# TOWARDS A COMPREHENSIVE APPROACH TO PRODUCT GENERATION FROM METEOSAT IMAGERY

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**Abstract**

In this paper we argue that complete fields (all pixels, cycles) of geophysical variables measured by geostationary imagers serves to supply more accurate boundary conditions for product generation than is available from the analogous completion of NWP fields (and other auxiliary data) alone. We suggest that the completion is an analogous operation to the use of NWP data and could be achieved using simple linear filters and demonstrate this with one simple example. The full power of the approach becomes available with a comprehensive system where all relevant physical variables are jointly available as completed fields and associated error estimates. Such an assimilation-type approach views, and aims to maximise information retrieval from, the geostationary data set as a whole.

An implementation of such a comprehensive system would require significant research effort and a substantial shift in the current notion of independent product algorithms and is therefore more suited as a preparatory activity for MTG rather than development activity for MSG. The current SEVIRI of course provides the best available test data.

## INTRODUCTION

This discussion paper sets out the rationale for adopting an integrated approach to geophysical product derivation from geostationary platform imagery, with reference to the current MSG SEVIRI measurements. It suggests that the best use of geostationary data demands that we regard the extraction of ‘products’ not as a collection of individual separately executed algorithms operated on individual image cycles, but as a consistent and continuously updated analysis of a sequence of images.

The basic underlying reason for this demand is that, as with any remotely sensed data available to date, SEVIRI measurements alone do not completely determine the geophysical parameters within an observed pixel. This is certainly true, and the related statement that a restricted sub-set of SEVIRI measurements cannot determine a sub-set of parameters with optimal accuracy we believe is also true in the vast majority of cases.

Consequent to this information deficit is the need to import boundary information (e.g. NWP fields). We argue in this paper that the current emphasis on individual product algorithms (IPAs) operating on individual images means that these boundary conditions are heavily relied upon, much more so than is necessary given the total information content of the entire SEVIRI measurement record. A direct analogy comes from the NWP area itself. If weather forecasts were to be based solely on the, albeit impressive amount, of data available at the analysis time, they would be much poorer. Instead, the analysis relies heavily on the accumulation of information from previous measurements. In NWP this information is propagated forward with an extremely expensive and sophisticated atmosphere model. In the case of geostationary satellite data product generation nothing like so much is required or desirable, but the principle is the same. The information available at an image cycle can be propagated forward and made available at the next cycle. With this type of information propagation, the entire SEVIRI measurement set is analysed ‘in one go’ as it were. Because of this much more optimal use of the measurement data, the reliance on boundary information is reduced.

In this paper we attempt to describe the characteristics of single pixel IPAs and set them in the context of a complete description of the geophysical parameters relevant to MSG observations. We argue that by ‘completing’ the picture in time and space, there are benefits to both products and product generation. The technique and benefits are illustrated using, because of space restrictions here, a single worked example, in SST. This example is necessarily limited in its scope. Finally we briefly discuss other possible benefits arising from the use of the techniques to complete product fields.

## SINGLE PIXEL LIMITATIONS

Within a single pixel, single cycle observation there are 11 SEVIRI channels measurements available (not including the HRV channel). These are not generally 11 independent measurements but include some redundancy. In any case, depending on the scene contents (e.g. predominantly cloud, predominantly clear land etc), a variable number of independently estimated parameters are available. For example, if a pixel is fully covered in cloud, then the measurements predominantly contain information on cloud parameters and very little on aerosol or surface characteristics. There may be some limited humidity and ozone information. In cloud free pixels, much more information is available on surface properties, humidity and skin temperature for example. What is sometimes overlooked from the IPA perspective is that simply categorising a pixel as, e.g. cloudy, does not remove the fact that there are uncertain humidity, surface temperature, ozone etc, variables within the pixel. The IPA concept is that once a pixel is categorised, the uncertain parameters are either supplied with values from boundary condition data, or, individual channels that depend strongly on a poorly observed variable are omitted from the operating IPA. We can draw an example from a Eumetsat prototype Optimal Estimation (OE) Day-2 cloud algorithm, OCA, where cloudy pixels are processed. It is assumed that if a pixel contains cloud, then cloud effects dominate measurements and surface parameters, ozone, aerosol and humidity cannot be coincidently estimated. The IPA concept is employed by two tricks, exampled here;

a) Omitting water vapour channels because errors in boundary water vapour estimates lead to forward model errors of several K, thus precluding any useful contribution to the cloud estimates. The ozone channel is similarly ‘dismissed’.
b) Assuming zero (or at best climatological) aerosol loading. This is acceptable at least because most aerosol is usually below cloud level and weak in radiative effect in comparison.

