Meteosat Third Generation
Progress on Space Segment System Feasibility Studies

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1. INTRODUCTION

Meteosat Second Generation satellite (MSG-1 and MSG-2 renamed Meteosat-8 and 9) providing about 20 times more observations than their predecessors, have been declared fully operational in January 2004 (Meteosat-8) and in January 2006 (Meteosat-9). They successfully cover Africa and Europe. The four MSG satellite series are expected to deliver operational services at least until 2018 time frame at which time a Meteosat Third Generation (MTG) system needs to be available. Considering the typical development cycle of new complex space systems, and the time required for the definition phases and the approval of expensive programmes, it has already become necessary for EUMETSAT and ESA to plan for MTG, based on a satellite delivery in geostationary orbit in 2015. More details of the MTG planning are described elsewhere[1, 2]. Early user consultation activities of EUMETSAT and ESA for the MTG mission culminated with a user consultation workshop held in November 2001. The User Consultation Process was devoted to the definition and consolidation of end user requirements and priorities in the field of Medium/Short Range global and regional Numerical Weather Prediction (NWP), Nowcasting and Very Short Term Weather Forecasting (NWC) and to the definition of the relevant observation techniques.

Studies on potential observation techniques and sensor concepts, covering five observation missions have been initiated, namely three distinct imagery missions dedicated to operational meteorology, with emphasis on nowcasting and very short term forecasting and two sounding missions:
- The full Earth disc high spectral resolution imagery (FDHSI) mission with 16 spectral channels, delivering high radiometric resolution performance and geometric performances of 1 km for solar channel and 2 km for IR channels in terms of Spatial Sampling Distance (SSD), with a Baseline Repeat Cycle (BRC) of less than 10 mn;
- The high resolution fast imagery mission aiming at BRC/n minutes (with n being equal to 1, 2, 3 or 4) revisit time with 0.5 km SSD for solar channels and 1 km SSD for TIR channels;
- The lighting imagery mission, capable of detecting very low energy flash events with high Detection Efficiency (DE);
- The InfraRed Sounding (IRS) mission supporting NWP through the provision of atmospheric motion vectors, temperature and water vapour profiles;
- The UV/VIS/NIR sounding (UVS) mission dedicated to atmospheric chemistry and Air Quality (under discussions as part of GMES payload to be embarked on MTG).

This paper addresses an overview of the outcome of the MTG space segment progress (spacecraft trade-off and concept, payload trade-off and preliminary design studies) accomplished so far in the frame of the first part of phase A. It namely highlights the requirements' evolution for the Imaging and IR Sounding Missions, introduces the platform and resulting instrument concepts, establishes the critical technologies and introduces the study progress towards the implementation of the MTG development programme. The results of the phase A should allow ESA and EUMETSAT to consolidate the mission, system and programmatic requirements and to select the architectural baseline leading to the preliminary design towards phase B.

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2. MTG MISSIONS: PRELIMINARY CONCEPTS

The MTG user requirements have been discussed extensively elsewhere[1-3]. In this paper, we will focus only on the updated specifications. As far as the Imaging missions are concerned, the user needs for the imagery are three-fold:

- The Full Disk High Spectral resolution Imagery (FDHSI) mission;
- The High Resolution Fast Imagery (HRFI) mission;

To meet those two imagery mission needs, a Flexible Combined Imager (FCI) has been selected to fulfill the mission needs following common agreement reached between ESA and EUMETSAT. In such a way, the FCI will be operated in an exclusive way to satisfy one of the two imagery missions at a time. With 2 satellites in hot redundancy, both the Local Area Coverage (LAC) and the Full Disc Coverage (FDC) should be met.

- The Lightning Imagery (LI) mission has been discussed extensively elsewhere [4, 5];

The platform carrying FDHSI, HRFI and LI will be called from now on: MTG-I. In addition, MTG-I will carry the Data Collection System (DCS) and the Cospas-Sarsat Geostationary Search and Rescue (GEOSAR) missions.

