}(R_s)$ will lower cost automatically ($J_m = (y_m - y(x))S^{-1}_y(y_m - y(x))^T$).

Similarly, the iterations may fall simply because the higher assumed measurement noise demands a less close fit. But these effects are opposing and the looser fit compensates the higher $S_{\gamma}$ so the lower cost is definitely indicative of a ‘better’ inversion. The ‘good’ local $R_s$ used here is only good compared to the crude one used by default; it is still a single vector for the whole image area. We should expect the MSG processing system to be able to provide more accurate and higher resolution values but we cannot realistically simulate that feature here.

In figures B4.1.12 and B4.1.13 we show the measurement residuals for the cases ‘poor’ local estimates and ‘good’ local estimate (but without $\text{EQMPN}(R_s)$) noise respectively. They are of interest, as they explain the contributions $J_m$ value (although remember they are weighted by $S^{-1}_y$). Most of the diagnosis of this case has been dealt with above but we can make some useful comments from the residuals plots.

Figure B4.1.12 for the ‘poor’ case shows the largest residuals in the 0.87 µm. This is particularly so over the clear and partly cloudy land (e.g around pixel [12, 3]), where the solution calculated values, $y(x)$, are too high (~3%). This corresponds to the difference between the ‘poor’ and ‘good’ $R_s$ estimates. An exception is the clear area around [19, 10] and [27, 5] where local small lakes are lowering the effective surface reflectance in all channels. This
demonstrates the need for high resolution reflectance maps. Residuals in the thermal channels are generally bland except for some rather high values in the 3.7 µm around \([10, 15]\).

In the ‘good’ case, figure B4.1.13, the residuals for the 0.6, 1.6 µm and the thermal channels do not change appreciably but the large negative values in the 0.87 µm are replaced, apart from in the lake areas, by near zero or large positive values (the latter especially surprisingly over the clear land \([12, 3]\) where the ‘good’ estimates were made). Residuals for the third case described above, where \(\text{EQMPN}(R_s)\) noise was included, show a very similar pattern to B4.1.13 except with increased amplitude in the 0.87 µm. This results from the scheme weighting the 0.87 µm less and therefore not forcing a fit to the measurements.

3.3 Case #3: Daytime, mixed-layer: stratocumulus and cirrus

This case was particularly chosen to test the scheme over a certain case of mixed layer cloud. Ideally, it would be hoped that the inversion of the data would produce diagnostics to indicate the retrieval is ‘unsafe’ since a single phase, single layer plane-parallel cloud model will not represent a multi-layer, multi-phase system.

The image A3 shows a classical area of marine stratocumulus off the south-west coast of Africa. The tendency towards a cyan colour shows a thickening layer of cirrus towards to top of the image; the presence of the ice cloud has a subtle effect on the reflectance channels that produced figure A3. The thermal channels show the cirrus layer much more clearly as is seen by the 11 µm brightness temperature image in figure 3.9.

![Image of marine stratocumulus off the south-west coast of Africa.](image)

Figure 3.9 11 µm brightness temperature image of case #3. Compare to figure A3

Retrievals were performed for this case following the details in the table.

<table>
<thead>
<tr>
<th>B4.1.14</th>
<th>(\tau)</th>
<th>(R_c)</th>
<th>(p_c)</th>
<th>(f)</th>
<th>(T_s)</th>
<th>(S_y +)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active?</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
<td></td>
</tr>
<tr>
<td>(a \text{ priori value?})</td>
<td>(\log_{10}(4))</td>
<td>8/60 µm</td>
<td>500 mb</td>
<td>1km Flag</td>
<td>NWP</td>
<td>Coreg</td>
</tr>
<tr>
<td>(a \text{ priori error})</td>
<td>(\infty)</td>
<td>(\infty)</td>
<td>1000 mb</td>
<td>0.1</td>
<td>1 K</td>
<td>1</td>
</tr>
</tbody>
</table>
The resulting **retrieved state** parameters are shown in figure B4.1.14. All parameters are retrieved without any obvious errors. The cirrus area is well shown by the gradual decrease in \( p_c \) from the stratocumulus deck at 740 mb to the cirrus deck at around 450 mb. The particle size also rises from its value in the stratocumulus of around 12 \( \mu m \) to a maximum around 18 \( \mu m \) in the centre of the cirrus; however, it is slower to react than the pressure and there is no phase change. The optical depth retrieval shows no discernable sign of increase or otherwise from the stratocumulus to the mixed layer indicating the cirrus is optically thin. The fraction field also appears to decrease from 1 slightly in the cirrus but this could be coincidental.

The data inversion for this case was technically very successful; the average number of iterations was around 2-4 and solution costs peak around 2 and are mostly less than 10. Measurement **residuals** are shown in figure B4.1.15 and show low values (around ±1 K/\%) and with only a hint of structure corresponding to the cirrus area. Figure 3.10 shows the residuals as a vertical cross section made at across track pixel 23, i.e. up through the main cirrus area.

![Vertical cross section](image)

**Figure 3.10** Residuals for vertical cross-section at across track pixel #23 through cirrus area. Upper: reflectance channels 0.67 (−), 0.87 (...) and 1.6 \( \mu m \) (- - -). Lower: thermal channels 3.7 (−), 11 (...) and 12 \( \mu m \) (- - -).

This makes it clear that the stratocumulus / cirrus combination could easily be accommodated by a water cloud model. There are signs of the increasing cirrus along track, especially in the 1.6 \( \mu m \) where the residual falls from +1% to −1%. Compared to the general level of noise however, this signal is small.

We must conclude from this example at least (but see case #4) that there is insufficient information in the channels available to identify this mixed layer case. We may conclude also that retrievals made over the mixed part of this scene, without additional information, would have incorrectly given water cloud with an \( R_c \) of 18 \( \mu m \), i.e. up to 6 \( \mu m \) error, and pressures that were up to 300 mb in error.

The ATSR-2 instrument allows us to check conveniently the retrieval characteristics of a
particular scene as viewed from a different angle. The ‘along track’ data from the ATSR-2 are measured with a view zenith around 55° (compared to the near 0° of the ‘nadir’ data). In figure 3.11 we show the retrieved $R_e$ field as obtained from the nadir and along-track measurements.

There are two points of note. Firstly, the retrievals from the along-track view are more sensitive to the ice cloud and a phase switch occurs for the denser part of the cirrus. Nevertheless, there is still a gradual increase in $R_e$ as the cirrus thickens and no indication in the QC field of the mixed layer until the phase change area is met (not shown). The increased sensitivity is simply a result of the cirrus cloud appearing optically thicker at the oblique view angle. The second point is that, away from the overlying cirrus i.e. in the lower and lower-left areas, the $R_e$ values from both measurement sets are consistent. This is as should be, of course, but it serves as a check on the radiative transfer and inversion models.

The inconsistent $R_e$ values in the mixed layer area do suggest that comparison of nadir and along-track values would be a sensitive QC method for ATSR retrievals, but this technique is unfortunately not available to a single view instrument.

3.4 Case #4: Daytime, midlatitude cumulo-nimbus and stratus

Figure A4 shows case #4, a mixed cloud area in the north-eastern Pacific. Centre-right the structured cyan area is a large (~100 km) convective system. Above this, and slightly detached, is a second system with an anvil-like structure. Elsewhere there is extensive low-level stratus cloud (the slight reddish colouration is due to extra reflectance in the 0.67 µm compared to the 0.87 µm from molecular scattering). On the right side of the image there are traces of thin cirrus covering the lower level cloud; similar to that shown in case #3.

The case was processed with the standard conditions and the retrieved state is shown in figure B4.1.16. A cumulus co-registration noise was used which would be appropriate for the convective area, but perhaps not for the stratus; an operational scheme would take account of local cloud types and assign noise at each pixel.
The retrieved fields are again qualitatively consistent with the imagery. The $\tau$ field shows very high values for the convective centre, moderate values for the anvil structure and moderate to low values for the stratus regions. The $R_e$ field shows a realistic phase change with values of between 8 and 12 µm in the stratus and 50 to 65 µm in the convective and anvil ice cloud. Large areas of ice phase are also identified to the right side of the image where the overlying thin cirrus was noted. $p_c$ values are as low as 220 mb in the main convection centre, around 400 mb in the anvil area and around 820 mb in the stratus. Values as low as 500 mb occur in the thin overlying cirrus areas. The fraction field is consistently near 1.0 except for three or four breaks in the stratus layer which are clearly seen on the image. Finally, the $T_s$ field has essentially remained at the a priori value because of the high cloud cover.

Solution costs and iterations are shown in figure **B4.1.17**. Both mean costs ($J_m$) and iterations are quite low compared to previous experiments and we conjecture this is because of the relatively high measurement noise assumed. Additionally, both the high costs and iterations occur in the convection, around the edges of the anvil and particularly in the overlying cirrus areas. Figure 3.12 shows a cross section at line 19 through the convection centre, across the stratus and into the mixed layer region.

1Note that all ice particle sizes are given as ‘proxy’ sizes - values used to facilitate the use of the radiative property look-up tables. These can be converted to real sizes through a simple quadratic fit.
The phase changes in the mixed layer to the right (around pixels 50 and 60) have resulted in $R_c$ values of exactly 60 µm which is the background value used for ice. These retrievals have failed and the cost values are high. Figure 3.13 is the same cross-section but with QC:J applied with a threshold $J_{\text{max}} = 5$.

![Figure 3.13. As figure 3.12 but with QC:J applied with $J_{\text{max}} = 5$.](image)

The grossly erroneous values in the mixed layer have been removed but there is some indication of rising $R_c$ values which may be due to increasing cirrus cover.

Measurement residuals for this case are shown in figure B4.1.18. They are somewhat larger than in previous examples and this is probably a result of both an increased assumed measurement noise forcing a looser fit, and the greater complexity of the scene. In the clean stratus areas the residuals are consistently low. The mixed layer areas show quite strong positive values (~ 3-6 %/K) for both the 1.6 and 3.7 µm channels and, a little surprisingly, negative values (~ −4%) in the 0.67 and 0.87 µm channels; normally the mixed phase do not affect the non-absorbing channels significantly and the cloud optical depth adjusts to fit them. In this case, it is possible the strong deviations in the absorbing channels is forcing a change in optical depth.

The other major area of large residuals is the convective and anvil centres where the 1.6 and 3.7 µm channels have opposite signs but it is the 3.7 µm which shows the highest residual. In this case we conjecture that the much discussed issue of optical properties of ice crystals is the cause of this discrepancy. The 11 and 12 µm also show negative residuals (calculated solution values too high) here, although less coherently, and it would seem that a slightly lower cloud pressure should have resulted. It is possible that the convergence criteria are too slack and the fit being obtained could be better. The very low iteration rate in this region lend support to this. The 1.6 µm channel also has high negative residuals (~ −6%) in the cumulus areas above and below the main convection centre; it is not clear why these arise.

Other high residuals in various channels surrounding the convective centre can be attributed to SEVIRI scale pixels containing mixed scenes.
Despite this concentration on the levels of residuals, the overall performance of the retrieval scheme on this case is quite successful. It would be of interest to repeat the experiment with tighter convergence criteria and a more adaptive coregistration noise level. Retrievals at full ATSR-2 resolution would also be of interest to examine how many of the SEVIRI retrievals with high cost and residuals are due to mixed scenes.