Channel omission as in a) leads to sub-optimal pixel retrievals because the information (on cloud in this case) is lost. Omission is a harsh form of down-weighting and in the context of strict application of OE, the channel could be retained with its assumed error raised to account for the effect of the (erroneous) boundary conditions. In practice, it would currently come to the same thing: water vapour channel errors would be around 1-3 K and their resulting weight in the OE insignificant compared to other channels. Because of the difficulty in assigning complex scene dependent errors to channels, and the ultimate negligible effect on the results, the channel ‘Omission’ method is clearly preferred!

Ignoring effects, as in b) above, is the second common ‘trick’. Of course it works to a certain approximation depending on the scene. Ignoring aerosol as in the example is of no consequence when deep convective clouds are observed, but of some consequence when a partially filled scene of stratocumulus is observed.

The question is whether this lack of sufficient boundary information is a fundamental problem that can only be overcome by appealing to better sources of external (to SEVIRI) information. Perhaps there are just some parameters that are so poorly measured that we will always have to supplement the measured imagery. The answer is not clear cut of course but there is the argument that if a parameter significantly affects SEVIRI measurements, it is likely that there is a chance it can correspondingly be estimated from the measurements, *at least when the scene type permits it*. Therefore, continuing to use the example above, if aerosol levels can affect measurements used for cloud estimation, then, in clear pixels, there must be a chance of estimating aerosol levels. Since clear and cloudy conditions are not available within the same pixel, then cloud and aerosol products are available in exclusive regions / times.

## SCALES OF INFORMATION

The 15 minute repeat cycle of SEVIRI measurements is a relatively high rate with respect to most geophysical parameters. This is no accident; it is set by meteorological requirements. Consequently, the value of most parameters at a pixel in a particular cycle will be more or less strongly auto-correlated with the value at the previous cycle. The degree of correlation will depend on the situation and the parameter. Clouds, for example will show high correlations in stable anticyclones and very low correlations in rapid convective conditions.
Similarly, the SEVIRI sampling of ~3 Km at SSP gives relatively high resolution with respect to atmospheric parameters (temperature and humidity) and lower resolution compared to surface parameters (albedo, emissivity). Figure 1 shows diagrammatically the temporal and spatial scales of parameters with relevance to SEVIRI image processing.
Clearly the location of various labels can vary as described depending on the scene, but the figure broadly shows the situation. Apart from the geophysical parameters, two symbols show the “Imagery” and the “NWP”. As interpolated 6 hourly ECMWF analyses are used to provide a boundary condition on the three dimensional state of the atmosphere at the imagery time, this location of this symbol is important. “NWP SST” is placed at longer times scales as this parameter is a fixed value taken from NESDIS SST fields. The green area above and right of the “NWP” symbol shows the x-t space definable by the NWP boundary conditions. The light blue area is that defined by SEVIRI imagery. The remaining grey is either “sub-pixel”, “sub-cycle” or both with respect to the imagery.
Figure 1 demonstrates that

a) most geophysical parameters lie within or close to SEVIRI time and space resolution but
b) few geophysical parameters lie within the NWP resolution.

The principle source of SEVIRI product algorithm boundary conditions is therefore relatively inadequate when viewed from either the spatial or temporal requirements. This is only partly a limitation of the NWP model. Its inherent time step is around 15 mins, i.e. similar to SEVIRI repeat cycle. However, the used disseminated NWP fields are at 6 hour resolution and fields are interpolated. Some improvement to this is clearly possible in principle although access to 15 minute NWP data unlikely. Spatially the global forecast models are currently resolving at around 40 Km and any approach to imagery resolution is a long way off.

