The In-orbit Performance of the Meteosat Second Generation SEVIRI Instruments

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The Meteosat Second Generation (MSG) programme was established to ensure continuity to the Meteosat First Generation system by providing an improved and reliable collection of environmental data from the geostationary orbit in support of weather forecasting and related services as defined by the European meteorological community. The fundamental product is the multispectral imagery of the atmosphere and surface to support now-casting and numerical weather prediction. The MSG programme includes four satellites which were procured by the European Space Agency (ESA) from Thales Alenia Space to be launched and operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Spin stabilised at 100 rpm, the main payload on board the MSG satellites is the Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) which was designed and manufactured by Airbus Defence and Space to image the earth in 12 spectral channels with a repeat cycle of 15 min for the full disc or 5 min for Europe. The SEVIRI design was driven by the stringent requirements on geometric performance, radiometric noise and on-board calibration accuracy which, together with the short repeat cycle, were particularly demanding for a geostationary mission. On-ground testing prior launch determined the radiometric characterisation of the instrument which was refined during commissioning through validation and verification tests using different reference sources for the calibration of the optical channels. After commissioning of Meteosat-11 which was completed in December 2015, there are currently four MSG satellites operational in-orbit (Meteosat-8 launched in August 2002, Meteosat-9 in December 2005, Meteosat-10 in July 2012 and Meteosat-11 in July 2015) and a significant operational experience has been accumulated on the in-orbit operations of SEVIRI. This paper reports the SEVIRI in-orbit performance as obtained from in-flight tests and routine operations and it discusses how this relates to the instrument design and to the performance predictions developed during the instrument procurement. Particular emphasis is given to radiometric, geometric and calibration performance of the four satellites including a discussion on the instrument capability to provide good quality data throughout the most demanding operational events as the eclipse seasons and satellite manoeuvres.

I. Introduction

The MSG satellites observe the Earth with an imaging radiometer whose performances are improved over its predecessors in the Meteosat Operational Programme (MOP) and Meteosat Transitional Programme (MTP). The design of SEVIRI incorporates many features which enable advancements in meteorology through state-of-the-art performances on pointing accuracy, simultaneous multi-spectral imagery/radiometry. SEVIRI is a 50 cm diameter aperture, line-by-line scanning radiometer which provides image data in 12 spectral channels: three visible (VIS), one Near Infra-Red (NIR) and eight Infra-Red (IR). The VIS channels include the High Resolution Visible (HRV) channel which contains 9 broadband detection elements to scan the earth at 1 km sampling distance accuracy. The other channels are designed with three narrow band detection elements per channel, scanning the Earth with a 3 km sampling distance accuracy.

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The purpose of this paper is to outline the SEVIRI requirements, its technical design description and its in-flight expected geometric, radiometric and calibration performances compared to the performance obtained in flight fourteen years after the launch of the first MSG.

A. Mission Objectives and Instrument Requirements

The main mission objectives concerning the imaging radiometer were defined by the European meteorological community and they include five core domains of interest:

- The basic multispectral imagery for the monitoring of cloud systems and surface pattern developments to support now-casting and short term forecasting over Europe and Africa;
- The Atmospheric Motion Vector (AMV) measurements in support of numerical weather prediction on a global scale and on a regional scale over Europe;
- The air mass analysis for the monitoring of atmospheric instability processes in the lower troposphere, by means of measurements of vertical temperature and humidity gradients, precipitable water evaluation, etc...
- The surface parameters consisting of measuring land and sea surface temperature and their diurnal variations which will be used in numerical models and in now-casting.

These core objectives led to the definition of 12 spectral channels in the VIS/NIR and IR bands. The MSG image area is defined as a square containing the earth disc as seen from the satellite. A flexible scanning capability will permit imaging of a smaller area, hence allowing for more frequent observations of severe storms for instance. For a reliable now-casting a short repeat cycle is implemented in conjunction with a rapid delivery of the images to the users. The nominal repeat cycle of 15 min was the driver for the selection of the number of detectors per channel and the spin rate. This is achieved by a bi-dimensional Earth imaging resulting on the combination of satellite spin (East to West) and scan mirror rotation (South to North). The imaging phase has been allocated into 12.5 min, leaving 2.5 min for calibration, retrace and stabilisation. The flexibility of the image format allows an easy size reduction, e.g. to the northern hemisphere: the repeat cycle can then be adapted to the image format, provided that the same scan and retrace rates are kept constant.

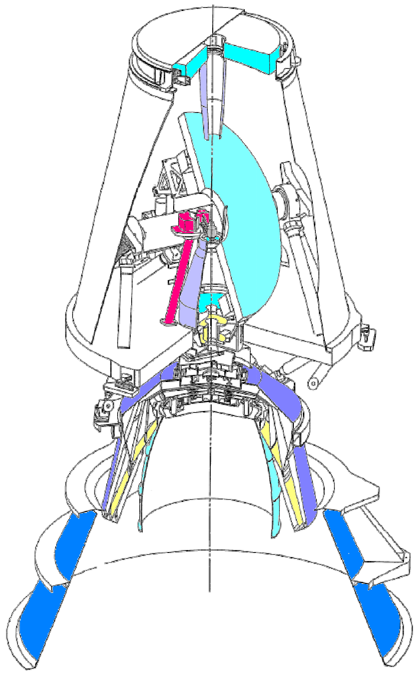

Figure 1 – SEVIRI main units overview

II. The SEVIRI Imaging Radiometer Design Description

The major physical dimensions of SEVIRI result from the requirement to have:

i. Low noise in the long-wave IR channels;
ii. Limited allocated volume within the spacecraft.