3.5 Case #8: Daytime, tropical convection and anvil

This case was chosen because of the presence of a classic tropical convection centre and anvil system. These are clearly seen in the top left portion of the image in A8. In the bottom right of the image the scene is mostly cloud-free apart from scattered low cumulus. However, this ATSR-2 nadir image contains also reasonably strong sunglint on the left half where the scan angle roughly equals the solar angle and the relative azimuth is low. This image area was processed using a co-registration noise level appropriate to cumulonimbus scenes.

<table>
<thead>
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<th>B4.1.19</th>
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<th>R_c</th>
<th>p_c</th>
<th>f</th>
<th>T_s</th>
<th>S_y +</th>
</tr>
</thead>
<tbody>
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<td>Active?</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>a priori value?</td>
<td>log_{10}(4)</td>
<td>8/60 µm</td>
<td>500 mb</td>
<td>1km Flag</td>
<td>NWP</td>
<td>Coreg EQMPN</td>
</tr>
<tr>
<td>a priori error</td>
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<td>∞</td>
<td>1000 mb</td>
<td>0.1</td>
<td>1 K</td>
<td>4</td>
</tr>
</tbody>
</table>

![Figure B4.1.19](image)

Figure B4.1.19 shows the retrieved state for this case. In the τ field, the two main convective centres are well shown. Cloud pressures in the convection and anvil system are as low as 160 mb and R_c sizes are consistantly around 50 to 60 µm. In the lower right corner the cloud the cloud fraction is clearly too high and has been ‘fooled’ by the sunglint; however, the optical depth and pressure are near-zero and near-surface respectively.

Measurement cost, J_m, and iterations are very high and low respectively for this case. As in the last case there is a suspicion that the high assumed measurement noise is leading to convergence before a reasonable fit is obtained. However, there is strong evidence from the measurement residuals shown in figure B4.1.20 that the ice model cannot simultaneously satisfy the short and longwave measurements. Figure 3.14 provides a cross section of the residuals vertically through the area at across trac pixel #7. It is useful to examine it in conjunction with B4.1.20. There are distinct areas.

In the optically thick convection (log \( \tau \) > 1, pixels ~23-38 in figure 3.14) the 0.67, 0.87, 11 and 12 µm residuals are small, the 3.7 µm negative (~ −5 K, i.e. calculations too high) and the 1.6 µm positive (~ +7%). The 3.7 µm measurement is indicating a larger particle, the 1.6 µm indicates a smaller particle. The 0.67 and 0.87 µm residuals are insensitive to particle size and are fitted well and in this thick part of the cloud the transmission is small so that the
pressure is easily adjust to satisfy the 11 and 12 µm channels.

In the optically thinner anvil edges there is a dramatically different picture. As the cloud thins (pixels 23-16 in figure 3.14), the 11 and 12 µm residuals become strongly negative (~ −10 K) whilst the 3.7 and 1.6 µm channels maintain their thick cloud values. For the very edges of the anvil (pixels 6-15), the 1.6, 11 and 12 µm residuals relax back to near zero whilst the 3.7 µm residual takes an initial swing to positive.

Although the results of an inversion scheme for a single case cannot be interpreted at all widely, the methods success on the previous case examples (and ones to follow) and the strong consistant conflicting residuals demonstrated above, do suggest a basic inadaquacy of the ice radiative model in this case. We did anticipate this at an early stage. It might prove more robust in the above case to remove either the 3.7 µm or the 1.6 µm so that particle size is driven by less conflicting measurements. The 3.7 and 11 / 12 µm may still conflict; it needs experiment and experiment on a much wider data selection than a single image. Ideally of course, improved ice optical properties are used that reduce the sort of residuals found. On the positive side, the present methodology is a powerful tool for evaluating the ability of the various candidate models to link optical properties across the visible to infra-red wavelengths.

3.6 Case #9: Daytime, Arctic mixed scene

Case 9 shown in figure A9 is fairly unpromising for cloud retrieval, containing large areas of clear land, clear ocean, sea ice and stratus cloud covering variously all surface types. The sea ice is obvious visually as the deep cyan colour caused by low reflectance at 1.6 µm: the same information that drives the cloud phase identification. We do not study this case in any great detail but it serves to show the value of the quality control measures.

We perform retrievals using the normal controls with stratus type co-registration noise assumed. The retrieved state is shown in figure B4.1.21 and appears fairly chaotic and not particularly consistant with the imagery. It is not worth detailing all the features of B4.1.21 since they are mostly driven by the a priori cloud flag. The flag is the cause of the ‘blocky’ nature of most parameters in the bottom region of the field as it is obtained by regional (128×128 ATSR pixel) histogram evaluation (described earlier). It has clearly has been
‘fooled’ by the sea ice in the centre top of the image and similarly at the centre bottom. Careful examination of the retrieved fraction field shows that it does follow the image reasonably well apart from the noted ice areas.

Solution costs for this case are quite high as seen in figure 3.15.

Figure 3.15. Solution costs and iterations for case #9

\( J_m \) are very high for all the clear land, for the sea ice and for some of the thin cloud over land. Local estimates of \( R_s \) and \( T_s \) were not used in this case and are no doubt responsible for the high values. As in case #2 the NWP fields do not resolve the land / sea boundaries on this kind of scale and significant errors may be expected. This is confirmed by the appreciable values of \( J_a \) over the land.

An interesting cross section of measurement residuals is shown in figure 3.16. This shows a vertical cross section at across track pixel #28 which, by careful reference to figures B4.1.21 and A9, can be seen to transect the following: (along track pixels in parenthesis) cloud over ice (0–5), ice (6–8), broken ice (8–11), broken cloud (12–17), stratus cloud (18–24), stratus over ice (25–30), stratus over land (31–34) and stratus (35–47).

Figure 3.16. Residuals cross-section at across track pixel #28. Key as 3.14
It is very obvious that low residuals are found only for cloud over ocean and gratifying to see high residuals were the model should not fit: ice, cloud over ice etc. Cloud over land should be possible of course but this experiment lacked a good $R_s$ estimate and the land area so small that the SEVIRI pixels were likely to be mixed land and sea.

Even in the suitable areas (pixels 12–24, 35–47) the $J_m$ are quite high (>10) and suggests, as previous experiments have suggested, that effective noise levels are higher than assumed (partly a function of the iterative solution). Using a threshold of $J_m=12$ the **QC:J retrieved state** shown in figure B4.1.22 is obtained. It is drastically reduced but a careful examination reveals that the areas that remain do correspond to the areas on the image where a retrieval might be expected to succeed. The exception is the stratus area top right of the image where few retrievals are obtained.

As a contrast to some previous cases, the **QC:S** with thresholds [40%, 2 µm, 50 mb, 0.08, 0.9 K] leaves retrieved fields as shown in figure B4.1.23. Many areas are retained where clearly the retrievals must be erroneous. This serves to demonstrate again the complementary nature of the two QC diagnostics.

### 3.7 Case #10: Daytime, midlatitude frontal system

The final ATSR-2 case image in A10 shows a small frontal system over N. Central Europe. A mixture of cloud types are present; frontal cirrus, stratus and cumulus. It would appear qualitatively that areas of ice and water and therefore no doubt mixed phase are present. A local $R_s$ estimate was made for this scene - [ 0.07, 0.28, 0.14, 0.03 ].

<table>
<thead>
<tr>
<th>B4.1.19</th>
<th>$\tau$</th>
<th>$R_c$</th>
<th>$p_c$</th>
<th>$f$</th>
<th>$T_s$</th>
<th>$S_y +$</th>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$a$ priori value?</td>
<td>$\log_{10}(4)$</td>
<td>8/60 µm</td>
<td>500 mb</td>
<td>1km Flag</td>
<td>NWP</td>
<td>Coreg</td>
</tr>
<tr>
<td>$a$ priori error</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>1000 mb</td>
<td>0.1</td>
<td>1 K</td>
<td>3</td>
</tr>
</tbody>
</table>

The **retrieval** is shown in figure B4.1.24 and is qualitatively reasonable with a band of ice phase following the higher cloud around the frontal structure. Fraction cover is high everywhere except for a few clearer pixels towards the bottom left of the area and some apparently erroneous pixels centre top (e.g. [12, 33]) and centre right ([33, 21]) where compensating high optical depths are required. It is interesting that the line of high cloud and ice phase is not also the line of high optical depth which appears to lead off the top of the image area. A few ice phase pixels are found outside the high frontal band but these often correspond to pixels with low $p_c$ and the image shows many growing cumulus which could well be ice phase. **Solution costs** are shown in figure B4.1.24 and are generally low and scattered mainly around the frontal system. The convergence rate is very fast with most convergences in less than 4 iterations.

The retrieved fields with **QC:S and J** applied at levels of [40%, 2 µm, 50 mb, 0.08, 0.9 K] and 12 respectively are shown in figure B4.1.26. (The level of $J_{\text{max}}$ applied here is perhaps rather high.) It is hard to judge the impact of the QC in this case since the original fields were quite plausible. However, the few noted high optical depth retrievals are removed as are some of the ice phase pixels lying outside the frontal zone.

There are some problems with this case which the high assumed measurement noise ob-
scured by lowering the solution cost. The measurement residuals in figure B4.1.27 once again show opposing effects in the 1.6 (~+4%) and 3.7 µm (~−2 K) channels although by no means as large as the tropical convection case #8. The 1.6 µm also has significant residuals (~ −4%) in the water phase cloud surrounding the frontal region; this is worthy of investigation since the water cloud cloud radiative properties should be well defined. It is possible that the clouds in question are mixed phase. The 0.67, 0.87, 11 and 12 µm channels all show relatively low residuals but there is an interesting ~2.5% reflectance bias between the 0.67 and 0.87 µm residuals. This is in the sense that the 0.87 µm measurement is higher than the solution calculated value, and the 0.67 µm measurement is lower. This is in the opposite sense to a molecular or aerosol scattering effect which might be significant over central Europe.

### 3.8 Case #5: Nighttime, marine stratocumulus

<table>
<thead>
<tr>
<th>B4.1.28</th>
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<th>R_c</th>
<th>p_c</th>
<th>f</th>
<th>T_s</th>
<th>S_y +</th>
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<td>Coreg EQMPN</td>
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<td>∞</td>
<td>1000 mb</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

The simulations of WP2.5 sections §3.4.2 and §3.4.4 suggested that retrievals of the full state would not be possible using nighttime 4-channel data. Here, we have only three channels (3.7, 11 and 12 µm) and attempted retrievals of the full state do fail comprehensively as expected. The simulations did suggest that the reduced state [τ, R_c, p_c] should be retrievable for cloud covered (f=1) pixels. This is the state that we firstly attempt for case #5 (figure A5) which shows an area of stratocumulus, overcast in the centre-left region and broken either side of this. Clear areas of land and sea are also prominent. The retrieval is shown in figure 3.17.

![Figure 3.17. Retrieved [τ, R_c, p_c] from case #5.](image)

The optical depth shows no consistancy with the imagery and is high because the first guess value used was τ=80 as low values (normally 4 is used) led to non-convergance. However, the R_c field is plausible (the first guess is R_c = 8 µm and values of ~12 µm are retrieved) for where the cloud field complies with f=1 and the pressure field is remarkably consistant even where there is obviously no cloud. Figure 3.18 shows the measurement residual fields and histograms; it is quite clear that where the cloud field is unbroken the retrieval is successfully fitting the measurements and elsewhere it is not. QC:J successfully eliminates the unbroken cloud and clear areas as shown in figure 3.19 (J_{max} = 2.0 used). QC:S also eliminates the whole of the field for τ in this case (not shown), and probably correctly since it appears
the cloud is optically thick and therefore $\tau$ is not estimable by IR alone.