As far as the sounding missions (also called MTG-S) are concerned, the users have defined two missions:

- The Infrared Sounding (IRS) mission focusing on operational meteorology (profiling of small scale water vapor and temperature structures, and tracking of water vapor features in time), with some relevance to atmospheric chemistry as a secondary application;
- The UV/VIS/NIR sounding (UVS) mission dedicated to atmospheric chemistry and Air Quality.

The overall requirements of those missions are summarized in Table 1 & 2, for what concerns first two priority missions.

The user requirements led to very ambitious mission requirements and thereby to demanding system concepts. EUMETSAT in coordination with ESA and industry recommendations has established priorities vis-à-vis of the overall mission. The highest priority is for the Imaging missions (HRFI + FDHSI), which provide enhanced continuity to the MSG mission and must be ready in 2015. The infrared sounding mission and the lightning imagery mission are the second and third priority, respectively. The UVS sounding mission has only priority four, and following a EUMETSAT Council decision was not considered at the beginning of MTG Phase A studies. The UVS mission, however, may be reconsidered in the frame of the ESA GMES Sentinel 4/5 programme, with the aim of embarking it on MTG-S. For what concerns the number of spacecraft necessary to meet the 15 years operational continuity with the aim of a first MTG-I launch compatible to year 2015, a four satellite-series has been selected for the Imagery missions to fully meet the 15 years lifetime required (availability of 95%) with a fuel extended margin of 5 years as depicted in the MTG deployment in Figure 2 here after. For the Sounding mission, a two-satellite series concept has been selected to cover the 15 years lifetime, with an availability of 85%. A trade-off has been performed showing that a single spacecraft carrying all the missions would not be compatible to a launch date of 2015, thus endangering the first priority imagery mission continuity with 95% availability rating (risks and cost aspects included).

Extensive discussions have been carried out between ESA/EUMETSAT and Industries, with the aim at achieving the user needs without leading the space system into an over-design leading to risks and therefore cost impacts. For instance, a clear need of having the imagery data at level 1b (before image rectification) has been adopted. The discussions which focused on the geometric performances took into account image deformations induced by the satellite and instruments pointing, thermo-elastic aspects and micro-vibrations. Thanks to extensive Image Navigation and Registration (INR) simulations, industries were able to provide during this current phase A, preliminary assessment that allows to consolidate the imagery requirements. ESA and EUMETSAT converged in having the requirements as following:

- Imagery data will be delivered to the users at level 1b;
- Co-registration error is specified at level 1b; In-flight assessment at level 1c is welcome if it can allow to determine the achieved performances at level 1b;
- In-flight absolute and relative image geometric quality of FCI will be assessed after image rectification (level 1c), so that high accuracy landmark processing can be fully applied.

The following definitions of data levels are used for the FDHSI and HRFI missions:

- Observation Level 0: Raw data after restoration of the chronological data sequence for the instrument(s) operating in observation mode;
- Level 1a: Level 0 data with corresponding radiometric, spectral and geometric (i.e. Earth location) correction and calibration computed and appended, but not applied;
- Level 1b: Level 1a data radiometrically corrected and calibrated in physical units. Earth location is appended for every sample, but data is not resampled;
- Level 1c: Level 1b data resampled to a specified reference grid (Image Rectification);
- Level 2: Earth located pixel values converted to geophysical parameters.

For the IRS mission, the science data will always be delivered at level 1b. The term "appended" which appears in the level 1b data definition shall be understood as following:
The observables that are appended (auxiliary data and any other measurements which can allow the image correction before rectification, including level 1c findings) can be used to correct the image if this can be performed without re-sampling. The appended observables shall be delivered as auxiliary data.
For what concerns radiometric aspects, other than the updated number of channels for both the FCI and IRS missions, all specifications remain unchanged as depicted in the previous papers [4, 5]. The latest update appears in Table 1 for the FCI instrument and in Table 2 for the IRS instrument.