Requirement (i) introduces a consequent requirement on the detector temperature which reflected on the size of the cooler. To guarantee the radiometric quality for images in the IR channels, a working temperature of 95 K was identified. To reach such low temperature a large passive cooler is needed.

Requirement (ii) led to the instrument being centred on the satellite spin axis (see) with its field of view clearances on the south side for the IR detectors passive cooling and through the satellite cylindrical body for the Earth imaging. The overall design of SEVIRI included the following main parts represented in Figure 2:

- The Telescope and Scan Assembly (TSA);
- The Focal Plane and Cooler Assembly (FPCA);

- The Calibration Unit (CALU)
- The Main Detection Unit (MDU);
- The Functional Control Unit (FCU).

A short description of the sub-units is reported in the sections below. For a more accurate description, please refer to "Characteristics of the Meteosat Second Generation (MSG) Radiometer/Imager: SEVIRI"[5].

A. The SEVIRI Telescope and Scan Assembly

The design of the SEVIRI telescope was driven by the requirement to keep a limited volume so to allow the passive cooler implementation but also by the need of inserting a small black body in the instrument optical beam for full pupil calibration. The three-mirror (3M) architecture was selected on the base of these requirements.

The scan mirror is allocated at the middle of the spacecraft to avoid deterioration such as interplanetary dust. The Scan Assembly (SA) consists of the scan mechanism, the scan mirror and the related supporting structure. The scan mirror is driven by the scan mechanism to scan the Earth from South to North collecting the radiation emitted or reflected from the Earth. The scan mechanism was designed to meet the specifications consisting of imaging by a continuous bi-dimensional scan of the Earth. Stringent requirements were applied to the pointing directions and their respective stabilities during the imaging phase: electrical end-stops allow knowing the position of the first line (with respect to the scan assembly reference frame providing safe movement range of the mirror) while the position of the scan mirror assembly is read out through a double potentiometer. The scan retrace motion is programmable such that the dynamic effect of nominal scan and retrace motions of the scan mirror causing spacecraft attitude disturbance can be reduced.

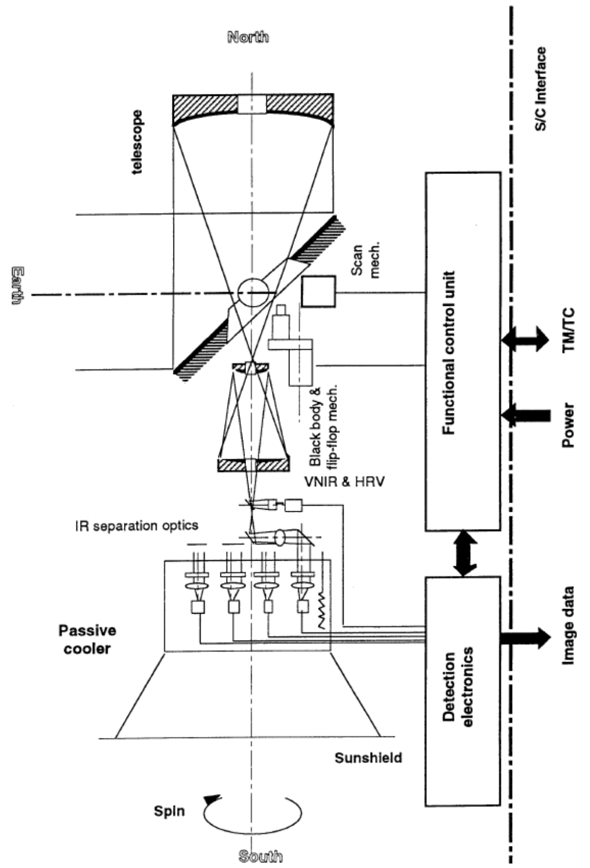

Figure 2 – SEVIRI functional block diagram and scan principle

B. The Calibration Unit (CALU)

The CALU consists of a mechanism which performs the insertion/removal of the Calibration Reference Source (CRS) in the optical beam allowing the calibration of the IR channels. A flip-flop mechanism is used to insert the calibration source into the optical path at Ml focal plane, right underneath the scan mirror. The control of CALU as well as the other mechanisms is handled by the FCU. To support the correct image processing providing the correct radiometric quality, blackbody calibrations are nominally performed at ambient temperature every hour, while calibration with the blackbody at a delta-temperature of 20 deg are performed twice a day. The reading of the blackbody temperature is the result of the computation of four thermistors providing an extremely high accuracy due to the criticality of this unit. To detect potential drifting of the reading value, a calibration of the blackbody thermistors is performed twice per year and so far no drifting has ever been detected in any of the four spacecraft.

C. The Focal Plane and the Cooler Assembly (FPCA)

The FPCA includes the Focal Plane Optical Benches (FPOB) and the Passive Cooler Assembly (PCA). They are together attached on the lower side of the instrument/spacecraft interface base plate which supports, on the upper side, the TSA. The FPCA uses state-of-the-art technologies including high throughput relay optics, cooled detectors and low noise amplifiers, including the cryogenic hardware. The PCA structure provides highly stable support to the optical elements including thermal insulation to the cold IR optical bench.

The FPOB is designed to accommodate the twelve channels of SEVIRI. It consists of 2 main assemblies, physically and thermally decoupled, the warm (VNIR) and cold (IR) optical benches.