Although the above retrieval appears reasonably successful, the caveats expressed in WP2.5 §3.4.2 about the meaning of parameters so obtained are worth remembering. To illustrate this, we change the state parameter to $[R_c, p_c, f]$ and set the (fixed) optical depth to $\tau=80$ (for the same reason as above). The a priori $f$ is set to 1 but with a high error (10.0). The retrieval is shown in figure 3.20 and again appears reasonable. However, the fraction is low in the unbroken cloud area and high in the broken area centre top, presumably in response to the assumed optical depth being too high and low respectively. $R_c$ values are lower than in the previous retrieval and $p_c$ values are higher. The measurement residuals are once again low in the main cloud area suggesting a successful retrieval.

These results serve to demonstrate the lack of information: different but apparently successful retrievals can be obtained using different definitions of the state vector; i.e. there are multiple solutions to the nighttime problem and it is impossible with the nighttime measure-
ments alone to distinguish them.

3.9 Case #6: Nighttime, mixed-layer: stratocumulus and cirrus

This case is shown in figure A6 and shows a field of large area stratocumulus with a patch of overlying cirrus extending from the centre to the top right.

Results from experiments with this case lead to similar conclusions to that from case #5 in §3.8; setting the problem in different forms gives rise to different but equally valid solutions (from the point of view of measurement / a priori residuals). We demonstrate by showing results from two experiments, both using a state vector \([R_e, p_c, f]\), the first with an a priori \(\tau\) of 80 (figure 3.21), the second with \(\tau = 8\) (figure 3.22).

Figure 3.20. Retrieval using the state \([R_e, p_c, f]\)

Figure 3.21. Retrieval from case #6 using \([R_e, p_c, f]\) and a priori \(\tau = 80\)
Both results show recognisable and plausible features in the f and p\textsubscript{c} fields which are comparable between experiments. Somewhat higher values of f and are required by the lower optical depth in figure 3.22 and the p\textsubscript{c} field in this case is more erratic in the stratocumulus area and shows higher values in the overlying cirrus. The dramatic difference between the results is the R\textsubscript{e} field which is ice phase in figure 3.21 and water phase (and even small R\textsubscript{e} values) in figure 3.22. The sensitivity of R\textsubscript{e} results from the weak (nighttime) signal present in the measurements and the consequent dependence on assumptions.

### 3.10 Case #7: Nighttime, frontal cirrus and stratocumulus

This case is shown in figure A7 and contains areas of thin cirrus overlying stratocumulus (left and centre-right), broken (sub-pixel at SEVIRI resolution) stratocumulus (centre) and frontal cirrostratus (right). We use this case to demonstrate at least superficially the possibility of aiding nighttime retrievals using a priori information from the imagery.

The basic retrieval from this case using the state [τ, R\textsubscript{e}, p\textsubscript{c}] is shown in figure 3.23 for f = 1 and an a first guess τ = 8. The τ field appears reasonable although it is of course compensating for the fixed f = 1 in the broken cloud areas. The R\textsubscript{e} retrieval does not follow intuitively any of the features of the imagery although, partly this may be due to the way the scheme uses the phase from the previous retrieval as a starting point for the next. This explains the stripy nature of the phase boundary but is nonetheless due ultimately to the lack of a signal in the measurements regarding the R\textsubscript{e} and phase. The p\textsubscript{c} field is also poor, with some indication that a good result is obtained in the solid cirrostratus to the right.

To show the merit of additional information from the ensemble characteristics of the data we show in figure 3.24 a plot of the scatter of brightness temperature differences (dBt) against the brightness temperature in the 11 µm channel. dBts for 11 / 12 and 11 / 3.7 are shown at ATSR-2 resolution (~1 km, every 4th pixel selected for clarity) and at approximate SEVIRI resolution (8 km). This is a widely used technique for analysis of multispectral imagery and well known features can been seen. Principally, the presence of ‘feet’ (dense congregations of pixels with low dBt) indicate either clear pixel areas of homogeneous (f = 1) cloud areas. Between the ‘feet’ are ‘arches’ caused by either varying optical depth or vary-
ing cloud fractional cover. The top right-hand plot of 11-3.7 at ATSR resolution shows the feet and arch due to the broken sc best. The arch in this case is caused by differential planck function response to fractional cover at the two wavelengths. The clear sea brightness temperature appears at one foot at 280 K and the sc cloud top brightness temperature at the colder foot at ~262 K which corresponds to around $p_c \approx 780$ mb for the given NWP profile.

The arch due to varying optical depths in the cirrus is seen more clearly in the 11-12 scatter plot from ATSR where both feet are at a dBt of around +1 K. It is also in the 11-3.7 plot but the high transmission of the 3.7 µm radiance means the ‘cold foot’ has a dBt of around −10 K. The temperature of the cirrus from this appears to be around 232 K corresponding to a pressure of 400 mb.

The retrieved $[\tau, R, p_c]$ from case #6

Figure 3.24. Scatter plots of 11−12 and 11−3.7 µm brightness temperatures for case #6. Plots at ATSR-2 resolution (but sampled every 4th pixel) shown at top, plots at 8 km SEVIRI resolution shown bottom.
The essential features can be seen in the SEVIRI resolution plots but they are necessarily less clear.

Assuming automated analysis of such scatter plots (and similar techniques using spatial coherence) can be successfully automated, we can simulate the effect of *a priori* estimates of $p_c$ on the retrieval. Using a somewhat simple classification based on the 11-3.7 µm dBt:

**IF** [ dBt(11-3.7) > −5 K AND Bt(11) > 260 ]

**then** *a priori* $p_c = 780$ mb and phase=water

**else** *a priori* $p_c = 400$ mb and phase=ice

with an *a priori* error on $p_c$ of 50 mb we obtain the retrieval results shown in figure 3.25.

![Figure 3.25. Retrieved $[\tau, R, p_c]$ from case #6 using *a priori* phase and $p_c$ from dBt analysis](image)

The phase and pressure retrievals are much more intuitively reasonable and the optical depth field is mostly unchanged from figure 3.23. It might be argued that the phase and pressure would have to appear better, but, in the case of phase, there was no additional constraint on the retrieval, only an ‘improved’ first guess.

The above is presented simply to show what might be achievable when a detailed analysis of the ensemble characteristics of the radiance field is used to supply *a priori* information to constrain the retrieval. It may be that such analysis could be more or less powerful than the one done here which has had the benefit of human interpretation but only used a single ensemble (11-3.7 µm dBt) characteristic. Assessing what information might be available from the ensemble characteristics of the SEVIRI measurements is beyond the scope of this study.

### 3.11 Sensitivity to resolution

This section compares two experimental retrieval runs using different simulated SEVIRI resolutions on the ATSR-2 case #4. The low resolution run is that for which results were presented in §3.4 using a resolution of ~8 Km (8×8 ATSR-2 pixels); we compare this with a run made using a resolution of ~4 Km (4×4 ATSR-2 pixels). The high resolution run is shown in figure B4.1.28 and should be compared to figure B4.1.16. Apart from the obviously more detailed structure in B4.1.28 there are no really significant differences. The high resolution field has more retrievals with intermediate fraction (around 0.6-0.8) but this is expected from the smaller pixel. Figure 3.26 shows a cross-section at line 40 (20 in the low resolution case) of the two retrieved fields of optical depth with the measurement cost, $J_m$, plotted underneath. The figure confirms that the fields are similar and that the costs (i.e. fit
to measurements) are similar. There is some evidence that there are significantly more poor fits in the high resolution case. This latter point is of some interest because it is not at all obvious whether a very small pixel, or a large pixel is best used when a plane parallel cloud model is employed (obviously, the instrument defines the lower limit possible). The small pixel is most likely to observe a single scene type; the large pixel much more likely to include mixed phase, multiple height etc. On the other hand, the smaller pixel is more subject to detailed problems, side illumination / shadowing, local cloud slopes etc, whereas the averaging that is implicit in the large pixel may make the scene effectively one of a plane-parallel cloud.

Figure 3.26. Across-track cross section at line #40 (20 in the low resolution field) of retrieved optical depth and solution measurement cost.

Figure 3.27 shows histograms of $J_m$ for the whole processed image area normalised to the same total. It again suggests that, in this case, the overall fit to measurements is marginally
better at the lower resolution although the effect is hardly significant.

![Histograms of measurement cost for ATSR case #4 processed at two resolutions](image.png)

Figure 3.26. Histograms of measurement cost for ATSR case #4 processed at two resolutions

3.12 Concluding comments

The above examples have demonstrated the suggested retrieval methodology over a wide range of cloud, surface and solar-satellite geometries.

- For daytime retrievals the iterative inversion scheme was robust and produced cloud products that appear consistent with the scenes they were derived from.
- The schemes diagnostic output was shown to be capable of quality controlling the results in a range of situations. Errors arising from cloud conditions which are close to the plane parallel model but where errors are theoretically high are flagged successfully by the expected error diagnostic, S. Conditions where the cloud model is inadequate are often successfully detected by a poor fit to the measurements: the solution cost diagnostic, J. An exceptional case where both diagnostics failed to flag poor retrievals was thin cirrus overlying a second cloud layer, although a similar case was flagged. The reasons for the difference are unclear.
- The J diagnostic acts as a quality control indicator on the whole retrieval whereas the S diagnostic acts on parameters individually.
- The J diagnostic is sensitive to the assumed measurement noise and appears to be sensitive to the convergence criteria applied. The consequence is that, unlike the S diagnostic, some experience will be required in order to establish suitable thresholds for quality control using J. This is not strictly an empirical tuning since the threshold does have a theoretical basis: it should be 1 for ‘one-sigma’ confidence, 2 for ‘two sigma’ etc. The experience is required to adequately specify the true noise levels and we believe these are best found from the diagnostics of the system themselves.
The average characteristics of J can be used to assess the value of information in the system. If a ‘measurement’ is assigned either too high or too low an error then the value of J becomes larger than the optimum level. This demonstrated using the cloud flag \textit{a priori} estimate.

Measurement residuals are individually not a quality control indicator but they provide information on the reasons for high cost retrievals. In most experiments residuals were acceptably small when the scene was amenable to analysis. Important exceptions to this were found for ice clouds, particularly the tropical example. Residuals monitored over larger data sets will provide information on channel noise, calibration and model deficiencies although it may not always be simple to dis-entangle the effects.

Retrievals were aided significantly by the availability of \textit{a priori} information, both in accuracy and convergence speed and it was found important to assign such \textit{a priori} appropriate errors.

The method of accounting for errors in model parameters that are not retrieved by addition of the equivalent measurement noise they produce was demonstrated for the case of surface reflectance. Without detailed \textit{in situ} validation it could not be confirmed that resulting retrievals were more accurate, but lower solution costs were indicative that the method is useful.

Retrievals made from the two separate views of the same scene from the ATSR–2 instrument were consistent showing that view geometry effects are modelled correctly.