Solar Channels	Central wavelength (μm)	Width (μm)	Minimum Signal (reflectance)	Maximum Signal (reflectance)	Reference Signal (reflectance)	SNR
FD-VIS 0.4	0.444	0.06	0.01	1.20	0.01	25
FD-VIS 0.5	0.510	0.05	0.01	1.20	0.01	25
FD-VIS 0.6#1	0.645	0.08	0.01	1.20	0.01	30 12#1
FD-VIS 0.8	0.860	0.07	0.01	1.20	0.01	30
FD-VIS 0.9	0.96	0.06	0.01	0.80	0.01	12
FD-NIR 1.3	1.375	0.03	0.01	0.80	0.01	40
FD-NIR 1.6	1.61	0.06	0.01	1.00	0.01	30
FD-NIR 2.2#1	2.26	0.05	1%	100%	1%	25 12#1
TIR Channels	Central wavelength (μm)	Width (μm)	Minimum Signal (K)	Maximum Signal (K)	Reference Signal (K)	NEdT (K)
FD-IR 3.8#1,#2	3.8	0.40	200 350#2	350 450#2	300 350-450#2	0.1 0.2#1 1#2
FD-IR 6.3	6.3	0.40	165	270	250	0.3
FD-IR 7.3	7.35	0.50	165	285	250	0.3
FD-IR 8.7#2	8.7	0.30	165 330#2	330 400#2	300 330-400#2	0.1 0.5#2
FD-IR 9.7	9.66	0.30	165	310	250	0.3
FD-IR 10.5#1	10.5	0.7	165	340	300	0.1 0.2#1
FD-IR 12.3	12.3	0.5	165	340	300	0.1
FD-IR 13.3	13.3	0.60	165	300	270	0.2

Table 1: FCI Channels radiometric requirements.

#1 identifies the FCI channels to be delivered in both the HRFI and FDHSI sampling modes together with the SNR/NEdT figures applicable for the HRFI sampling mode.

#2 represents the fire application channels with extended dynamic ranges, reference temperature and relaxed noise requirements applicable for the application. The noise requirement is applicable to the complete extended range, i.e. the reference signal is the complete extended range. The fire channels with their top dynamic ranges being 450K for FD-IR3.8 and 400K for FD-IR8.7 shall not saturate within the dynamic range.

The MTG preliminary deployment strategy should follow the lay-out depicted in Figure 1.

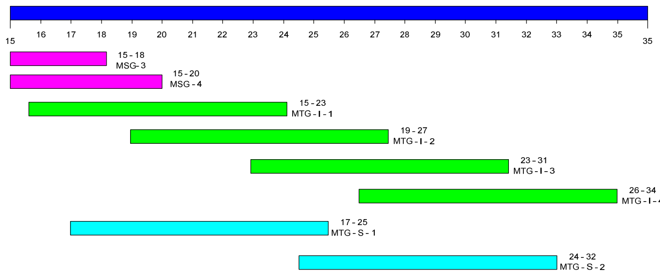


Figure 1: MTG deployment of the twin satellite type of implementation (MTG-I and MTG-S). MTG-I stands for the Imagery mission and MTG-S for the Sounding mission.

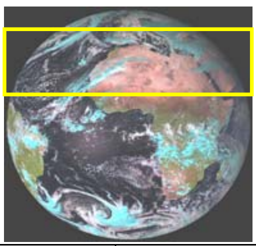
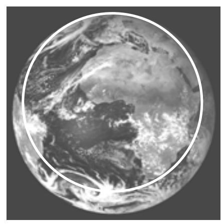
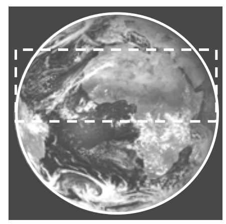
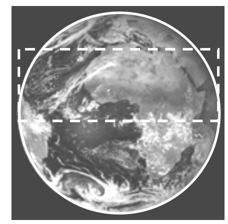
	FDHSI (FCI)	HRFI (FCI)	LI	IRS	UVS
Coverage					
BRC	BRC FDC: 10 min LAC: ~ 10/n min	BRC/n min n=1, 2, 3, or 4	~ 10^{-3} sec	FDC: 60 min LAC: 10 min	FDC: 60 min UVS shall be a payload with: < 140 kg, <24 Mbps data rate
λ	16 core channels Including 2 fire channels	4 channels	OI line at 774.4 nm	LWIR: 700-1210 cm^{-1} MWIR: 1600-2175 cm^{-1}	Same as before but without SWIR channels
SSD	VIS-NIR: 1 km SWIR-TIR: 2 km	VIS-NIR: 0.5 km SWIR-TIR: 1 km	10 km at 45^{o} lat.	4 km for both spectral bands	Under study