The PCA consists of a cooler assembly including a sunshield. Radiating the heat into space, the PCA has a two stage radiator, where the second stage houses the electro-optical elements which are to be cooled and it is suspended onto the first stage of the radiator. The sunshield assembly is a large conical high performance reflector, which shields the PCA from incoming solar radiation. Both optical benches are kept at stable temperature for the whole year via closed loop thermal control: the warm bench, located on top of Passive Cooler housing, at 20 °C, and the cold one, located inside the second stage of the Passive Cooler, at 95 K. The design is also driven by clearance constraints needed for physical integration and access to detectors and optical elements. The Visible and IR channel separation is performed using the in-field separation of the telescope focal plane.

D. The refocusing mechanism (REM)

The telescope focal length may vary over the lifetime of the satellite due to thermally induced deformations, aging effects, moisture and gravity releases. After the assessment of the focus stability, it was decided to implement a refocusing mechanism, acting on M2/M3 assembly, to compensate the telescope long term deformations over the mission life time. Until today, 14 years after the launch of the first MSG, the refocusing was never needed and never performed on the flying spacecraft.

E. The Detection Unit (DE)

The DE consists of the detectors, the Pre-amplifier Unit and the Main Detection Unit (MDU).

1. The detectors

SEVIRI is an instrument with 12 channels and 42 detectors. All channels are composed of an array of 3 elementary detectors, with the exception of the HRV channel which has 9 elementary detectors. They are located in the cold FPOB. The detectors determine the IFOV (Instantaneous FOV) of the instrument.

2. The Pre-amplifiers

The signal acquired by each detector of the 42 chains is amplified at first at this level. The general preamplifier design is of a modular approach common to all photovoltaic (PV) or photoconductive (PC) amplifiers. This subsystem consists of three assemblies: the Cold Unit (CU), the Warm Unit (WU) and the Preamplifier Unit (PU).

For any given detector type (VNIR, HRV, IRPV or IRPC), there is a common preamplifier design: all the individual adjustment and setting facilities required to compensate the channel peculiarities and detector variability are implemented at pre-amplification level.

3. The Main Detection Unit (MDU)

The MDU is the signal processing electronics, including conditioning, filtering, sampling and digitisation. It applies to each of the 42 SEVIRI detectors: each individual detector is connected to its own preamplifier and processing chain before the digital data are filtered, multiplexed, processed and prepared to be transmitted to the MSG on-board data handling subsystem (DHSS).

F. SEVIRI Functional Control Unit (FCU)

Today most modern instruments and spacecraft tend to have on-board computers. For SEVIRI, with a goal to achieve high reliability, it was decided instead for the SEVIRI Functional Control Unit (FCU) to rely on carefully designed logic circuitry, with no on-board computer in the instrument. Although there were some limitations and constrains respectively for downloading of all register content and for the full range of internal FCU cross strapping, the final result was a highly reliable control unit capable of commanding calibrations at different timings, and the scan mirror to image at different temporal frequencies and different geographical areas. A large amount of housekeeping telemetry from SEVIRI was achieved by a decision to have a platform RTI (Remote Terminal Interface) card located within the SEVIRI FCU, providing SEVIRI the capability to send to the spacecraft significant amounts of telemetry nominally possible only by instruments with an on-board computer.

Years of operation of all the MSG spacecraft have proved this FCU design a significant success, with only one Single Event transient (which easily recovered from) in over 27 years of combined MSG SEVIRI operation.

III. Functional Overview

G. Imaging Principle

The SEVIRI instrument is designed to produce the image of the Earth full disk from a spinning geostationary satellite. The scanning of the Earth disk is obtained by using the satellite spin (100 rpm) in the East-West direction and by stepping a flat scan mirror in the South-North direction after each East-West line, to set up the instrument for acquiring the scan of image data. Figure 3 shows the Earth imaging principle used by SEVIRI. One complete revolution of the satellite lasts 0.6 seconds of which only about 30 milliseconds are available over the Earth disk to acquire one scan. After the 30 ms spent imaging the Earth, the remaining 570 ms are used mainly for scan mirror stepping, data transmission and deep space data acquisition for Direct Current Removal

(DCR). The image nominal repeat cycle is 15 minutes, including on-board radiometric calibration and scan mirror retrace. Shorter repeat cycles are programmable if an image of a reduced area of Earth is required.

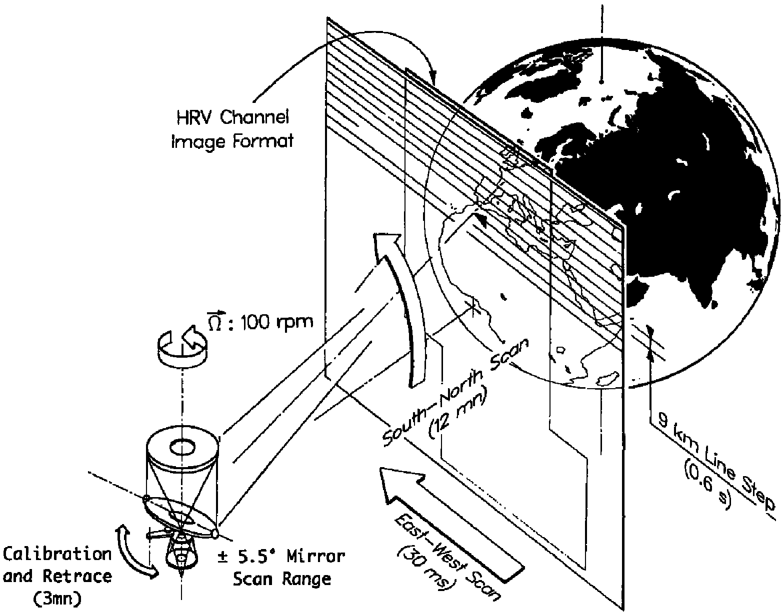

Figure 3 – SEVIRI Earth imaging principle

Table 1 – SEVIRI channel bands

Channel	Band [µm]	
HRV	0.7	warm
VIS 0.6	0.6	warm
VIS 0.8	0.8	warm
NIR 1.6	1.6	warm
IR 3.9	3.9	cold
IR 6.2	6.2	cold
IR 7.3	7.3	cold
IR 8.7	8.7	cold
IR 9.7	9.7	cold
IR 10.8	10.8	cold
IR 12.0	12.0	cold
IR 13.4	13.4	cold