Retrievals made at two SEVIRI pixel sizes (4 and 8 Km) were consistent and showed only marginal differences in the ability of the scheme to fit the measurements.

There was evidence that convergence criteria were too slack in some circumstances leading to poor fitting and higher residuals and cost. The convergence criteria used were initial estimates of reasonable quantities and an operational scheme should address this issue more carefully.

For nighttime retrievals the situation is much poorer. Results supported the simulations with poor stability of the retrievals and multiple solutions depending on the state vector employed. Phase detection from the measurements alone is poor and particle size retrievals highly sensitive to assumptions made to constrain the problem. It is quite clear that the information content of the reduced SEVIRI complement studied here (i.e. without the 8.7 and 13.4 µm channels) is not adequate to perform retrievals with the method as proposed. The use of additional \textit{a priori} from ensemble characteristics (simulated in a very approximate way) showed promise but further detailed study would be needed to establish if this could really result in well constrained retrievals.

Simulations for nighttime suggested that joint retrieval of optical depth, particle size and pressure should be possible, indeed quite accurate, for pixels identified as cloud covered. The retrieval experiments in this section did not confirm this and it is not clear why. It is possible that the explanation lies in a) the difference between theoretical solution error and the problem of finding the solution, b) effective noise levels higher in the data than in the simulated results or c) a misleading conclusion from the simulations as these were done at a particular optical depth in this case. Certainly, with regard to a), we found the behaviour of the inversion scheme hard to predict and control in the nighttime case compared to the daytime where it was robust. Finding a solution in a poorly constrained system may demand finer tuning and more careful consideration of the minimisation procedure.
4. Retrievals from MODIS AS data (WP4.2)

A limited amount of MODIS airborne simulator (MAS) data from the CEPEX campaign was acquired from the NASA Langley DAAC data centre. Instrument and further campaign details are discussed in WP2.4a.

Most aspects of the retrieval of cloud parameters have been covered in the preceding demonstrations using ATSR-2 data. The MAS data does have the advantage of including a channel similar to the SEVIRI 8.7 µm channel (and also a 13 µm channel which could be used to evaluate the suggestions made in WP2.5 §3.4.2 regarding lack of information at nighttime). MAS data is not well suited to simulation of SEVIRI in the spatial sense as they consist of narrow ground tracks at very high spatial resolution over limited areas. Thus we have limited the use of MAS data to examination of one or two flight tracks with particular reference to the consistancy of the cloud model between the various spectral channels.

4.1 Case #1: CEPEX Tropical anvil cirrus

We selected track #4 from the CEPEX flight on the 17 March 1993 and the pseudo-true colour composite using 0.6, 0.8 and 1.6 µm channels (see ATSR-2 examples) is shown in figure 1.

![Figure 1. [0.6, 0.8, 1.6 µm] composite image for CEPEX track #4 17 March 1993.](image)

The start (left end) of the track is clear of cloud and the central area appears to be a thin cirrus shield area. Beyond half way, the cirrus is overlying small cumulus and at the end of the track (right) there are clearly some cumuliform clouds. The vertical (across track) stripe just before half way is probably an instrumental effect, certainly the 3.7 µm channel is very noisy at this point; it is difficult to conclude anything from the other channels.

The inversion scheme was applied to the data using all channels and with the constraints etc. defined in the following table.

<table>
<thead>
<tr>
<th>Active?</th>
<th>τ</th>
<th>R_c</th>
<th>p_c</th>
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<th>S_y +</th>
</tr>
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<tbody>
<tr>
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<td>log_{10}(4) 8/60 µm 500 mb 0.8 µm flag</td>
<td>LWT Tropical Coreg EQMPN</td>
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<tr>
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<td>∞</td>
<td>1000 mb 0.2</td>
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</table>

The use of the LOWTRAN tropical case to define the atmospheric profile was not because of unavailability of NWP values. The ECMWF profile in this case was found to be very warm and moist compared to the LOWTRAN version, so ‘extreme’ in fact that it caused...
failure of the RTTOV IR transmittance model. (The RTTOV coefficients are derived from a standard set of screened radiosondes, see WP2.2 §3.2, and do not perform well when applied to profiles from ‘outside’ the training set.) Figure 2 shows the ECMWF and LOWTRAN tropical temperature and humidity profiles.

Figure 2. LOWTRAN tropical profile and the ECMWF temperature and humidity profile obtained for the CEPEX 17 March case.

The profiles are comparable at near surface levels, especially in the temperature part due to the low variability of sea surface temperature in the tropics. Above 850 mb however, the ECMWF temperature and humidity are both higher than the LOWTRAN version and by considerable amounts. By 400 mb the temperature difference is as high as 20 K and the humidity 5-10 g/kg. Although the LOWTRAN profile is not part of the training set used for RTTOV, examination of WP2.2 §3.2 figure 3.4 shows that it conforms to the training set used and that the ECMWF profile does not. The reason for the large discrepancy lies in the origin of the profiles. The training set and the LOWTRAN profiles are all based on clear column soundings; the ECMWF model is a cloud-resolving model and as such produces atmospheric profiles with cloudy atmosphere characteristics when the model physics determines the presence of cloud. With this in mind, it is readily apparent that the ECMWF profiles shown above represent a convectively active area where the condensation level is around 850 mb. The elevated temperatures are then just the wet adiabat whereas the LOWTRAN and training profiles follow more closely the dry adiabat. The humidity profile shows large quantities of water being raised to high levels in the atmosphere.

We detail this subject because it does raise the issue of training sets for fast radiative transfer models for cloud parameter retrieval. Most fast models will be tuned to clear radiances unless explicit care has been taken to include representative cloudy soundings; this is the case in the present study. In retrospect, the version of RTTOV used here should have been based on a wider selection of soundings. Indeed, it could be argued that only cloudy soundings should be included in the training set but this could potentially lead to problems of the reverse kind.

For now, however, we have to resort to use of the LOWTRAN profile in order to proceed with the CEPEX data analysis. Figure 3 shows the retrieved state for the case using all seven channels of MAS. The orientation is such that the lower part of the plot corresponds
to the left end of the image in figure 1. The cloud flag in this case was supplied by a simple threshold (6%) on the 0.8 µm reflectance value. The two channel method developed and used in §4.1 for the ATSR-2 data produced too high a coverage of cloud. This perhaps points to small calibration errors in the MAS 0.6, 0.8 µm data especially as residuals in these channels (see later) show a discrepancy. Areas with cloud flag estimates < 0.05 were considered clear and no retrievals performed (unlike the ATSR-2 results of §4.1).

The retrieved fields are consistent with the imagery in figure 1. The cirrus is identified (by ice phase $R_e$ results) although the areas between 80 and 120 along track appear to correlate with pressures that are too high for ice cloud. The curious feature around 40 along track is a result of the 3.7 µm data problem mentioned earlier.

Rather than exhaustively detail the behaviour of the retrieval of this case with varying constraints etc (covered using the ATSR-2 data) it is more interesting to examine the measurement residuals. These are shown in figure 4. Large positive values are seen in the 1.6 µm channel over the cirrus area with corresponding negative values in the 3.7 µm and erratic behaviour in the 8.7, 11 and 12 µm. Elsewhere, residuals are smaller but a persistent bias is seen between the 0.6 and 0.8 µm. As in the ATSR tropical case #8 it appears there are large discrepancies between actual and assumed optical properties of ice cloud, particularly in the responses of the 3.7 and 1.6 µm channels. A cross section of the residuals up the track centre
in figure 5 reinforces this impression.

Figure 4. Measurement residuals for the CEPEX case, all channels included.

Figure 5. Measurement residuals along track at pixel #7
The large and consistent residuals in the IR channels between along 30−40 and 58−60 suggest more of a problem with the solution finding process than intrinsic faults in the ice optical properties; nevertheless it is obvious there is again the conflict between the 1.6 and 3.7 µm measurements, the 1.6 µm ‘requiring’ a smaller particle, the 3.7 µm requiring a larger particle. This is the same result as was found in the ATSR case, §3.8. To examine better the fit in the IR alone we ran the inversion without the 1.6 µm. The retrieved state does not appear radically different (not shown) but the overall residuals shown in figure 6 are significantly lower as would be expected.

The same cross section shown in figure 5 is shown in figure 7 for comparison. Residuals are generally lower everywhere, but particularly in the cirrus area (excepting the data problem area around line 40). Figure 7 especially indicates a well converged retrieval solution and clearly highlights some consistent channel residuals that were obscured by the poor retrievals of the full channel experiment.

Of particular note are the consistent biases between the 0.6 and 0.8 µm and the 8.6 and 11 µm channels. In the former case, the ~3% bias is much too high to be explained by molecular scattering and is unlikely to be an aerosol effect as it appears to be largest in the thickest and highest cloud. It suggests a calibration offset in the MAS data but this would need more detailed study to establish. In the infrared channels over the cirrus area there is a consistent bias of around 5 K between the 8.6 and 11 µm; the calculated 8.6 µm values are low.

Figure 6. Measurement residuals for the CEPEX case, 1.6 µm not used.
compared to the measurements, the calculated 11 µm values too high. Notice that outside the cirrus areas the IR residuals are much reduced. Again we can speculate that this is a result of inadequate representation of ice optical properties in this wavelength region although other explanations are possible. It is unlikely that the undoubtedly poor atmospheric profile used here (LOWTRAN tropical) is the cause since this would probably lead to larger discrepancies over low cloud areas.

![Figure 7](image1.png)

Figure 7. As figure 5 but for retrievals without the 1.6 µm channel

However, there are other effects to consider, the non-isothermal nature of the cloud, for example.

Finally, we show the same residuals cross-section, figure 8, for an experiment where the 1.6 µm was reinstated and the 3.7 µm channel removed.

![Figure 8](image2.png)

Figure 8. As figure 5 but for retrievals without the 3.7 µm channel
The retrievals appear to be far less stable in this compared to the omitted 1.6 µm experiment and there is much less consistancy in either the reflectance of IR channel plots. It is possible that these results suggest that using the 3.7 µm channel effectively estimates a particle size that is more consistant with the longer wavelength IR channels than using the 1.6 µm, and one can speculate that the reason is that the optical properties of ice are more consistantly calculated between 3.7 and 12 µm than they are between 1.6 and 12 µm. Results from track #1 of the same CEPEX campaign day are similar in that using all channels lead to poor convergence and high residuals. In this case however, the residuals for retrievals with omitted 1.6 µm, figure 9, and omitted 3.7 µm, figure 10, are of similar magnitude.

This is particularly the case in the cirrus areas along track 0–34, 43–65. In the lower and broken cloud areas elsewhere residuals are also similar except that both the 1.6 and 3.7 µm
are poorly fitted in their respective images.

4.3 Concluding comments

The experiments using MODIS AS data have demonstrated the retrieval scheme successfully producing cloud parameter estimates from remotely sensed data of the type that the SEVIRI instrument will make.

The use of the CEPEX case data highlighted the issue of ensuring that radiative transfer models are trained (if ‘training’ is part of the model) on suitable atmospheres, i.e. those typical of all conditions including moist cloudy ones.