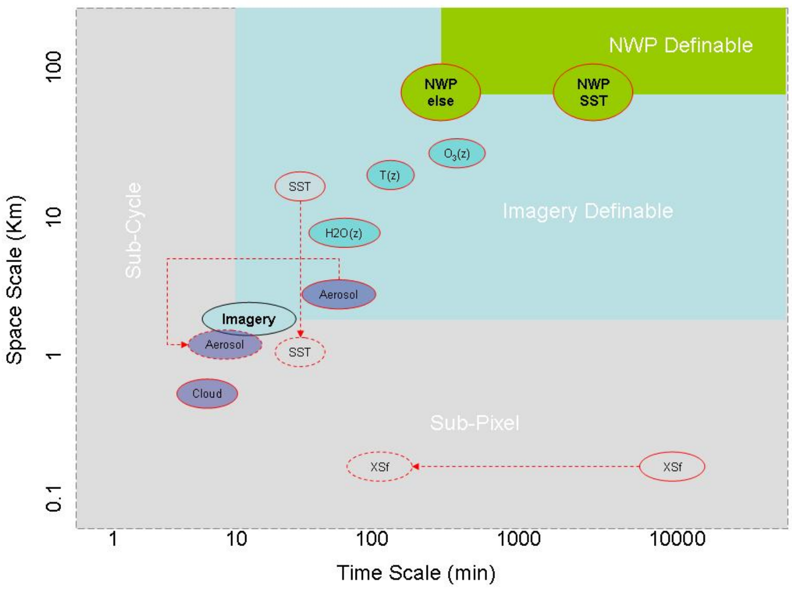


***Figure 1:*** **Temporal and spatial scales of variation in geophysical parameters compared to the SEVIRI imagery and NWP boundary condition sources.**

Examples of the limitations of NWP boundary conditions are numerous (including humidity, aerosols, ozone, surface temperature etc.)
If the NWP source is so poor – do we need it? What we haven't discussed is the vertical dimension; the dimension that SEVIRI only poorly observes and for which the NWP boundary conditions are important for providing the background against which subtle deviations can be used to infer parameter values. Vertical structures of temperature and water vapour are essentially not observed well by imaging instruments with few channels but are very well determined by the wealth of information and physical modelling that constitutes an NWP analysis. SEVIRI cannot specify the detailed vertical structure in temperature or humidity fields, but it can measure the overall 'total column' effect; it can indicate that the NWP analysis is "too wet" (or maybe that the moisture is placed "too high").

## COMPLETE FIELDS

We can think of fields of geophysical parameters as being *completely* or *incompletely* specified in space or time, with both **coverage** and **resolution** being important properties. For the purposes here, we can take the SEVIRI pixel and repeat cycle as the highest required spatial and temporal resolutions and define complete coverage as being values available at all pixels and all cycles.
The basic NWP boundary information, at 6 hours and ~100 Km is incomplete in both respects. SEVIRI itself, by these definitions, can provide geophysical products with complete time and space resolution but incomplete coverage (i.e. no aerosol when there is cloud etc.).
The suggestion of this paper is that we can combine effectively the complementary aspects of NWP boundary conditions and SEVIRI geophysical parameters to obtain a more complete picture. In the one direction, NWP data is already, in the current EUMETSAT IPAs, *interpolated* to obtain complete time and spatial resolution. The complementary action, to interpolate SEVIRI products to obtain complete coverage is so far not exploited. One reason is that few users want geophysical products that are partly the result of an interpolation process; most prefer to perform gap-filling, interpolation etc according to their own requirements. However, here we are referring only to the benefit that would be gained from complete fields within the *product generation process*, not the product dissemination process. Figure 2 shows diagrammatically the mapping of incomplete fields.