The instrument generates images of the Earth in twelve different spectral channels from VIS to IR with a sampling distance of 3 km at Sub Satellite Point (1 km for High Resolution Visible channel on a reduced Earth area). These channels are known as either "cold" channels or "warm" or "solar" channels (see table). For each spectral channel there are three detectors, hence in one revolution of the satellite, three lines of image are acquired simultaneously. For the HRV channel there are 9 detectors and 9 lines are obtained per revolution.

H. On-board Blackbody Equipment

The SEVIRI instrument has been equipped with a blackbody radiance source which is periodically brought into the optical path in order to perform a calibration measurement for the IR channels (the "cold" channels). For the "solar" channels there is not an on-board calibration source, so that the calibration of these channels relies on ground based methods. The on-board calibration blackbody is not temperature stabilised, but it is floating with the environment. Some heaters are provided on the calibration blackbody to allow calibration at a second temperature (nominally 20 K higher) when required.

The incoming radiance $L(\lambda,T)$ (from the Earth, deep space, etc.) is transferred from the entrance pupil of the telescope through to the detector. Note, that the optics is split into two parts – front optics and common optics – which are defined by relative position to the blackbody calibration source which is inserted between the front optics and common optics. This design feature, (the positioning of the blackbody) has advantages and drawbacks. The main advantage is that the blackbody calibration source, being in the focus of the primary mirror, is very small. This translates in a full pupil calibration with a very uniform source and allows heating up the source with negligible effects on the surrounding elements that is another desirable condition.

The main drawback is that, when inserted, the blackbody obscures the front optics (scan mirror and primary mirror) which is, of course, in contrast to an imaged target (i.e. the Earth) which is seen by the detectors through both the front and common optics. This means that the effect of the front optics is not taken into account when viewing the blackbody and the unknown effect must be accounted for by on-ground modelling of the optics equipment. A further point that should be noted is that a function called Direct Current Removal (DCR) is implemented in SEVIRI. This function removes the offset in the output digital counts due to the instrument self-generated radiance and detector dark current. Furthermore it strongly reduces the 1/f noise in the image. It is obtained by acquiring deep space data just before the acquisition of each image line. These deep space counts are then subtracted from the earth count in order to remove the offset. This function is an integral part of the on-board calibration.

IV. Instrument Performance

The radiometric characteristics of the SEVIRI instrument have been defined to provide improved image quality as compared to the first generation of the Meteosat imager. The SEVIRI requirements apply simultaneously on enhanced performances in both noise and bandwidth figures. This is because the MSG mission covers both radiometric and imaging functions demanding high spatial resolution and short repeat cycle together with very low noise. Only nominal orbital parameters and time frames are considered for the impact on the spacecraft, i.e. discrepancy on altitude, spin rate, sampling clock and attitude. The instrument performance are hereafter characterised through the comparison between the estimation made before launch and the observed performances in flight in terms of radiometric, calibration and geometric performance. The data here presented are based on observed behaviour of the SEVIRI instrument mounted on Meteosat-8, the first of the second generation (MSG1).

I. Radiometric Performances

Amongst the SEVIRI radiometric performance requirements, the noise is the parameter which drove the overall instrument sizing where the DE is the main contributor and in there, specifically the detectors and preamplifiers. These stringent requirements on the radiometric performances led to a chain by chain optimisation. This calls for a specific design and development for the detectors and the associated detection electronics, including an optimised approach for the detection signal handling and processing.

Straylight analyses have shown that there will be no imaging outages when the sun is separated from the SEVIRI image area by more than 20 degrees along East-West direction. The straylight impact is taken into account for the instrument radiometric budget determination and characterised during commissioning tests. As discussed, three main targets are involved in the process of signal acquisition: the deep space, the earth and the calibration black body for the IR channels or the vicarious calibration (landmark observations) for the visible channels.

Table 2 – SEVIRI channels, radiometric bias and long term drift

	Channel Band [μm]			Upper limit of the dynamic range	Mean error + long term drift
	λ	λ_{MIN}	λ_{MAX}		
VIS and NIR channels				[W·m^{-2}·sr^{-1}·μm^{-1}] **Normalised radiance of a 5750 K black body at λ_0, for a vegetated target*	[W·m^{-2}·sr^{-1}·μm^{-1}]
HRV	0.75	0.6	0.9	460	9.2
VIS 0.6	0.635	0.56	0.71	533	11
VIS 0.8	0.81	0.74	0.88	357	7.1
NIR 1.6	1.64	1.5	1.78	75	1.5
IR channels				[K] **temperature of a black body*	[K] **Radiometric drift at the upper limit of the dynamic range*
IR 3.9	3.9	3.48	4.36	335	1
IR 6.2	6.25	5.35	7.15	300	1
IR 7.3	7.35	6.85	7.85	300	1
IR 8.7	8.7	8.3	9.1	300	0.8
IR 9.7	9.66	9.38	9.94	310	0.8
IR 10.8	10.8	9.8	11.8	335	1
IR 12.0	12	11	13	335	0.9
IR 13.4	13.4	12.4	14.4	300	0.7

Radiometric accuracy or radiometric error quantifies the ability of the instrument to relate the measured signal to the absolute or relative radiance of the calibration target. For visible channels, the noise is expressed as the Noise Equivalent delta radiance (NEdL) or as the Signal to Noise Ratio (SNR) while IR channels are characterised through the Noise Equivalent delta Temperature (NedT).