Retrievals from the CEPEX data, which were mainly of high tropical cirrus, showed similar characteristics to that from the tropical ATSR-2 case – characteristics are dominated by inconsistancies in the ice cloud optical properties. Retrievals and measurement residuals were considerably improved by omission of either of the 1.6 or the 3.7 μm channels which appears to be where the largest inconsistancies lie. Speculation on the detailed causes of this problem is beyond the scope of this study and a matter of ongoing research in many institutions. The diagnostics of the scheme do at least provide a good measure of the problem and of the accuracy of the representation of the optical properties used.

Problems of this sort clearly also affect interpretation of the 8.7 μm measurements for which the MAS data were particularly useful. The results showed that there was no particular anomaly with this channel but its usefulness in parameter retrieval will not be exploited well until the ice optical properties are better specified.
1. Introduction

This workpackage takes the results obtained throughout the study and considers the implications and opportunities for retrieval of cloud parameters operationally from SEVIRI. In section §2 we consider whether the basic methodology that has been demonstrated in theory and on real data should be used for SEVIRI and if so, what principal modifications should be made. Section §3 discusses the requirements of the atmospheric radiative transfer models and examines whether they are met by the current MPEF processing specifications. It also addresses the question of cloud radiative transfer and particularly the single scatter optical properties.

Section §4 examines each of the principle a priori inputs to the scheme and section §5 considers implications of operational implementation.

2. Adaptation of the methodology

We believe that during this study we have demonstrated that the proposed methodology can be successfully applied to remotely sensed data and could therefore be successfully applied to measurements made by the MSG SEVIRI instrument. What we discuss here therefore are more or less subtle changes in view of the results obtained and the particular SEVIRI characteristics.

The ‘optimal estimation’ method described in WP2.5 and demonstrated in WP4 is essentially a pixel-based method, based on an explicit representation of the radiative transfer and with the flexibility to use diverse sources of a priori information. The method is theoretically sound, and because of this, it is straightforward to estimate the error budget. A more or less complete set of diagnostic information is available from the data inversion process.
2.1 Time-series information

Opportunities offered by SEVIRI that we have only been able to theoretically test, or superficially test on real data, arise from the time-sequence data presented by a geostationary platform. The two extremes of exploitation of time series data are treating each data time independently and Kalman filtering the whole sequence. Neither is really appropriate here since there is definitely useful information to be communicated forward but the nature of cloud fields (broken, rapidly changing in time and space) is not suitable for serious filtering. Therefore, each piece of information from one measurement time must be treated for use in the following measurement time on its own merits. Variables that are expected to have slow time varying behaviour (surface reflectance, temperature etc) can be heavily used sequentially: they can be used as a priori information (see discussion in WP2.5 §3.7) if they are in the state vector. Variables that change rapidly (e.g. cloud fraction) are less useful, they can be used as a priori with high errors attached but it is recommended they are used to initialise the first guess (there is no reason why an estimate should not be used as both of course). More discussion on this is given in section §4.

An operational scheme for SEVIRI could become quite sophisticated with its use of time sequence information and, if the rules described in WP2.5 §3.7 are followed, the system could be very powerful.

In summary, we are not suggesting a modification to the demonstrated technique here, but recommending that the framework it offers to absorb many types of information be exploited to the full.

2.2 Scenes and cloud analysis information

We can recommend that information on the scene type and information from the cloud analysis be used in the operational system. Again, we do not foresee any major adaptation of the method used in the study; this information can be effectively used as a priori and or first guess and is dealt with in §4.

2.3 Additional measurements

In WP2.5 section §3.4.2 it was found that the nighttime interpretation of the SEVIRI IR measurements was an underconstrained problem and it was suggested that use of more of the SEVIRI channels may provide the necessary information. We cannot recommend that operational implementation of the studied scheme include these measurements since we have not studied their impact. However, we can recommend that this study be made.

3. Radiative transfer models

3.1 Atmospheric

The radiative transfer models used in this study were of sufficient accuracy. This is judged by the level of error associated with the model parameters assessed in the simulation studies. There we found ‘measurement noise’ due to profile (and surface reflectance) errors around 1K in the thermal channels and of the order of 0.5–1% in the reflectance channels. Thus the use of more accurate atmospheric radiative transfer models is not warranted. In the infrared case, the model is fast and (potentially) provides gradient information without perturbation
being required. The LOWTRAN visible model used is too slow to be useful in an operational context. Results in WP2.1 section §5 show that a reasonably accurate visible wavelength atmospheric transmission model is required as transmissions can be appreciably low in certain atmospheres and solar−viewing geometries.

The MSG MPEF IR radiative transfer model can almost certainly provide the variables, accuracy and speed required by the inversion (see WP2.2 §4.2) although it is not clear that the current output is sufficient. There is no current facility in the MPEF for visible radiative transfer so this would need to be addressed.

If the methodology of adding equivalent model parameter measurement noise is adopted (and we recommend that it is) then the radiative transfer models need to be able to quickly calculate the gradient values with respect to the atmospheric profiles. Perturbation methods are far too slow. It is possible that this could be circumvented with sufficient accuracy by pre-calculating look-up tables of the transmission perturbations but the algorithmic method is preferred one.

3.2 Cloud

Cloud bulk radiative properties probably have to be provided through pre-calculated lookup tables as in the scheme demonstrated in the study. In the infrared, two stream methods are possible but do not provide good accuracy for radiances. In the visible, asymptotic theory provides analytic expressions for optically thick clouds but LUTs are still required for optically thin cases.

In the studied scheme all clouds were modelled as single layer and polydisperse. It is possible that LUTs calculated using clouds with realistic vertical size gradients would be more accurate. When a single absorbing channel (e.g. 1.6 µm) is used for particle size information, it probably is of little significance since an effective particle size is obtained representative of some depth in the cloud. However, when two or more channels are present (1.6 and 3.7 µm) and responsive to different depths in the cloud, the gradient may be important. Results from the study suggested this was certainly not always a problem since fitted radiances were low in all channels over stratus cloud. We suggest that LUTs be calculated with vertical gradient clouds but cannot supply evidence to deem this necessary at this point.

Modelling water clouds as gamma-distributions of spherical drops is an accepted and apparently successful representation. No modifications are required here.

The uncertainty over the optical properties of the irregular crystals in ice clouds has been demonstrated in the study. There are likely to no short-term improvements to this situation but we recommend that current research literature on the subject is monitored and any improvements to the state of knowledge incorporated. Further studies will be required to see if the undoubted inadequacies of the ice optical properties were causing additional errors in the retrieved cloud parameters. The inversion was at least superficially robust to the problem in the sense that it would converge to a solution albeit one poorly fitting the measurements. The question remains whether the basic parameters were affected by the joint visible-infrared inversion. It is likely the optical depth retrieval was reliable but there must be some question over the pressure estimation when 11 µm residuals are high. More research would be needed to explore these questions and come to some short term expediency (which would probably be the ‘removal’ of one or more channels from the inversion). As we stated in WP4, the diagnostics of the retrieval provide insight into the ice optical properties but to operate in this way might be seen to be biased more towards basic research than towards the
production of operational cloud parameters.

4. A priori and model information

Much discussion has already been made regarding a priori and model information sources so we restrict ourselves here to comment regarding the adaptation of the studied methodology for SEVIRI.

4.1 Cloud fraction from the HRV channel

The study showed the importance of the independent estimate of the cloud fraction from the sub-pixel HRV channel. We recommend that this product from the SCA is evaluated in some detail. The error in the fraction derived from a sub-pixel source is not independent of the scene type nor is it independent of the cloud fraction itself. The demonstrated scheme used a single value for all scenes and fractions (except in deliberate experiments). It would be advantageous to evaluate the error as a function of these variables and to use the adaptive estimate in the inversion process.

4.2 Surface reflectance - scenes analysis product

An important part of the scene analysis is the fractional cloud estimation procedure after which see §4.1. The static data used (albedo etc) are crucial to the inversion accuracy over land.

The obvious adaptation of the tested methodology here is to use local values for surface reflectance rather than ‘image wide’ values. The scene albedo is the required value; the BRDF refers to a directional source and we can, for most clouds, consider the cloud−ground multiple reflections as more or less isotropic.

4.3 Surface emission database

Simulations showed that retrieval accuracy was not particularly sensitive to reasonable errors in surface emissivity. A basic emission climatology is therefore necessary but probably need not be

4.4 NWP atmospheric and surface definition

The MSG MPEF system makes use of the NWP fields of temperature and pressure and they are specified to sufficient accuracy. We do not see any major adaptation of the method used in the study regarding NWP fields. A consideration, however, is the diurnal cycle of land temperature which is not well defined by 6 or 12 hourly NWP estimates.

4.5 MPEF clouds analysis products

The cloud analysis product includes information on phase, optical depth, temperature (~pressure), height and fractional cover. Depending on how these are derived and the confidence that is attached to them, they should be used according to the rules given in section §3.7 of WP4. Cloud phase and the semi-transparancy flag can only really be used as first guess information. Cloud type may be used to set noise levels as described in WP2.1,2.2 and used in WP2.5 and 4. Optical thickness and cloud pressure (from the height or temperature) could be used as either a priori or first guess information but the derivation appears to use single pixel estimates and thus the same measurement information as the cloud parameter retrieval would employ. The use is therefore restricted to first guess.

Use of SCA and CLA information will probably considerably speed the inversion process and may add accuracy through less false solutions caused by poor first guess conditions.
5. Operational considerations

The main issues to arise regarding operational implementation are as follows; some are highlighted in the above discussion.

a) The availability of IR radiative transfer variables from the MPEF RTM.
b) The requirement for a VIS wavelength radiative transfer model.
c) The desirability of gradient versions of both the above; LUTs possible.
d) Additional verification procedures to monitor output diagnostics and products.

The cloud processor would operate well as a post-processor to the MPEF CLA operation. Extracting and simplifying from figures 2-2 and 2-3 of the MSG MPEF documentation the following figure 1 shows how such a processor (CPR) might link to existing modules.

![Diagram showing the simplified location of the cloud products processor (CPR) within existing MPEF structure.](image)

**Figure 1.** Simplified location of the cloud products processor (CPR) within existing MPEF structure

Boxes and link marked in solid are existing (in the MPEF). Boxes and links marked with a dashed line would be new. The cloud processor is labelled CPR and the required visible radiative transfer model as VIS RTM. The scenes analysis products and the IR RTM variables are supplied to the CPR as model parameters. Clouds analysis products are used in the CPR as either *a priori* constraints on the retrieval or to initialise the inversion procedure. The CPR itself produces products and diagnostics which are analysed over time to extract information on appropriate noise levels etc.
6. Product validation considerations

Cloud parameters retrieved from remotely sensed data are difficult to validate because of the lack of ‘conventional’ or in situ measurements. Even when in situ measurements are available they tend to be (e.g. from aircraft) sampled at a much higher resolution, with poor time coincidence and from (internal) parts of the cloud not measured particularly well by the remotely sensed data. The inhomogeneity of clouds in both space and time exacerbates these problems.

Regarding the validation of the state parameters employed in the retrieval described and demonstrated here, we can note the following.