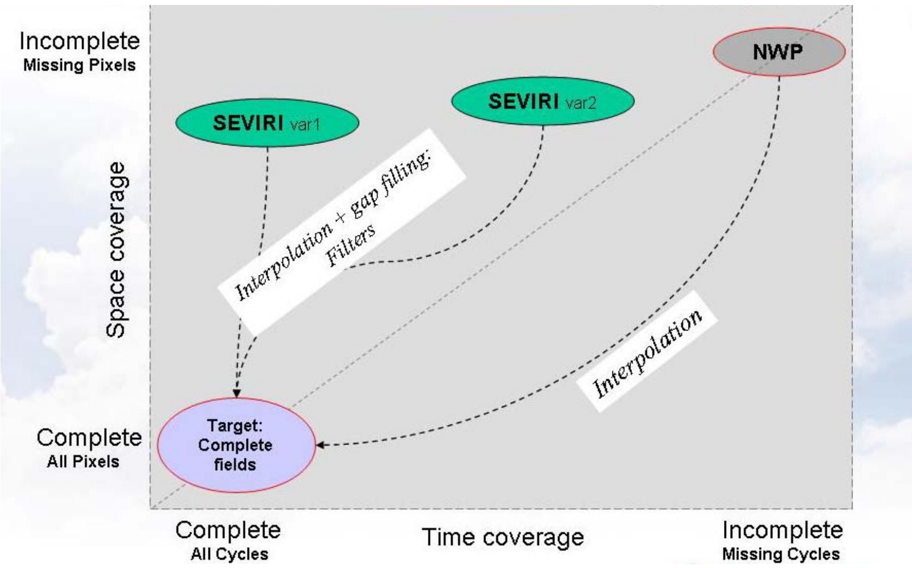


***Figure 2*** **Mapping or interpolation from 'incomplete' to target 'complete' fields, NWP and SEVIRI products.**

As described, the NWP route to the target is already in place, and is made relatively straightforward as NWP information is available on regular completely filled grids. That is, only straightforward time and space interpolation is required.

What is the potential and requirements to make a product field 'complete' in space and time (pixel and cycle)? In effect, the requirements are not so very much more than that for the regularly gridded NWP

data. With the regular but low-resolution grid of the NWP data, bi-linear interpolation is suitable and is used. With the intermittently high resolution, gap-filled product data simple two or three-dimensional filters perform the equivalent operation. They can be made more or less sophisticated in order to handle boundaries or error characteristics, but essentially also perform a bi-linear interpolation / extrapolation function. The potential of such field ‘completion’ for products depends very much on the characteristics of both the parameter and the sparseness of the data field. Essentially, what is the accuracy of the ‘completed’ pixel/cycles? At one end, nearly complete fields with low natural resolution (e.g. UTH) can be completed accurately since the gaps are small and the random excursions small. At the other, sparsely estimated fields with high natural resolution (e.g. LST) will be very hard to complete as gaps are large and random excursions also large – estimates in remote locations (time and space) are more or less useless.
This doesn’t mean however, that the completion process should only be used for the ‘easy’ parameters. Whatever the sparseness or natural variability, estimates for all parameters are required completed; the completeness currently comes from the interpolated NWP boundary data. So which would be more accurate and therefore useful – the completed NWP or completed SEVIRI product? Fortunately we do not have to decide since it is perfectly possible to use the both together. A simple way to achieve this is to map fields of deviations from the NWP background.

We now demonstrate the potential benefits of completed fields using an example implementation of the technique. Sea surface temperature is a ‘product’ field and its completion should allow better subsequent cloud detection and improved products including cloud and OLR for example. In the following we describe the use of *filters* to *complete* fields, therefore the term *filtered* is equivalent to *completed*.

## ILLUSTRATIVE EXAMPLE

The **SST field** from the NWP boundary data is used, somewhat critically, in the detection of cloud in pixels through the IR channels. This field, although generally accurate to around 1 K, is relatively static (based on daily updated NESDIS fields) and, after going ‘through’ the NWP system, resolves only ~100 Km features. Particularly in coastal and strong current areas, or tropical low wind events, the lack of resolution can lead to quite significant errors at the 3 Km / 15 minute scales. A retrieved SEVIRI SST field is, on the contrary, able to see structures at the 3 Km / 15 minute scales but with sparse coverage because of cloud. By means of the time and space mapping described above, a complete field of SST (or perhaps more correctly of SST deviations from the NWP value) is available, and can be continuously improved as more cycles are involved. Clouds move and allow SST values where previously there were none. ‘Best’ quality will be available only after a certain number of cycles has been involved. This asymptote is reached when the additional but steadily *decreasing* information from new cycles balances the natural randomness in the field. The errors in the completed parts of the SST field will be naturally higher than in the cloud-free pixels but less than in the original completed NWP field. For SST we might expect a relatively high gain in accuracy because on a 15 min / 3 Km scale natural changes are normally moderate in size. And *what is the use* of this completed SST field? Not for dissemination as discussed, but in order to have an improved boundary condition for the product generation. A significantly improved SST field will give directly significantly improved boundary IR radiance calculations and consequently better cloud detection, cloud properties, etc. One can see that a similar argument would follow for ozone, aerosol etc.
The filtering and use of a completed SST field is demonstrated in the following figures. Figure 3 shows the interpolated ECMWF SST field for a test area off the SW African coast. It is an area affected by the Aghulas current which leads to strong SST gradients. Figure 4 shows the discrepancy in cloud-free pixels between the 11 micron observed and calculated values using the ECMWF SST at 0600Z. A considerable range of values ranging between -3 and +3 K is seen with some strong structures apparent. The large negative values are not due to cloud; they are obvious as quasi-static eddy structures in an animated loops of cycles between 0600 and 1430Z which unfortunately we cannot display satisfactorily here. From these residuals and similarly derived 12 micron values we derive an SST field based on a simple linear estimator. This SST field is then filtered including use of the previous cycle where it is available (in this case from the 0615Z image onwards). The result at 0600Z is shown in Figure 4 right. Compared to the ECMWF field in Figure 3 there is more structure and steeper gradients.