The SEVIRI noise is determined using the root sum square of all noise sources in the system. It is calculated over a full image with the signal computed from the specified scene radiance, using the transmissions of the optical elements, the detector responsivities and the self-emission of the instrument. There are many potential sources of radiometric error in the instrument, all of which must be minimised by design to achieve the accuracy goals defined by ESA. The primary noise sources are: photon noise, detector/preamplifier noise, quantization noise, miscellaneous sources including temperature uncertainties, straylight, various losses from optics, cross talk, linearity knowledge, wave-length shift and/or out-of-band impacts.

Uncertainty and error contributions from all signal and noise terms are combined as a means of budgeting tolerances on the system. The performance modelling consists of providing figures of merit of the instrument sensitivity to input radiances. The radiometric accuracy is computed considering an albedo of 39% of the reference target. All the considered reference targets are displayed in . The long term drift is assessed at the upper limit of the dynamic ranges. The noise equivalent delta radiance and temperature (NEdL and NEdT) at the reference targets specified prior launch at 95 K for all channels (specified in a requirements document referred to as SY2) are compared to the observed in-flight performance in Table 3 (**Figure** 4).

Table 3 – Specified noise budget compared to observed performance in-flight at operating temperature of 95 K (measured 2015-09-23 T12:30:00)

	Specified (SY2) noise budget	Measured noise budget			
		MSG1	MSG2	MSG3	MSG4
VNIR (SNR)					
HRV	1.2	2.95	3.47	2.68	3.19
VIS 0.6	10.1	427.04	650.94	48.80	222.64
VIS 0.8	7.28	29.08	52.94	29.72	39.97
NIR 1.6	3	9.31	10.64	11.04	10.90
IR (NEdT) [K]					
IR 3.9	0.35	0.07	0.09	0.10	0.09
IR 6.2	0.75	0.04	0.04	0.04	0.05
IR 7.3	0.75	0.05	0.05	0.06	0.05
IR 8.7	0.28	0.06	0.07	0.06	0.07
IR 9.7	1.5	0.10	0.11	0.09	0.09
IR 10.8	0.25	0.06	0.06	0.06	0.06
IR 12.0	0.37	0.16	0.11	0.11	0.10
IR 13.4	1.8	0.24	0.23	0.22	0.22

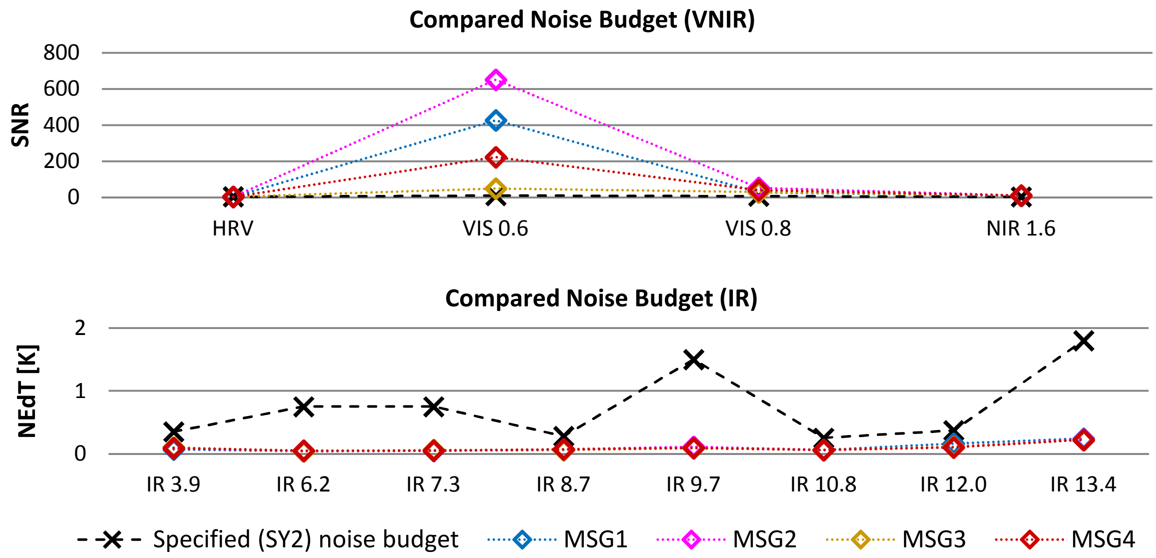

Figure 4 – Compared noise budget for solar and cold channels

1. Radiometric Performance and Decontamination

The presence of contaminants on the detectors reduces the instrument performance. These contaminants are the product of the condensation of air particles when the S/C is transferred from ambient temperatures to cold space. As the contaminants could also damage the instrument, it is recommended at system FOM level to perform the PCA decontamination after launch within 12 hours from the ejection of the SEVIRI baffle as part of the LEOP activities. Following the first decontamination, two further are performed during commissioning and once per year the first 2 years after commissioning.