Table 2: Summary of MTG Observation Missions

The imagery mission has been updated as depicted in Table 1. Basically, the number of channels has been reduced to cover only priority applications. Channel FD-VIS0.9 has been added to cover clear sky total precipitable water (TPW) in particular over land. Optional channels have been removed. The fire application remains with 2 channels at 3.8 μm and 8.7 μm. The overall Signal to Noise (SNR) has been reviewed and updated. The radiometric noise of the FCI channels shall be determined over their full dynamic range. The values depicted in Table 1 are applicable only at the reference signal.

In the nominal imaging mode, the FDHSI covers the full Earth disk with a 10 minutes Baseline Repeat Cycle (BRC). A rapid scan mode is required with a coverage equivalent to BRC/n referred to as Local Area Coverage (LAC). The LAC coverage can be variably placed anywhere over the Earth (this shall be taken into account for the scan mechanism qualification).

The InfraRed Sounding (IRS) Mission shall cover the spectral domain from 700 to 2175 cm^{-1}. This is done through two spectral bands, a longwave (LWIR) and a midwave (MWIR) bands according to the boundaries provide in Table 3.

The spectral sampling ($\Delta\nu$) for both IRS bands LWIR and MWIR shall be better or equal to 0.625cm^{-1}:

0. 625cm^{-1} $\geq \Delta\nu$ = 1/(2*MOPD), with the Instrument Spectral Response Function (ISRF) being:

a. The FWHM of the ISRF shall be better than $<$ or $=$0.754 cm^{-1}

b. The distance between the first minima of the ISRF shall be < or = 1.787 cm^{-1}
thus limiting the broadening of the ISRF due to self-apodisation and other parasitic effects.
Table 2 provides a summary of the MTG various observation missions main parameters.

In Table 2, BRC stands for Baseline Repeat Cycle, FDC for Full Disk Coverage and LAC for Local Area Coverage. λ is represents spectral channels / spectral range and SSD stands for Spatial Sampling Distance at Sub-Satellite Point (SSP).

Mission Band	Frequency range [cm^{-1}]	Threshold Task	Main Contribution by
LWIR	700-1210	Temperature profile, Window observation, Tracer profile/Chemistry	H_20, O3, CO_2 Surface, Clouds, Aerosols
MWIR	1600-2175	Humidity/tracer profile, Chemistry	H_2O CO, N_2O, and NO

Table 3: MTG IRS reference mission bands

3. SPACECRAFT AND PAYLOAD TRADE-OFF's: THE ACHIEVABLE PERFORMANCES

Supported by the system level trade-off's carried out under two distinct ESA contracts, industries will be able to select their concept(s) at the Preliminary Concept Review (PCR) planned for October 2007. Each industrial consortium will further refine their space segment concept about 6 to 8 months after this review. They will come up with a final concept, consolidated to a level where commitment can be partially made for the achievable performances. This will be closed by a Preliminary Requirement Review (PRR) planned for June-July 2008.

It is not an objective of this paper to discuss the trade-off's performed for the spacecraft itself. In the earlier studies trade-off, it has been already decided that only 3-axis stabilized platforms could meet the users' requirements [2]. However, it is worth noting that our trade-off on the spacecrafts included single and dual wings, petals and body mounted spacecrafts. Depending on the solar influence to the thermo-elastic aspects, the necessary Image Navigation and Registration (INR) and the needs of cooling the instruments, one or the other solution could be adopted. Since the overall concepts are still in competition at industry levels, we will limit our discussions with the statement made above (non-disclosure agreement). The selection of the baseline and possibly optional concepts will be decided after the PCR wrap-up/closure. Each consortium will then optimize their baseline concept/design towards the PRR.