One immediate benefit of the completed SST field is demonstrated in Figure 5. Here we see the 11 micron residuals as they appear at 1045Z for calculations made both on the original ECMWF SST and the completed SST field. The analysed anomaly (difference to ECMWF) in the SST is also shown.

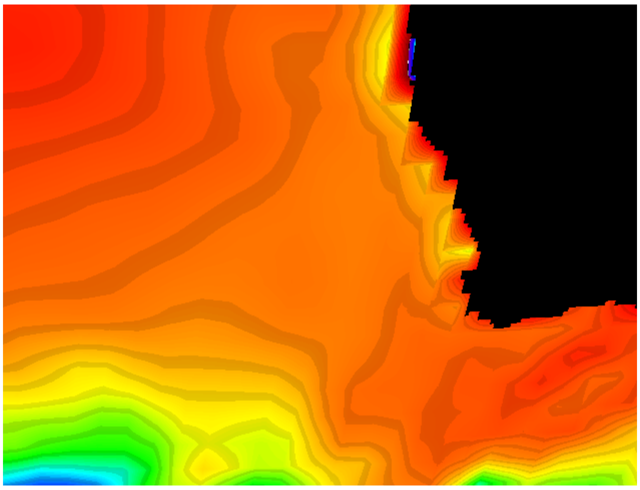

***Figure 3*** **ECMWF SST field off SW African coast.**

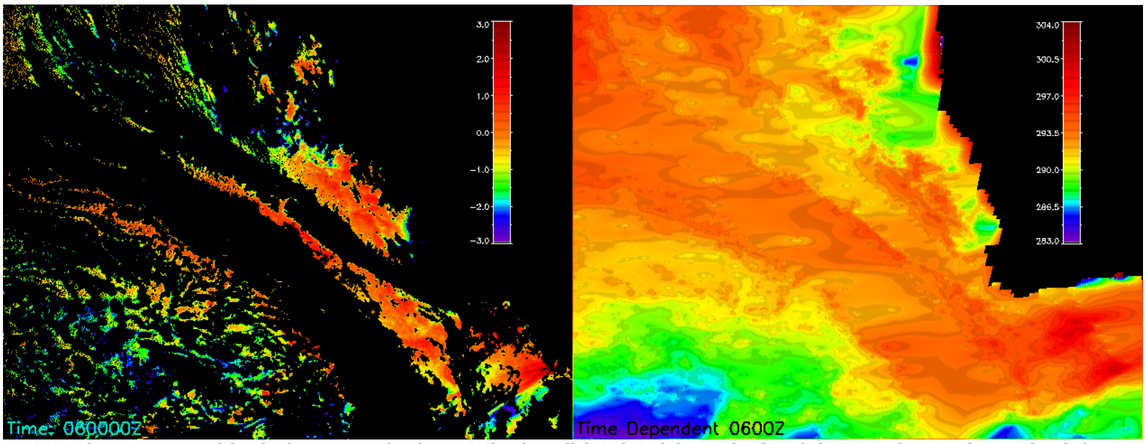


***Figure 4*** **Left: 0600Z Residuals (measured minus calculated) in cloud-free pixels of the 11 micron channel. Right: 0600Z SST field estimated from 11 and 12 micron channel residuals and original ECMWF SST.**