After that, decontaminations are performed on the basis of the observation of the detector efficiency (referred to as g0 values). These values represent the “reduced gain”. If the total gain G is defined as $G =$

$\frac{\partial C_{Off}}{\partial L_0}$, where C_{Off} is the Count minus offset and L_0 is the radiance, measured at 0 level, the reduced gain is $g_0 = \frac{total\ gain}{electronic\ gain}$. Thus, g0 is independent of the detection chain settings (within the limit of the electronic model) and in this sense, it is absolute. In terms of decontamination, g0 provides a measure of the improvement respect to before and after. Figure 5 shows the Meteosat 8 g0 behaviour from 2005 to 2015 (data from BOL are not available). Decontaminations can be identified in the curve discontinuities. Channel IR12.0 is represented alone on purpose as it is the most affected. From the plot we can notice that coefficient of deterioration is proportional to the presence of contaminants, i.e. the slope of trend lines is steeper in the earlier years due to the higher contamination and it flattened after performing several decontaminations. The minimum acceptable value of g0 to ensure the image radiometric quality is 0.4.

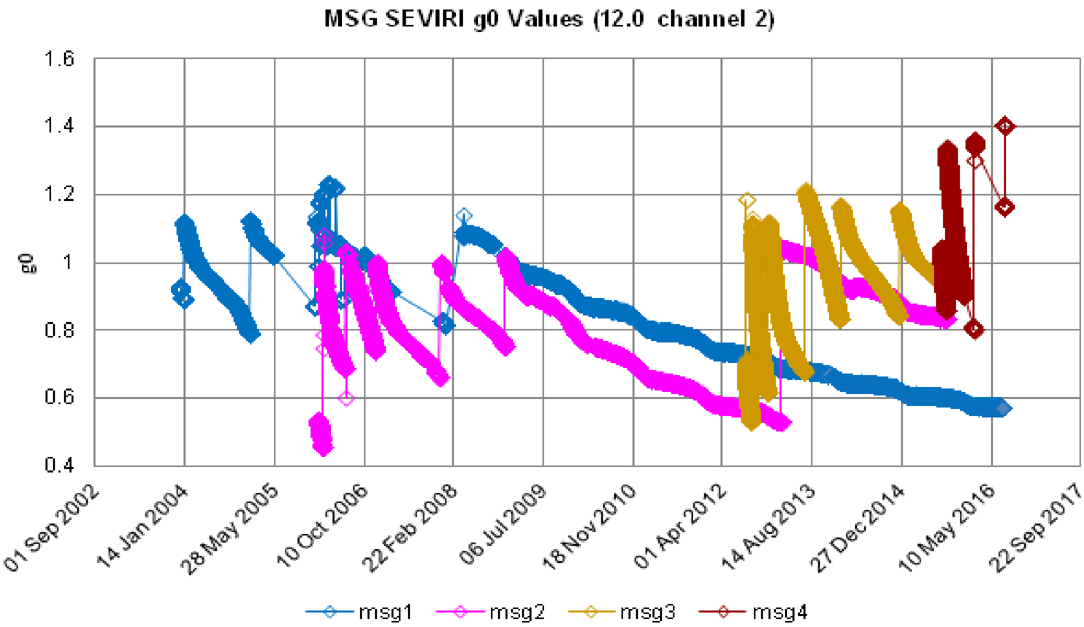

Figure 5 – Detector Efficiency (g0) values for all MSGs

J. Calibration Performance

At any instant of the Earth imaging, the instrument collects a flux determined by the radiance of the current target, which flux is distributed to each detector. This useful flux includes parasitic radiation from stray light (affecting all channels) and from the instrument self thermal emission (also called background, affecting only IR channel). The signal offset, including the instrument background and the detection dark signal, is measured at each line scan during the deep space viewing and removed from the detector output signal (DCR function). Because the gain of the detection chains varies with the instrument ageing and thermal variations, it is also necessary to calibrate the IR channels using a well characterised radiance source in order to maintain the required absolute radiometric accuracy. For that, a full pupil calibration is periodically performed by moving a reference black body (of accurately measured temperature) into the optical path, between Ml mirror and M2/M3 assembly. The absolute radiometric accuracy of the VNIR channels is based on a vicarious calibration process, by observation of landmarks with well known radiative properties, at different periods of the year.

One special characteristic of the calibration technique that has been defined for the SEVIRI IR channels is that the scan mirror and the telescope primary mirror (called the front telescope: FT) are not included in the calibration path during the on-board blackbody viewing. The radiometer entrance aperture being 500 mm, a blackbody of the same size would have been necessary to provide the calibration with the whole optical path viewing the calibration source. An alternative (low mass) has been found, through performing full calibration by using 2 different temperatures of the blackbody. The back telescope (M2/M3) response curve is measured at two different points and thus allows compensating the front telescope transmission which is not included in the calibration path. Hence, the instrument response curve is clamped on a point, the other one being obtained by deep space viewing.

The calibration process consists of three steps:

- Measuring the cold deep space radiance;
- Measuring the radiance coming from the on-board blackbody (at temperature T0), resulting to an output (in counts) as measured by SEVIRI; The blackbody true radiance is determined through the knowledge of the thermal and optical properties, including the responsivity of the instrument;

- Measuring the on-board blackbody at temperature $T_0+\Delta T$ with $\Delta T \sim 20$ K.

It is important to understand that $T_0+\Delta T$ calibration is needed only for the purpose of determining a correction term in the instrument gain that accounts for the missing Ml and scan mirrors whose contributions are translated through the temperature differences between FT and the on-board calibration black body. Hence, measured temperatures of Ml, scan mirror, Ml baffle and the related transmittances and emissivities will allow computing the missing delta background. But, such a correction can only be applied when the following assumptions are added to the knowledge of the front telescope contribution: homogenous thermo-optical characteristics of the optics, no background variation between deep space and target viewings, no noise related to the calibration occurred, the instrument is linear and the bidirectional response of the detectors is isotropic. Apart from the temperature measurement inaccuracies, the radiometric error induced by the Ml, the scan mirror and their surrounding environment is negligible. The blackbody is nearly perfect as it is well calibrated on ground. Its error contribution is dominated by its temperature measurement accuracy during the satellite lifetime. This calibration technique is feasible because the SEVTRI scan mirror is placed in the middle of the satellite, thus avoiding deterioration as a result of the interaction with interplanetary dust. This was not the case for e.g. the NOAA AVHRR radiometer which scan mirror suffered from such deterioration.