**Optical depth, \( \tau \), drop size \( R_e \) and phase** can probably only reliably be validated using aircraft in situ measurements with the problems noted above. \( \tau \) is particularly difficult as it requires transit of the cloud from base to top with measurement of both particle size distribution and number density. The transit can take many minutes and necessarily covers a significant horizontal range during which the cloud can change character. Some clouds develop faster than others; stratocumulus convective overturning times are as short as 5-10 minutes and strongly convective systems are even more rapidly changing. However, the geostationary platform is well suited to allow for these changes and to obtain coincidence with aircraft observations. Aircraft measurements are of course expensive and offer results of limited coverage. \( R_e \) is probably easier to validate from an aircraft measurement, particularly in a cloud field with a relatively well defined and flat top. There are still difficulties since \( R_e \) has a vertical gradient in the cloud and the flight level needs to be compatible with the depth ‘sounded’ by the remote measurements or some adjustments made.

**Cloud top pressure, \( p_c \),** can be reliably obtained from ground based lidar measurements in the case at least of thin cirrus. The lidar systems also have the advantage that they can monitor continually and inexpensively although they are of course limited to sampling specific locations. The restriction to a particular cloud type is however a serious limitation. For the same type of cloud but more generally available, values estimated using TOVS sounding channels may provide useful validation data albeit of lower accuracy than from lidar.

**Fractional cover, \( f \),** may prove to be one of the easier parameters to validate. Ground based visual observations have been used and can provide large and readily available data sets. Their accuracy, or at least representativeness compared to the satellite measurements are doubtful however. Coincident observations by satellites with resolutions much higher than SEVIRI (e.g. SPOT, LANDSAT, AATSR, AVHRR) may be more powerful although the highest resolution (\(< 1 \) km) may be necessary to obtain useful validation data.

**Surface temperature, \( T_s \),** although part of the retrieved state vector used in the study, is unlikely to be a useful validation for the cloud parameters; information on \( T_s \) from SEVIRI is available largely when information on the cloud parameters is poor. It is also the parameter most constrained by a priori information and only over land is the retrieved value expected to significantly differ from the background value and land \( T_s \) values are very difficult to validate.

Time series consistancy of the retrieved values is not a validation as such, but nevertheless a useful check on the retrieved parameters. A certain degree of consistancy in values of \( R_e, p_c \) may be expected for the same location over a short interval of time (~fraction of an hour). Less or even no time consistancy can be expected for \( \tau \) and \( f \).
APPENDIX A Reviewed BIBLIOGRAPHY (WP 1.1)


[12]Crystal size, shape and IWP retrieval using ATSR observations of Tropical anvil cirrus at 0.87 and 1.6 µm. 1996. Baran A.J. Watts P.D.


[37] Information content of AVHRR channels 4 and 5 with respect to the effective radius of cirrus cloud properties. 1991 Parol F. Buriez J.F. Brogniez G. Fourquart Y. *J.Appl.Meteor.* 30 p973


APPENDIX B BIBLIOGRAPHY (not reviewed) (WP 1.1)


(11) Validation of ISCCP cloud detections Rossow W.B. Garder L.C. Journal Of Climate, 6, 12, P2370-2393


(13) The international-satellite-cloud-climatology-project (ISCCP) the 1st project of the world-climate-research-programme. 1983. Schiffer R.A. Rossow W.B. Bull. Amer. Met Soc. 64, 7, p779-784


(20) Determination of scaled optical thickness of clouds from reflected solar radiation measurements. King M.D. *J. Atmos. Sci.* **47** p1734-1751


(41) Microphysical characteristics of three anvils sampled during the Central Equatorial Pacific Experiment. 1996. McFarquhar G.M. Heymsfield A.J. *J. Atmos. Sci.* 53 17 p2401-
(43) A parameterization of the particle size spectrum of ice clouds in terms of ambient temperature and the ice water content. 1984. J. Atmos. Sci. 41 p846-
(54) Two-stream approximations to radiative transfer in planetary atmospheres: a unified description of existing methods and a new improvement. 1980. Meador W.E. Weaver W.R. J. Atmos. Sci. 37, p630-
(56) Studies of the radiative properties of ice and mixed-phase clouds. 1994. Sun Z. Shine K.P. Q. J. Royal Meteorol. Soc. 120 515 PtA, p111-


Appendix A Bibliography Review: Keyword assessment and comments

List of abbreviations:

<table>
<thead>
<tr>
<th>Type of Platform</th>
<th>GEO - Geostationary; LEO - Polar orbiter (Low Earth Orbit); A/C - Aircraft; G/B - Ground based</th>
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<tr>
<td>Type of instrument</td>
<td>RAD - Radiometer; SPECT - Spectrometer; INTER - Interferometer</td>
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<tr>
<td>Wavelength(s)</td>
<td>VIS - Visible 0.6 to 0.8 µm region; NIR - near infrared 1.6 µm; SIR - Solar Infrared (3.7 - 3.9 µm); WV - Water vapour channel 6 - 7 µm; IR8 - Thermal infrared 8.3 - 8.7 µm; IR11 - Infrared 11 µm window.</td>
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<tr>
<td>Type of Analysis</td>
<td>DETECT - Cloud detection; PROP - Cloud property retrieval</td>
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<tr>
<td>Methodology</td>
<td>STAT - Statistically-based retrieval; PHYS - retrieval based on real-time radiative transfer; NEUR - neural network based retrieval; TEMP - Temporal information used; SPTIAL - spatial information used.</td>
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<tr>
<td>Data Status</td>
<td>REAL - Real measurements available; SIM - Simulated measurements only; VALID - Validation data available</td>
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<tr>
<td>Auxilliary</td>
<td>NONE - No auxilliary data requirements; NWP - Numerical Weather Prediction model information used; CLIM - Climatological/archive data used; SND - local/non-local sonde data used.</td>
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*, (*) Key aspect of paper; incidental aspect of paper
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<td></td>
<td>Near global survey of effective droplet radius in liquid water clouds using ISCCP data, 1994, Han Q. Ros- sow W.B. and Lacis A.A. <em>J.of Clim</em>. 7 p465-</td>
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Summary: Global (±50°) survey using AVHRR data. ISCCP cloud cover combined with TOVS temperature and humidity and prior analysis of surface temperature and reflectance. Liquid water clouds determined as Tc<273.2. LUTs used. Methodology is to remove unwanted radiative effects (e.g. thermal in 3.7µm) rather than to solve explicitly for all effects.

Comment:

Visible and infrared cloud properties are consistantly retrieved. Retrieval system (p470) should be examined as potential guide for MSG

Key paper? ☑
Summary: Selection of cloud-free and therefore surface parameters by cluster analysis. Determination of microphysical model (4 categories) by best agreement with simply inverted radiances at 3.7 and 11 µm and vis: vis+11 µm inverted for Tc and τ and each microphysical model; best fit gives model.

Clusters are identified by local density increase (in 3.7/11µm space) and are attributed to fully cloudy pixels of different cloud types. Remaining data is adjusted to the nearest (+most attainable) cluster by adjusting cloud fraction.

Comment:
Ice spheres are assumed. Broad microphysical model rather than particle size retrieved and this is assumed constant within a large sample area. Tc, τ and cloud fraction allowed to vary. Optical effects of atmosphere are neglected.
The retrieval of total optical depth and effective radius of clouds from solar reflection measurements using the Along Track Scanning Radiometer −2 (ATSR−2), 1995, Evans S.J., Haigh J.D. *Geophys. Res. Lett.* 22 no. 6 p695-698

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**Summary:**

Simulation study of retrieval of $Re$ and $\tau$ from ATSR 0.55 (vis) and 1.6 (NIR) nadir (0°) and along-track (55°) measurements. Suggests that the small $Re$ ambiguity problem is removed by use of dual-look.

**Comment:**

Interesting normalisation of 1.6µm measurements in Chi-squared - to reduce effect of surface reflection. Suggest investigate.

**Key paper?**
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**Summary:**

mainly a study of the benefit of adding µ-wave LWP measurements to avoid cloud homogeneity problems retrieving optical depth from vis measurements. But it contains useful information on effects of these cloud inhomogeneities. Gives good back references to the Foot, Rawlins, Taylor papers.

**Comment:**

| Key paper? |

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<td>Principally and argument for the non-Mie treatment of ice crystal infrared interaction. Retrieval is using manually found Tc and Ts and Tropical convective systems. Non-scattering(?) simple RT model used to retrieve optical depth at 8.3 and 11 µm, this ratio compared to absorption efficiencies to retrieve particle size.</td>
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<td>Useful demonstration of 8.3 µm data in use as cloud particle size estimator.</td>
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**Summary:**

Demonstration of size measurement capability of cirrus crystals using 8–12 µm measurements. Not a demonstration that the 8 µm region is particularly useful and suggests that transmission modelling is important for interpretation.

Only a very basic retrieval done.

**Comment:**

Claims ADT shown to be more appropriate than Mie for ice but not clear at brief reading how this is shown.

**Key paper?**

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**Summary:**

Demonstration of habit and then size retrieval of tropical ice clouds. Dual view required for habit determination by sampling scattering phase function. Size from vis/NIR method but basic retrieval method (manual).

**Comment:**

Key paper?
Paper no.: 8  

Journal spec:


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Summary:

Uses time varying solar illumination available to GOES VISSR instrument to decouple the solar and thermal radiance at 3.9 µm.

Comment:

Implies stationary (in time and space) cloud fields but worth considering?

Key paper?
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<td>Mainly a review paper and very useful as such. Adjustment procedure for marine SC correction of Re to A/C flight level. VIS/NIR method discussed, VIS/NIR/SIR/IR method mentioned. Cirrus detection / size estimation using IR8/IR11 also discussed, ice spheres used. Phase (ice) identified if Bi- and multi- spectral methods give different Re. Also demonstrates the 1.6 ( \mu \text{m} ) channel for this. Textural differences claimed useful. (Cloud, aerosols and water vapour also dealt with in some detail.)</td>
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<td>Comment:</td>
<td>Uses asymptotic theory (analytical) for ( \tau &gt; 8 ). LUTs for ( \tau &lt; 8 ). References p8 col 2 for phase identification methods using multi-spectral and p9 col 1 for same using textural</td>
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**Journal spec:**

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**Summary:**
Demonstration of retrieval of cirrus (phase) particle size and optical depth from VIS/NIR methods; habit from dual view; height from dual view; temperature from dual view IR11

Summary statistics of particle size in several anvil cases.

**Comment:**

<p>| Key paper? |</p>
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**Summary:**

Demonstration of phase id based on 1.6 µm reflectance with 0.87 µm. Demonstrates also a viable inversion method using steepest descent and Newtonian iteration and quality control information arising from these.

Cloud height from parallax also discussed.

**Comment:**

Key paper?
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<tr>
<td>Crystal size, shape and IWP retrieval using ATSR observations of Tropical anvil cirrus at 0.87 and 1.6 ( \mu \text{m} ). 1996. Baran A.J. Watts P.D. Foot J.S. Mitchell D.L.</td>
<td>IRS '96 Current problems in atmospheric radiation.</td>
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Summary:
Demostrates dual view determination of habit determination and shows size dependency effect. Sensitivity of IWP calculations to crystal shape shown.

Comment: | Key paper? |
Paper no.: 13

Journal spec:


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Summary:

Dual view ATSR data at 3.7 and 11 µm used via 2-stream radiative transfer for analytical solution for optical depth at both wavelengths. Assuming hexagonal columns. Comparisons with full radiative transfer code made. Crystal size assumed. ADT optical properties assumed.

Comment:

Night-time data only.