As the completed SST field for 1045Z would not be available at the 1045Z image, we use the 1030Z completed field. In the residuals from the original ECMWF SST, shown in black and blue (for cloudy and clear adjudged pixels respectively) we see a general negative bias; the calculation being too warm. The residuals from the analysed SST (orange) cluster closely around the zero mark. These improved residuals would potentially lead to improved products (e.g. better cloud estimates around pixel #150) and allow tighter thresholds on the 11 and 12 micron residuals themselves for cloud detection. In this experiment there was no feedback of the adjusted SST into the cloud detection, but the idea is clear from the example.
There is a danger in this particular application because of the generally one-sided (negative) effect of cloud, and that is that feedback of the residuals could lead to drift in cloud detection. If significant cloud contamination is permitted to affect the completed SST field then subsequent cycles will permit more cloud and a stronger deviation in SST etc. The effect will be quickly obvious. Only experiment can resolve whether such an undesirable feedback would be kept under control by the hopefully improved infrared channel detection and the daytime visible channel checks. Already in Figure 5 we see potential feedback issues – the blue symbols showing the clear detected pixels occasionally deviate colder than the overall trend potentially biasing the analysed dSST field (cyan) cold (the fact that the dSST shown is larger than the residuals is *not* evidence of this as the atmospheric absorption always reduces the residuals compared to corresponding SST differences). This evidence alone suggests that cloud detection *would* benefit from the completed SST field but that a strategy to use the most confidently assigned subset of the total clear pixels in the analysis would be a wise precaution.

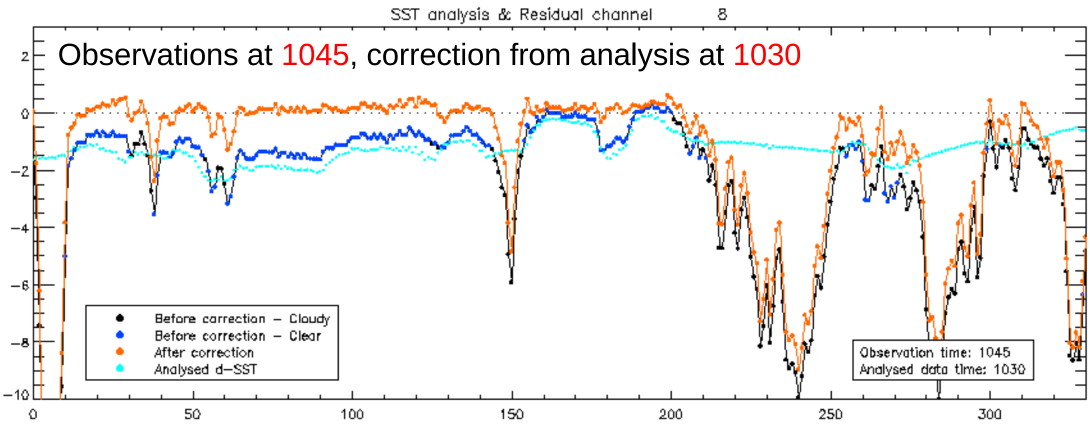


**Figure 5 Cross section through the image area showing 1045Z 11 micron residuals calculated using ECMWF SST (blue and black, 'clear' and 'cloudy') and using this SST corrected by the 1030Z filtered SST anomaly (orange). The SST anomaly (deviation from ECMWF) is shown in cyan.**

## FILTERING AS THE PRODUCT GENERATOR

The filtering process can also potentially improve / allow estimation of parameters in a more direct way than simply supplying improved boundary values. Parameters that are only weakly observable within a single SEVIRI pixel may be estimable with observations from a larger number of cycles. The Meteosat First Generation land surface albedo product and equivalent for SEVIRI already essentially use the equivalent of a two-pass time dimension filter to extract aerosol optical depth and surface albedo from an entire daytime record at a pixel and it has been developed because decoupling aerosol and albedo effects at a single pixel/cycle over reflecting land surfaces is not possible, the information content is too low.
A simple simulation experiment has also shown there may be potential to estimate IR emissivity and land surface skin temperature using a Kalman approach to long series data; another case where single pixel information is completely inadequate.
The differences between using filters as product generators and as suppliers of passive boundary information are not great. A system architecture designed to do one could accommodate the other relatively easily. In the latter, a forward time filtered value acts only as a first guess or boundary condition on the algorithm (e.g. filtered SST for use in a cloud algorithm). In the product generator case, the filtered value is a product in itself and is active as a constraint in the algorithm (as prior information in the OE sense).