Table 4 – Mean bias for reference temperature scenes evaluated by inter-comparison with Metop-A/IASI on 2015-09-23 (k=1 uncertainty ~0.01K)

IR channels	Radiance [K] Standard Scene	Bias [K]			
		Met-8 – IASI	Met-9 – IASI	Met-10 – IASI	Met-11 – IASI
IR 3.9	300	+0.66	+0.56	+0.66	+0.02
IR 6.2	250	-0.19	-0.11	-0.13	-0.08
IR 7.3	250	+0.81	+0.20	+0.07	+0.25
IR 8.7	300	-0.06	-0.05	-0.04	+0.09
IR 9.7	255	+0.01	+0.22	+0.08	+0.10
IR 10.8	300	-0.05	-0.05	+0.03	+0.14
IR 12.0	300	-0.03	-0.08	+0.04	-0.03
IR 13.4	270	-1.48	-1.09	-1.16	-0.23

Table 5 – Mean rate of IR channels' calibration drift for standard radiance scenes evaluated by inter-comparison with Metop-A/IASI over 1 year from 2014-12-05 to 2015-12-05 (3 months 2015-09-04/12-06 for Meteosat-11)

IR channels	Calibration Drift [K/yr]			
	Met-8	Met-9	Met-10	Met-11
IR 3.9	-0.01	+0.15	-0.10	+0.16
IR 6.2	+0.01	+0.06	+0.00	+0.35
IR 7.3	+0.16	+0.05	-0.16	+0.79
IR 8.7	+0.01	+0.04	-0.05	-0.04
IR 9.7	+0.03	0.12	-0.06	+0.12
IR 10.8	-0.01	+0.03	-0.11	+0.08
IR 12.0	+0.01	+0.04	-0.08	+0.04
IR 13.4	-0.31	-0.17	-0.61	-4.24

The accuracy of the operational calibration for the IR channels is routinely validated by inter-comparison against collocated observations from Metop/IASI, following GSICS methodology. The resulting biases and their rate of drift wrt IASI are shown in Table 4 and Table 5, respectively. The rate of calibration drift of the VIS/NIR channels is assessed in Table 6 over the instruments' operational lifetime using the Lunar Calibration System. These results confirm all channels were within the required limits given in , except the IR13.4 channel, which is affected by ice contamination, and Meteosat-11, which was relatively young at this time, still experiencing a significant rate of contamination and only operated for a short period, leading to larger uncertainties on the calibration drift (shaded grey).

Table 6 – Mean rate of VIS/NIR channels' calibration drift from Lunar Calibration System over operational lifetime

IR channels	Calibration Drift [%/yr]		
	Met-8	Met-9	Met-10
HRV	+0.53	+0.49	+1.24
VIS 0.6	+0.52	+0.57	+1.08
VIS 0.8	+0.49	+0.52	+0.83
NIR 1.6	+0.03	+0.10	+0.15

K. Geometric Performance

The geometric performance is the other major requirement applied to the SEVIRI instrument. The image area is denned as the square circumscribing the earth disc as seen from the satellite. The scan area shall be larger than the image area to enable navigation and to account for different orbit inclinations: a scanning capability of up to 22 degrees (South-North) is implemented. The imaging principle is shown in Figure 3. The implementation of a star sensing function using the 9 HRV detectors of the imager (nominally used for imaging) allows to accomplish precise orbit determination, thus reducing the errors that affect the accuracy of image navigation and/or registration, especially after station-keeping. The effect of the scan mirror slew motion disturbance on the spacecraft which results in registration error is deterministic and can be compensated by programmed retrace motion.

The separation of the channels at the telescope focal plane, level is performed as shown in Figure 6. The diamond shape of the detectors, their size and positioning and the sampling interval are all optimised to satisfy the system modulation transfer function (MTF) requirements. The nominal sampling distance along east-west and north-south directions is 3 km at the Sub-Satellite Point (SSP), except the HRV channel which sampling distance is 1 km at SSP. The distances between the channels are about 8 mm at telescope focal plane level, corresponding to 54 km on ground at sub-satellite point.