Key paper?
Area-based retrieval of cirrus $\tau$, $T_c$ and $R_e$ using 3.7, 11 and 12 $\mu$m AVHRR LAC and GAC. FIRE region. Retrievals made during daytime (but 3.7$\mu$m use depends on nighttime or large particles so that reflection negligible). Mie theory and Eddington (2-Stream) used. Envelope in 11,12 $\mu$m space is fitted to theory using some iterative scheme. Assumes overcast (semi-transparant) cloud and therefore the higher the data resolution the better.

Supporting evidence for the use of 8$\mu$m data re cirrus retrievals is presented. Suggests much larger particle size (~200$\mu$m) is discernable compared to 3.7 or 11,12 $\mu$m pairs. (This conflicts with other refs?)
### Summary:

Parameterisation of VIS and IR radiance calculations. VIS as LUT for 4 microphysical models and includes Rayleigh scattering and ozone and other gaseous absorption. IR emittance is parameterised in terms of the VIS optical depth and viewing angle and is by regression.

### Comment:

May be useful for parameterisation methods and gives insight into radiative transfer.
<table>
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<tr>
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<tbody>
<tr>
<td>Inference of Cirrus cloud properties using satellite observed visible and infrared radiances Part II: Verification of theoretical cirrus radiative properties, 1993 Minnis P Heck P.W. Young D.F. <em>J.Atmos Sci.</em> <strong>50</strong> 9 (see paper #15)</td>
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**Summary:**

Partly a demonstration using multiple satellite bases that cirrus optical properties best described by non-spherical hydrometeors. Brief summary of retrieval scheme (described in detail elsewhere) Radiative parameterisation described in companion paper (#15 here). Clear sky VIS and IR radiances obtained. Histogram analysis of VIS/IR to classify broadly the cloud type (sonde used). Some strange summations take place; the methodology is not clear, earlier references may be more so. Appears that principle parameters retrieved are microphysical model, vis and thus IR optical depth and cloud height and temperature.

**Comment:**

Stresses importance of considering 'dark pixels': shadowed.

**Key paper?**
Wide area determination of cloud microphysical properties from NOAA AVHRR measurements for FIRE and ASTEX. 1995. Nakajima T.Y. and Nakajima T. *J. Atmos. Sci.* 52 23 p4043-

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Summary:

Thorough demonstration of cloud Re, τ retrievals from AVHRR 0.6 and 3.7, 11 µm data; and validation against a/c measurements. Iterative procedure linking VIS optical depth and thermal transmission through RT and LUTs. Slightly clumsy iterative procedure and ‘undesirable’ radiance components are removed rather than general inversion method used. Validation restricted to marine Sc. A little lacking in detail over algorithm.

Comment: Interesting comments on utility of 3.7µm measurements compared to 1.6 and 2.2 µm (in terms of calibration accuracy etc). The algorithm needs to assume a cloud type (for LWC) and surface albedo (which may be assumed to be spectrally invariant VIS/IR??). Mentions profiling capacity of 1.6,(2.2) and 3.7 µm. Scatter plots seem to show significant Re errors for τ < 5.

Key paper?  ✓ (for 3.7µm)

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Summary:
Detection based on a simple 3.7–10.9µm BT difference > 2K. Properties retrieval method developed by Ou 1993 Appl. Opt. 32 2171-2180; using thermal transmission rather than reflected radiation. Solar component removed by parameterised relation between 0.6 and 3.7µm reflectances. Simple transmission equation at 3.7 and 12µm inverted using iterative procedure and emmisvities parameterised from geometric optics optical properties: hence crystal size estimation. Upwelling radiance estimations required.

Comment:
See Ou 1993 for details? Probably some good validation data in this paper (#18).
### Summary:

Demonstration using HIS of a tri-spectral method for obtaining information on cirrus optical depth, temperature and particle size. No real retrieval methodology presented.

### Comment:

Useful plots of typical 3.7, 8, 11 and 12 μm measurements and relations over cirrus.
**Summary:**

Parameterisation of optical properties of cirrus using size distribution, shape and wavelength. Based on ADT.

Albedo and emissivity shown to vary by factor of < 2 depending on crystal shape.

**Comment:**

May be a critical source of optical properties for ice clouds.

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Summary:

Uses Mie theory to show effective emissivity of cirrus should be same to within 6% for 6 and 11 micron radiances. Then, ignoring above cloud absorption, the cloud temperature can be established with several pixels because of linear behaviour. Does not continue to derive optical. The method appears to circumvent establishing upwelling radiance at cloud base by using the spatially distributed data.

Comment:

A somewhat basic paper by more recent standards but does employ the WV channel. Worth pursuing because 6 µm does not have solar component. Check MSG ASD document for work following this method.
A method for remote sensing the emissivity, fractional cloud cover and temperature of high level, thin clouds. 1987, Wu M.C. *J. Clim. and Appl. Meteor.* **26** 2 p225-233

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Summary:

Bi- or tri-spectral technique. Bi-spectral can retrieve temperature and emissivity (through optical depth) if upwelling radiances are known and the size distribution is assumed. Tri-spectral can in principle retrieve fractional cover as well: microphysical model is assumed to relate $\varepsilon_1$ to $\varepsilon_2$ or $f\varepsilon_1$ to $f\varepsilon_2$. Method at first appears to use spatial data and scence analysis after Coakley et al. but is in fact independent pixel (having made assumptions) and is principally simulation study. The method is applied to HIRS data and shows realistic results. Based on Mie simulation of a C1 cloud.

Comment:

Problems encountered with real data not discussed: underlying cloud and upwelling radiance.

Presume the study was limited to night-time HIRS data.
Cloud top phase determination from the fusion of signatures in daytime AVHRR imagery and HIRS data. 1997 Hutchison K.D. Etherton P.J. Topping P.C. *Int. J. Remote Sens.* **18** p3245-

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**Summary:**

Improvements to thin cirrus detection in AVHRR using geometry dependent reflection test (0.7, 1.0 μm). Further test on ambiguous pixels uses 3.7 and 11 μm BTDs. CO2 slicing from TOVS also employed. Manual validation using nephanalysis.

**Comment:**

Simple relationships based on (sometimes) radiative transfer calculations. Useful information on *detection* not property retrieval. (But correct detection may be crucial to correct property retrieval.)

**Key paper?**
**Summary:**

Inversion for optical depth from ground based VIS measurements using non-linear least squares and adjoint coded discrete ordinates method (see comment). Surface albedo from clear sky reflection (aerosol + rayleigh). GOES retrievals from Minnis et al. 1995 NASA reference pub p1366.

Also sometime use microwave LWP to obtain also the effective radius.

**Comment:**

Delta-Eddington 2-stream used but as simple proxy for more ordinate calculations.

Simulation study of the remote sensing of optical and microphysical properties of cirrus clouds from satellite infrared measurements. 1995 Xu L. Zhang *J. Appl. Opt.* 34 15 p2784-

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**Summary:**

Starts with simulation of optical depth given a standard cloud which shows the sensitivity of basic parameters to habit. Then calculates BTs again showing habit dependence. Retrieval of optical depth, IWC and habit from 3.9, 13.3, 11.2 12.6 µm VAS channels: *statistical* method based on radiative transfer calculations. Column/plate discrimination suggested using two DBT differences: 11.2/13 and 3.9/12.6. Error analysis follows, sea surface reflection (using Masuda). Atmospheric effects appear to be largest through errors in temperature rather than humidity.

**Comment:**

Bimodal size distribution used. Ray trace optical properties used. Compares Mie and ray optics results and notes sensitivity to this. Suggest switch from Mie to RO for sizes > 70 µm

**Key paper?**
**Paper no.: 26**

**Journal spec:**


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**Summary:**

Amalgamation of HIRS for cloud top pressure (CO2 slicing) and AVHRR for scene analysis. Spatial coherence tests to obtain clear sky radiances. Normal Mie/Re calculations for water clouds and hexagonal columns for cirrus at 3.7 and 10.8 µm; but spherical model (Mie) used for small size parameters. DISORT used. Much discussion of BTD behaviour with conditions. Conclusion: Some apparent signal on multilevel cloud but very difficult to unravel and not necessarily unique.

**Comment:**

Good reference for multi-layer cloud analysis; nighttime only.

**Key paper?**
Summary: Simulation of the 8-11µm window effects by cirrus. Comparison to AVHRR/HIRS/MAS data. Particle absorption is a minimum at 8µm and atmospheric absorption is a maximum. Opposite is true at 12µm; therefore BTDs give information on cloud properties. Details depend on exact spectral regions used. Scatter of 8-11 against 11-12µm shows slope > 1 for cirrus. Gives useful table of thresholds on DBTs and standard deviations and BTS for cloud classification (these empirically derived for a particular scene/day - RT calculations and NWP fields could perhaps give real-time thresholds?) VIS/NIR delineates phase more completely (daytime only!) when no multiphase cloud is present. BT method is more robust in mixed scenes. In this regard, the HIRS fov is too large and screening is necessary.

Comment: Mie or infinite cyclinders used in simulations; no significant difference observed. The regions used are 8.3-8.4, 11-11.25µm and 11.9-12µm. Method also seems to work as well for 8.4-8.5 and 8.5-8.6µm (the latter better because of less H2O absorption). A broad 8-8.8µm also works. Careful choice of the 12µm window required. Typical 8-11µm DBTs of < 4 K. No automated scheme presented apart from simple thresholds.

Key paper? ⬤ for 8-11/12 thresholds/behaviour
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Summary:

Delimeation of cloud shapes (areal). No reference to cloud microphysics. Empirical thresholds and neural nets employed. Claims that neural nets are superior to (their own) use of stepwise discriminant analysis.

Comment:

Potentially useful to segment images before standard thresholding?  

Key paper? 

### Summary:

Analysis of 11/12µm scatter diagrams for features (feet etc) and fitting of theoretical curves (Mie). The scatter arch of 11/12 is affected by changes in upwelling radiance (i.e. H2O, T(p)); Cloud temperature; particle size and fractional cover. This paper fits an envelope to the whole (outside of the) scatter which corresponds to the highest absorption difference (smallest particles), to overcast pixels, to the warmest upwelling radiance, and to the coldest cloud.

### Comment:

Some interesting discussion on the results of their survey of 21 AVHRR images regarding particle size. A threshold around 235 K found where the size changes abruptly. Peraps a reasonable demonstration of spatial method for 11/12 pair.

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**Key paper?**
Cloud property retrieval using merged HIRS and AVHRR data. 1992, Baum B.A. Weilicki B.A Minnis P

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Summary: Cloud top pressure from CO2 slicing, AVHRR used to specify cloud fraction in HIRS fov. Emittance from HIRS IR and reflectance from AVHRR VIS is used is used to show ice hexagonal crystals fit much better than ISCCP Mie (FIRE region data) on some occasions, but on others appear to fit neither. Sondes available for atmospheric specification. Two ‘CO2’ slicing algorithms examined. AVHRR derived cloud fraction uses comparison of IR channel against radiative transfer calculations based on the sonde (comparisons of cloud pressure made also). Cloud bidir reflection obtained with a correction to the measured VIS values for surface reflection effects. Surface reflectivity from a measured in situ value (?)

Comment:

Shows that the high resolution AVHRR can significantly aid retrieval from the low frequency sounder. General principles and demonstration of microphysical dependence of data; but no retrieval strategy given.