The payload trade-off focused mainly on concepts allowing meeting the user requirements. For that, the preliminary imager concept studies have traded off scanning concepts (single mirror with 2-axis gimbals or 2 scan mirrors one per axis) to limit and/or control the image deformation with no image de-rotator being involved. The 2-mirror concepts give larger size scan mirror, thus introducing incompatibility with easier handling of solar impact at the front-end optics. Since the image deformation is specified at knowledge level, it has been agreed to adopt the single scan mirror concept, for the sake of design simplicity.

For the FCI, trade-off's between oversampling using staggered configurations (more spatial samples in the East/West direction) with digital filtering or the use of rhomboid shaped detectors to meet the geometric quality is still on-going. In both cases, the detector sensitive area shape and size are optimized to meet the MTF templates specified without penalizing the radiometric performances. The 2 concepts will be probably kept alive till the second part of MTG phase A. The digital filtering gives favorable ability for the MTF shape of the FDHSI applications. For the HRFI application, relaxation of the MTF above Nyquist has been accepted by the users, considering that filtering can possibly be applied on-ground. The channels are grouped to optimize detector arrays (similar cut-off), enhance the registration by putting detector packages together. In addition, channel groups requiring a high level of registration may be superimposed in the focal plane thanks to dichroic beam splitter separations. The detectors will be Si based for VIS channel (APS may be used) with a cut-off at 0.9 μm, HgCdTe for NIR and IR, all using CMOS ROIC. The ROIC may be used in low flux regime (CTIA injection stage for instance). TDI stages will be used wherever necessary. The operating temperature of the IR channels will be typically between 50 and 55K namely for MWIR/LWIR channels, whereas for the VIS, ~ 20^{o}C will be the operating temperature. A combination of active and passive cooling could be used to

reach the required performances. The overall design of the imaging instrument will consider also the thermal control of the telescope and the scan assembly.
After trading-off between an IRS with a Dispersive Spectrometer (DS) and a Fourier Transform Spectrometer (FTS) concepts, it was decided to carry out the phase A with the FTS concept [4, 5]. That explains the spectral sampling and waveband defined in Table 2. The commonalities between FCI and IRS instrument will also be exploited as far as possible, namely for spare parts and common supplier leading to cost reduction.
For both the FCI and the IRS instruments, the Focal Plane Array (FPA) has been traded-off extensively. A detector array pre-development has been initiated and implemented by ESA with 3 European detector suppliers, addressing namely the long wavelength channels. For the IRS_FTS, 2-D array up to 256 x 256 (at the most depending namely on the BRC selected) detector elements including trade-off for super-pixels is being considered. All the suppliers have proven to be able to extend the cut-off wavelength up to 15 μm and above. However, the radiometric performances have not yet been demonstrated (work on the way).
For both FCI and IRS, cooling of the IR focal plane is one aspect that has been worked-out by the various industries. It is driven by the performance of the LWIR channels, especially the CO_2 nearing 14μm channels. The infrared detectors are cooled down to 50 - 55 K with active cryo-coolers. Stirling coolers (from Astrium UK) and Large Pulsed Tube Coolers (LPTC) from Air Liquide (France) with heat lift of up to 2W are being considered. Pre-development approaches are on their ways thanks to ESA supported instrument pre-developments.
For the FCI, the imaging principle is based on a fast continuous scan performed from east to west and west to east alternatively and a step like scan in the NS direction to complete the Earth acquisition. As stated previously, the trade-off is in favor of scans performed with a single mirror on a 2-axes gimbaled mount. The spectral channels are in-field and/or beam splitter separated. For the IRS_FTS, staring is performed during a chosen dwell time (less than 10 sec per stare). The scan geometry is identical to the FCI concept, with simply a different scan law. Most of the studied FCI concepts led to telescope of circular unobstructed 300 mm entrance pupil diameter. For each concept, the orientation of the telescope is optimized to prevent direct solar entry into the instrument and with reduced stray light impact. With such a design optimization, the instrument radiometric performances are reached leading to a simpler and compact design allowing a scanning profile independent of the scan mirror position. Commonalities with the IRS design are being looked at. An example of achievable radiometric performances of the FCI concepts is shown in Figure 3.