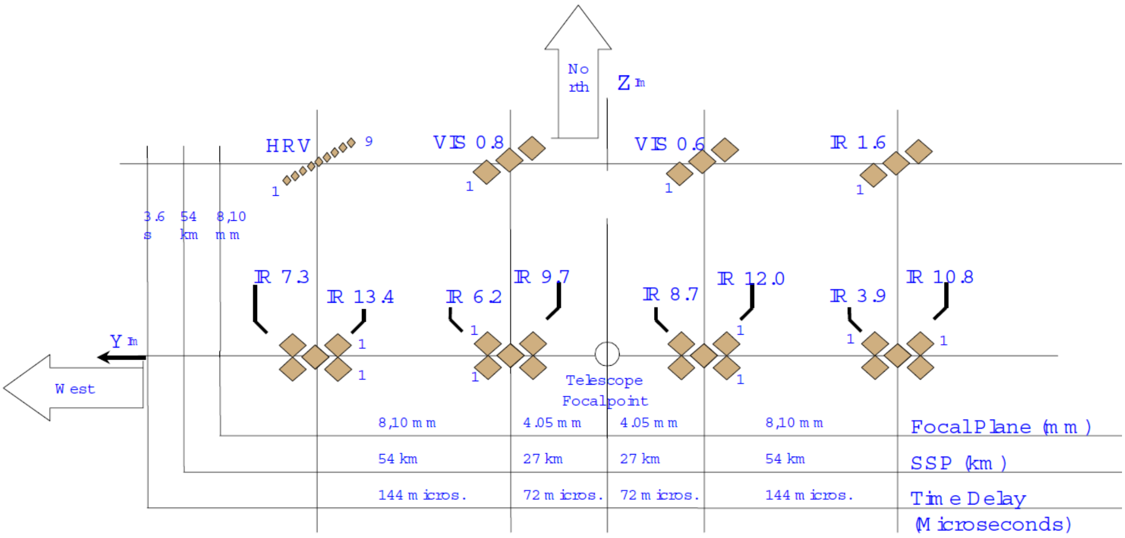

Figure 6 - South/North separation of HRV/VNIR channels

With the aim for enhanced imaging geometrical quality, stringent requirements are applied to the MTF of SEVIRI. The objective of these requirements is to have a high MTF for spatial frequencies below Nyquist frequency and very low MTF above this frequency in order to minimise aliasing errors. The overall instrument MTF is computed by cascading the MTF of each system contributing equipment. Among the parameters impacting the imaging performances, the following are considered in the MTF determination:

- The diffraction of the optics, the detector size, shape, spatial distribution, alignment/positioning, IFOV/pupil response, the thermo-mechanical variations, the scan assembly pointing stability;
- The electronics: filtering, phasing.

The results of the computation provide the expected achievement of SEVIRI as far as MTF is concerned.

No geometric deterioration has been observed wrt MTF or co-registration. Deterioration in the imaging performance can be introduced by the S/C attitude and the degraded performance of the scan module.

Meteosat 8 is affected by deteriorated orbital parameters due to its age and the effect can be observed in the RSS images where a tilt due to the orbital high inclination is introduced in the rectified images.

An anomaly on the imaging can be seen for Meteosat 8 and Meteosat 9 due to the deterioration of thermal protection on the exterior of those MSG spacecraft. This deterioration allowed sunlight to enter the interior of the spinning spacecraft, heating up (and cooling down) parts of the spacecraft interior exposed to deep space. The thermal regulation function has been adjusted to compensate for the heating/cooling effect, which lead to fuel migration between fuel lines and the fuel tanks, resulting in slight change of the spacecraft attitude. The fuel migration resulting in very sudden absolute S/C movement impacts on the SEVIRI images with jumps equivalent to 2-pixels to 5-pixel. This effect is compensated through the implementation of thermal regulation commanding and image processing.

The scan module performance, assessing the pointing accuracy, is monitored via potentiometer values analysis and after 14 years of continuous service shows no deviation from nominal behaviour.

The co-registration of the SEVIRI channels is measured using correlation of the images of the different channels. The result is shown in Figure for Meteosat 11.

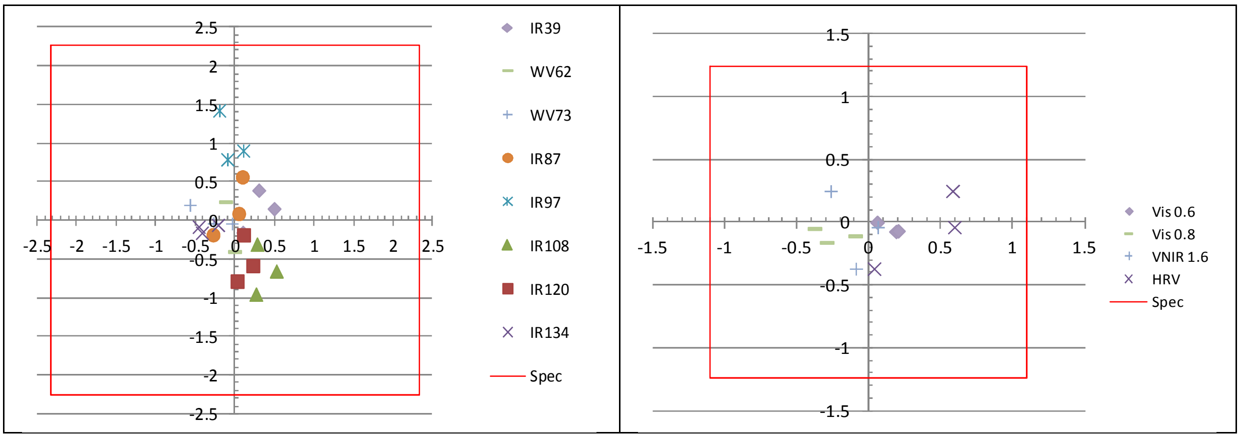

Figure 7 – Co-registration of the SEVIRI channels for Meteosat 11 (IR channels left, Visible/Near IR right).

V. Conclusions

MSG has been a successful successor to and major improvement over the Meteosat First Generation satellites - in a large extent due to the superb performance of the SEVIRI instrument. The careful work performed on ground in designing SEVIRI has been effective in ensuring a high quality in orbit instrument. SEVIRI has been proven to provide data with high availability, high geometric quality/accuracy and good radiometric quality, with an excellent signal to noise ratio - exceeded most specifications. Furthermore, Meteosat 8 has so far, exceeded specified lifetime by a factor of two - and the other MSG satellites are expected to continue to provide valuable geostationary images to support operational meteorology and climate monitoring for many more years.

References

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