Key paper?
### Summary:

Tests of sensitivity to assumptions: No. Legendre moments used to represent the phase function (see below); Spheres or hexagons; Equivalent volume/area spheres [composite spheres (SSA from one; extinction efficiency from the other) suggested]; surface type.

Useful reference on the expected effect of some of these parameters but be wary of the scary legendre moments!

### Comment:

DISORT used. Interesting but surely not entirely relevant way of assessing #terms in legendre expansion of phase function. Measured by rms error of phase function itself and leads to vast (>100) terms required to get rms < 10%. With multiple scattering and high IR absorption, isotropic source terms, the details of the peak phase function are not required for cloud properties?! (This seems to be confirmed by their fig C1 showing Bt errors < 1K for 20 terms in the expansion.) Could be relevant for solar transmission measurements.

### Key paper? 🕵️

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### Journal spec:
Removal of solar component in AVHRR 3.7 µm radiances for the retrieval of cirrus cloud parameters. Rao N.X. Ou S.C. Liou K.N. *J. Appl. Meteor.* **34** 2 p482-

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### Summary:
Scheme to estimate 3.7µm reflectance by cirrus by comparison to the 0.6 µm reflectance. Based on hexagonal columns and plates. Removal of reflectance terms allows the usual bi-spectral treatment of transmission / emission.

FIRE data examined and retrievals appear to be good.

### Comment:
Why? A joint retrieval is surely implied and even effectively done, so why not to it explicitly? IF, for some reason, the explicit removal of the solar component appears to be a good/ necessary approach, then this paper may offer clues. As is, it seems a clumsy approach.

### Key paper?
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**Summary:**

Demonstration using HIS data of 8-12 µm window usefulness in detecting and sizing of cirrus.

**Comment:**

(See #27 for more up to date and comprehensive study on this by related authors.)

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**Summary:**

Early demonstration using Landsat of 1.6 and 2.2µm (+0.8µm) retrieval of Re. (First part of paper deals with VIS/IR reflectance /emittance ratios). Evidence of non-spherical ice particles. Supports more the VPP (lab) phase function rather than hexagonal column function. Large discrepancy between VIS/NIR Re (60µm) and a/c in situ (200µm) attributed to a) refractive index b) phase function  c) particle sampling (>20µm) by a/c.

**Comment:**

Status of refractive index of water at NIR wavelengths worth investigating. Calculations used Mie, VPP and Henyey Greenstein phase functions.

**Key paper?**

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Summary: Retrieval of cloud top temperature; cloud center temp (!); cloud top, center heights and depth (!); cloud emittance and VIS optical depth from GOES VIS/IR and AVHRR 11/12µm. Assumes scene identification done. FIRE data. Hex columns of one size used (Albedos calculated but anisotropy taken from empirical factor measured; see previous paper Minnis et al. *Mon. Weath. Rev.* **118** p2402-). Inverts iteratively the VIS reflectance where VIS optical depth the only variable. Scene underlying albedos effectively pre-measured. Temperatures inverted from transmission equation where emissivity is estimated from the VIS optical depth assuming VIS $\tau$/IR $\tau = 2.17$ (from earlier FIRE results). Empirical relationships established from FIRE lidar / sat results (previous paper in issue as above) lead to cloud top (rather than center) temperature and thickness / height.

Comment: Very high accuracy of heights (0.6 Km) considering the empirical nature of the estimation - due to local area/ situation dedicated fit? Conclusions section supports this and suggests globally applicable method would need theoretical cloud BRDFs. VIS/IR optical depth ratio (~2) is crucial link in operational algorithm e.g. Rossow ISCCP.

<p>| Key paper? | ✔️ for a fair amount of useful insight. |</p>
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**Summary:**

Overview of ISCCP algorithm. Quite basic - relies on climatological environmental parameters and radiative transfer calculations based on water Mie 10µm for optical depth estimation. Clear scenes detected on one pass through data; second pass give cloud parameters.

**Comment:**


**Key paper?**
Information content of AVHRR channels 4 and 5 with respect to the effective radius of cirrus cloud properties. 1991 Parol F. Buriez J.F. Brogniez G. Fourquart Y. *J.Appl.Meteor.* **30** p973-

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<td>Analysis of brightness temperature relationships with microphysical dependence. Check effects of cylinders against sphere and suggests significant differences. Inoue method (non-scattering) can be used if effective emissivity is employed where scattering is implicit. This effective emissivity depends weakly on view geometry. In comparison with data the cylinder simulations appear poor. They suggest the 11 /12µm combination is not sufficient for size determination when the particle shape is not constrained.</td>
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Summary: nighttime retrieval of temperature, size, optical depth of cirrus using 3.7 and 11μm AVHRR radiances. Detection by DBT>2 K. Effective emissivities (to account for extinction properties and multiple scattering effects) linked by radiative transfer calculations using hexagonal columns for a variety of observed size distributions. These (emissivity factors) are linked to particle size via an empirical relation and the size D is linked to cloud temperature by another. Hence closure so that effectively only optical depth and temperature are retrieved. (However, by linking in this way the emissivity ratios etc are at least broadly consistent.) Clear pixels needed for upwelling radiances. FIRE data validation.

Comment:

No daytime capability, but extendable? Size, temperature, effective emissivity relationships could be useful.

See Ou and Liou IRS ’96 for updated version regarding two layer cloud systems.

<p>| Key paper? | ✓ |
| Model working scheme for 3.7/11 + params. |</p>
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**Summary:**

Extension of classification system described in [40] to include VIS/IR local slope angles (analysed by principle component). Appears to increase classification accuracy.

**Comment:**

Addendum to Seze G. and Debois [40] paper.

**Key paper?**
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<td>Cloud cover from satellite imagery using spatial and temporal characteristics of the data. 1987. Seze G. Debois M. <em>J.Clim. Appl.Meteor.</em> <strong>26</strong> 2 p287-</td>
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**Summary:**

Description of classification system based on VIS/IR histograms and local variations (sds) for determination of cloud types and surface variables. Temporal behaviour used. Daytime and for one time of day (local 12). Information on averaging scale and time series lengths required for reliable estimates. Classification into around 10 scene types. ‘Validated’ against nephanalysis.

**Comment:**

Classification could prove essential for following property retrieval and this and [39] could provide basis if not already covered by MSG ASD.

**Key paper?** ✅

for classification using Meteosat

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**Summary:**

Study, mainly simulation, of the bispectral (VIS/IR) signatures of clouds, water, ice, multilayer (2), broken (in sense of fractional cover). Mie and cylinders used. Comparison with histograms from GMS VISSR data.

**Comment:**

Early paper, superseded in some respects. But good insight on effects mentioned.
### Summary:

Retrieval using 1.0 and 1.55 µm reflectance pair for phase, Re and cloud optical depth. Comparison of effects of using spheres, columns, plates and polycrystals in retrieval. Validation of Re against FSSP values shows only polycrystal pase function gave agreement with data. Re values corrected to flight level using simulated situations.

### Comment:

Supports polycrystal phase function choice.
A four channel method for deriving cloud radiative properties from meteorological satellite data. 1996 Young D.F. Minnis P. Smith W.L.Jr Gerber D.P. IRS '96 Current problems in atmospheric radiation. Deepak, p 612

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Summary:

Study on ambiguous Re, optical depth retrievals using 3.7, 11 and 0.6 μm daytime data. Suggests that use of 12μm data also will constrain the problem to remove some ambiguity. Not developed fully in short paper and not explained too well.

Comment:

Questionable how ambiguities of the size they suggest arise. They stress the backscatter region (3.7) is the problem area and this may be the small Re ambiguity problem except they suggest Res up to 12μm may be affected. Need to check whether our known ambiguities with 1.6μm data (Re<4μm ) are similarly affected or circumvent this problem.
EUMETSAT MSG cloud parameter study: WP 1.1 Bibliography, APPENDIX B


(11) Validation of ISCCP cloud detections Rossow W.B. Garder L.C. *Journal Of Climate*, **6**, 12, P2370-2393


(20) Determination of scaled optical thickness of clouds from reflected solar radiation measurements. King M.D. *J. Atmos. Sci.* **47** p1734-1751


(38) Parameterization of tropical cirrus ice crystal size distributions and implications for radiative transfer: results from CEPEX. 1997. McFarquhar G.M. Heymsfield A.J. J. Atmos. Sci. 54 p2187-


(41) Microphysical characteristics of three anvils sampled during the Central Equatorial Pacific Experiment. 1996. McFarquhar G.M. Heymsfield A.J. J. Atmos. Sci. 53 17 p2401-

(43) A parameterization of the particle size spectrum of ice clouds in terms of ambient temperature and the ice water content. 1984. *J. Atmos. Sci.* 41 p846-


(54) Two-stream approximations to radiative transfer in planetary atmospheres: a unified description of existing methods and a new improvement. 1980. Meador W.E. Weaver W.R. *J. Atmos. Sci.* 37, p630-


(56) Studies of the radiative properties of ice and mixed-phase clouds. 1994. Sun Z. Shine K.P. Q. J. Royal Meteorol. Soc. 120 515 PtA, p111-


Figure A2
Figure A3
Figure A4
Figure A5
Figure A6
Figure A8
Figure A9
Figure A11
Figure A14
Figure A15
Figure A16
Figure A17
Figure A18
Figure A19
Figure A20
Figure A21
Figure A22
Figure A23
Figure A24
Figure A25
Figure A26
Figure A27
Figure A28
Figure A29
Figure A30
Optical depth

- $S_M$: Measurement
- $S_N$: Null space
- $S_N + S_M$: Total
- $S_b$: T/H(z)
- $S_b$: Rs
- $S_x$: A priori

Particle size m

Pressure mb

Fraction

Skin temperature K

Error K

Equiv. Meas. error: T/H(z)

Equiv. Meas. error: Rs

Figure A31
Figure A33
Figure A36
Figure A37
Figure A38
Figure A39
Figure A40
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**ATSR–2 Case no. 1**
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Sun_zen 50°
Rel_azi 50° − 110°
Scene type Sc, clear ocean, clear land
Channels: 0.6 0.8 1.6 3.7 8.7 11 12

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Rel_azi –
Scene type Sc, broken Sc, overlying Ci
Channels: 0.6 0.8 1.6 3.7 8.7 11 12

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SunZen 55°
RelAzi 40° − 130°
Scene type: Land, ocean, sea ice, St
Channels: 0.6 0.8 1.6 3.7 8.7 11 12

 ATSＲ−2 Case no. 9
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ATSR–2 Case no. 10
Figure 4.1.1
Figure 4.1.2
Along Track

S: Optical depth - Active

S: Particle size m - Active

S: Pressure mb - Active

Along Track

S: Fraction - Active

S: Skin temperature K - Active

Across Track

Figure 4.1.3
Figure 4.1.5
沿着轨向和横轨方向的对数光学厚度、有效粒子尺寸、压力和皮肤温度的分布。图4.1.6
Figure 4.1.7
Figure 4.1.8
Figure 4.1.9
Figure 4.1.10
Figure 4.1.11
Figure 4.1.13

ATSRPW$DKB300;[WATTS.MSG];LANDSEA3_2.RET;2
Figure 4.1.15
Figure 4.1.17
Figure 4.1.18
Figure 4.1.19
Figure 4.1.20
Figure 4.1.23
Figure 4.1.24
Figure 4.1.25
Figure 4.1.27
Figure 4.1.28