The AOCS, the alignments (at instrument and at spacecraft levels), the scan law, the overall thermal aspects and other mechanical motions of the spacecraft and its payload are being analyzed in more depth in conjunction with the INR simulations. This is even more important when considering the solar aspects during midnight, since the operational meteorology need to have availability at all time and conditions.

For IR channels of both FCI and IRS, the calibration will be performed by inserting in the useful beam path a black body in addition to the deep space for offset correction. For solar channels, diffuser target plates illuminated by the Sun through the front optics will allow the calibration. Both are full pupil coverage. Due the complexity of the implementation of diffusers of the size of the entrance aperture to cover the absolute calibration requirement (3% goal), analyses shall be made in inserting smaller diffusers in “strategic position” along the beam path of the telescope in combination with vicarious calibrations. The trade-off is on-going.
As shown in previous papers [(3, 4, 5)], the analysis of the FCI radiometric performances has always shown promising results. It has shown that most of the requirements can be met with the available technologies. Only the LWIR bands were showing shortage in terms of dark current noise, leading to cooling down to 55K. For the IRS, as depicted in Figure 4, the radiometric requirement can also be met with a 60 minutes BRC and 50-60K cooling. It is shown that photonic noise and ROIC noise are the most dominant noises that are to be carefully handled for any potential improvement around 1100 cm^{-1}. For all IRS samples the Integrated Energy (IE) over a square 4x4 km^2 shall be equal to or larger than 67% (spatial oversampling is allowed). This requirement shall be met at least for all spectral channels from 2175 cm^{-1} to 900 cm^{-1}. For channels with wavenumbers below 900 cm^{-1} a non compliance should be acceptable (diffraction effects). The IRS geometric requirement is met with more than 67% integrated energy of the PSF at ν=900 cm^{-1}.
The Lightning monitoring Instrument (LI) mission is intended to provide a real time lightning detection (cloud-to-cloud and cloud-to-ground strokes) and location capability in support to nowcasting and VSRF of severe storm hazards and lightning strike warning. As lightning is strongly correlated with storm related phenomena

like precipitation, hail and gust, a further objective of the LI mission is to serve as proxy for intensive convection related to ice flux, updraft strength and convective rainfall. With uniform day and night detection efficiency greater than 90% over large areas, a very complete lightning climatology could be generated. The mission requirements of the LI are summarized elsewhere[3-5], taking into account achievable performances with limited pre-development. A critical driver for the LI is the narrow band interference filter. The filter must be located at the point in the optics which minimises the field angles though the filter, in order to have the least bandwidth, and so best SNR for the O_2 triplet to be detected. In addition the filter must be of a 'manageable' size. It will certainly be a specialised component requiring non-standard manufacturing. The advancement of CCD's and Active Pixel Sensor (APS) technology allows an asynchronous data read-out system to be considered which reduces the data read-out to levels to a range of thousands of samples/second, which can be handled by more conventional data processing techniques.

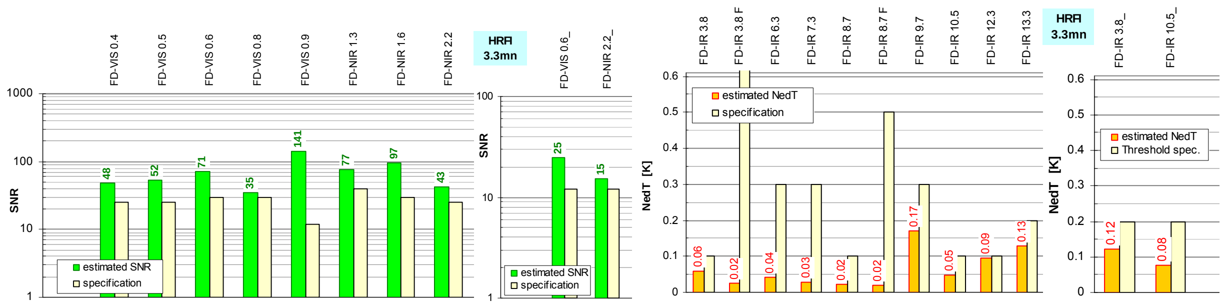


Figure 3: Example of a FCI achievable Radiometric Performances with a FPA cooled at 55K for the TIR channels. This example shows that all noise requirements can be met with margin, with a 300 mm entrance aperture.