## OPPORTUNITY FOR SYNERGY

A further advantage of an integrated product generation system as described is that data from other sensors is more readily used synergistically than with the IPA approach. The geostationary imager pixel and repeat cycle would most likely set the high resolution framework into which other sensor data with usually lower repeat or spatial resolution would be assimilated. By considering the problem as the specification of a general atmospheric state at the imager pixels/cycles rather than as a collection of products to be derived, data with different characteristics to the imager are able to contribute systematically and effectively.

## FILTERING TECHNIQUES

We are not yet at the stage where we can state with certainty how the incomplete fields are completed, but a short description of current ideas is useful to give an idea of how it might work.
Simple linear filters can interpolate / extrapolate values from pixels where results have been obtained to pixels where they have not. To account for variations in data quality, two-pass Kalman smoothers

can be used to give the statistically 'optimal' value at any point, advecting information spatially in all directions. Error handling in such operations however, is not straightforward and approximations will need to be made. Two-pass smoothing in the time dimension is likely to be impossible logistically and computationally, but a forward one-pass filter will be effective.

For the **spatial filtering** consider again SST. If we suppose that all SST retrievals are of the same quality when they can be made, then we have at a particular image cycle, *t*, and at each pixel, j,k, an SST value with an error, e.g. 0.8 K if the pixel were cloud-free, and much larger if it were cloudy. The larger error represents the error in the completed NWP boundary value. A single pass of the Kalman filter makes an estimate of the SST value at each pixel from the values at the previous pixel (same line) and the same pixel (previous line). The entire image is worked through in a L-R, R-L, L-R… sequence. This filtering strategy is found to advect information evenly and with a low computational burden, however, problems arise because of correlated errors which we currently handle in a crude fashion. Pixels with low errors tend to retain more or less their original values, pixels with high errors are heavily influenced by remote pixels. The components of the filter which inform it how remotely to spread the information are the value of the **auto-correlation** expected (at 1 pixel range) and the '**stochastic**' noise expected. Both filter parameters can be estimated offline from areas of clear pixels. An output of the filter is the expected error in SST at each pixel, a value which rises away from clear areas. Note that as we become more remote from retrieved SST values, the filtered SST value reverts gradually to the NWP boundary value. How fast this happens is a function of the errors assigned, and the spatial pattern of cloud-free pixels. The auto-correlation parameter can be drastically reduced at, e.g. land-sea, boundaries to prevent using estimates LST in SST estimation.
The 'two-pass' smoother simply means that a second 'backward' run through the data is performed reversing the direction through the image, combining for the final estimate the pre-calculated forward pass value.

**Temporal** filtering might be a modest extension of the spatial filtering, but in the 'forward' direction only. The Kalman filter would use the cycle *t-1* SST value (and its associated error) additionally to the spatially adjacent pixels at *t*. Auto-correlation and stochastic parameters appropriate to 15 minute separation ensure the previous cycle estimate is not under- or over-used.

The Kalman filter parameters allow for the different characteristics of various geophysical parameters. For LST for example, the spatial auto-correlation would be typically much lower than for SST. Pixel/cycles remote from actual LST retrievals would revert faster to the NWP background. The temporal auto-correlation would also be lower although perhaps not so much.
Note that the Kalman filter is quite general. It requires only a 'model' to predict the value at the next pixel/cycle and its associated error. In the above the 'model' is purely statistical; an "Auto Regressive order 1" to use the full title. This should be effective for many applications. However, the model can also be a physical model if desired. For LST in the time direction this might be quite plausible, using a diurnal heating (/cooling) prediction. For most SEVIRI products however, use of predictive models is unlikely to be required.

## SUMMARY

Completing (filtering, analysing) retrieved fields of geophysical variables of direct relevance to radiative transfer in the SEVIRI channels supplies more accurate boundary conditions for product generation than is available from the analogous completion of NWP fields (and other auxiliary data) alone. We have suggested that the completion is an analogous operation to the use of NWP data and might be achieved using simple linear filters. We have demonstrated with a simple example both the field completion and potential benefits. The full power of the approach would however only become available with a comprehensive system when all relevant physical variables are jointly available as completed fields and associated error estimates. At this stage, products unavailable with the independent approach potentially become retrievable; surface albedo and emissivity are examples.
An implementation of such a comprehensive system would require significant research effort and a substantial shift in the current notion of independent product algorithms and is therefore more suited to preparational activity for MTG rather than development activity for MSG. The current SEVIRI of course provides probably the best available test data and results to date using Kalman filters serves as a first step in this direction.