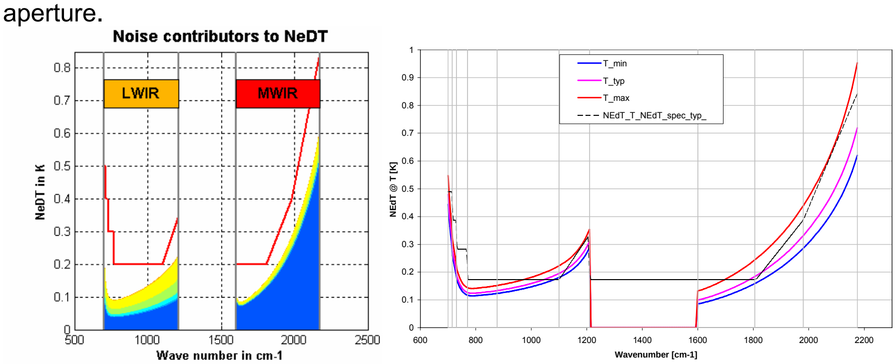


Figure 4: Example of an IRS achievable Radiometric Performance with a FPA at 55K using 8-10 sec dwell time for BRC=60 min including calibration, with a 300 mm circular aperture. The red (left) and black (right) curves indicate the specifications whereas the yellow drawing (left) and red line (right) highlight the photonic noise contribution.

After trade-off, considering, deployment strategy, complexity, risk mitigation and cost aspects, the selected overall satellite and payload configurations are depicted in Table 4.

	FCI	LI	IRS	DCS	SAR
Twin Satellite Configuration					
4 imaging satellites (MTG-I)	**X**	**x**		**x**	**x**
2 sounding satellites (MTG-S)			**x**		
Sum of P/L complement	**4 x FCI**	**4 x LI**	**2 x IRS**	**4 x DCS**	**4 x SAR**

Table 4: MTG satellites and payload configurations. UV/VIS/NIR Sounder would be embarked on MTG-S if selected.

3. CONCLUSION

The Meteosat Third Generation (MTG) mission will substantially enhance the European capability in operational meteorology and climate applications with the implementation of five observation missions described in this paper. The MTG mission has been reviewed and preliminary instrument concept discussed including the achievable performances, and the critical technologies have been highlighted. Despite its low priority from the MTG requirement point of view, the UVS mission is reconsidered for implementation onto the MTG-S spacecraft to potentially fulfill the GMES requirements. Note that the UVS (UV/VIS/NIR) Sounder has been further assessed leading to favorable simplifications not discussed in this paper. The UVS could for instance (potentially) be part of MTG-S payload.

The preliminary results discussed in this paper (resulting from the first part of the phase A study) have allowed ESA and EUMETSAT to consolidate the mission, system and programmatic requirements with the aim of narrowing down the architectural options prior to more detailed feasibility study in the second part of the MTG phase A.

The preliminary work performed on the MTG mission conceptual design has traded-off the possible designs and achievable performances of the 3 main missions (FCI, LI, and IRS) embarked on 3-axis stabilised satellites. For each mission and associated instrument concept, trade-off's have been carried out, parametric analysis performed and critical areas identified. Major findings are on the focal plane array technology that is the main development axis to focus on and this is applicable to both FCI and IRS instruments. Associated cooling facilities, and related implications at Spacecraft level are also highlighted (namely the satellite pointing and its related INR). Although ESA has launched technology pre-development on LWIR detectors and coolers, still, all missions present highly challenging performance requirements, which lead to complex optical instruments and overall spacecraft system. The radiometric performances are reachable as shown in this paper; however lot of effort in technology development is necessary. The performed study allowed to extensively reviewing the mission requirements thus helping to consolidate the specifications. The MTG phase A activities including the review of the technical requirements, the selection of a system concept, the assessment of feasibility and the cost estimate will be performed in its second part and will be finalised in July 2008, the outcome of which will be presented next year.

ACKNOWLEDGMENTS

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