Meteosat SEVIRI Performance Characterisation and Calibration with Dedicated Moon/Sun/Deep-space Scans

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The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) aboard the EUMETSAT Meteosat Second Generation (MSG) geosynchronous satellites provides real time imagery in 12 spectral channels (from 0.6 µm to 13.4 µm) of the Earth full disc (every 15 min) and Europe (every 5 min), for weather forecasts and severe weather warnings. Launched on July 15th 2015, MSG4 is the last of the MSG series; it has completed its commissioning phase and it has been placed into in-orbit storage on December 7th 2015. As part of the commissioning activities, the radiometric performance of the instrument is tested via dedicated scans of different radiative sources, namely the Sun, deep space and the Moon. These tests are part of the Image Validation and Verification and are aimed to characterise respectively the stray-light entering the instrument baffle, the 1/f noise and the drift of the Visible and Near Infra-Red (VNIR) channels over 24 hours. This paper, introducing the basic concepts of characterisation and calibration, describes the different steps that led to the acquisition of these different radiative sources and their results assessing the imaging performance of the MSG4 SEVIRI instrument.

Nomenclature

C	=	digital count
DC	=	Digital Count
E	=	electrical signal
Φ	=	irradiance
FDS	=	Full-Disk Service
FES	=	Full Earth Scan
HRV	=	High Resolution Visible
IMPF	=	IMage Processing Facility
IVV	=	Image Validation and Verification
λ	=	wavelength
L	=	radiance
LUT	=	Look Up Table

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MPEF = Meteorological Products Extraction Facility
MSG = Meteosat Second Generation
NIR = Near Infra-Red
RSS = Rapid-Scan Service
SEVIRI = Spinning Enhanced Visible and Infra-Red Imager
SSP = Sub-Satellite Point
VIS = VISible
VNIR = Visible and Near-Infra-Red

I. Introduction

A. EUMETSAT and Meteosat

EUMETSAT is the "European organisation for the exploitation of meteorological satellites", founded in 1986 to monitor weather, climate and the environment. The operated system of meteorological satellites monitors the atmosphere, oceans and land surfaces. The weather and climate-related satellite data, images and products are delivered to the users 24 hours a day, 365 days a year[1]. EUMETSAT currently has seven operational satellites: Meteosat-7,-8, 9 and 10, Metop-A, -B and Jason-2. The Meteosat are the satellites of the geosynchronous (GEO) fleet. There are two generations of active Meteosat satellites, Meteosat Transition Program (MTP) with Meteosat-7 and Meteosat Second Generation (MSG) with Meteosat-8, -9 and -10 (see Table 1). The Metop are the low-Earth polar orbiting meteorological satellites which form the space segment component of the overall EUMETSAT Polar System (EPS). Low orbit satellite Jason, joint project of NASA and CNES, is the satellite oceanography mission to monitor global ocean circulation, study the ties between the ocean and the atmosphere, improve global climate forecasts and predictions, and monitor events.

Meteosat-7 (launched in 1997) is the last of the first generation of EUMETSAT Meteosat satellites and currently operates over the Indian Ocean. The Meteosat Second Generation[2] provides real time imagery rectified to 0° longitude of the Earth full disc (Full Earth Scan, FES) every 15 minutes, and Europe (Rapid Scan Service, RSS) every 5 minutes.

The EUMETSAT satellites are re-named after in-orbit commissioning. For the GEO mission, it is Meteosat with a progressive number regardless of the program/generation, as listed in Table 1. Meteosat-11 is not currently operational but in In-Orbit Storage (IOS)[4]. The Meteosat satellites of second generation are spin-stabilised at 100 rpm to support imaging via the main payload Spinning Enhanced Visible and Infra-Red Imager, SEVIRI. In the next section a specific description of the instrument is presented.

Table 1. General information about current Meteosat satellites

Satellite		Launch date	Longitude	Services
Meteosat-11	(MSG4)	15/07/2015	3.4° W	Back-up, In-orbit Storage
Meteosat-10	(MSG3)	05/07/2012	0°	Full-Disk Service, Real-time Imagery
Meteosat-9	(MSG2)	22/12/2005	9.5° E	Rapid Scan Service, Real-time Imagery
Meteosat-8	(MSG1)	28/08/2002	3.5° E	Backup service for 0°, RSS gap-filling
Meteosat-7	(MTP)	02/09/1997	57° E	Indian Ocean Data Coverage, Real-time Imagery

B. SEVIRI Instrument Functional Overview

The SEVIRI imaging principle is illustrated in Figure 1. SEVIRI is designed to image the Earth from a geostationary satellite spinning at 100 rpm (0.6 sec rotation period). Within each revolution, the east-west (Earth) scan, also named Earth Acquisition Window (EAW), corresponds to 30 msec. The image is obtained by deflecting the radiation beam towards the SEVIRI telescope (right in Figure 1) at each revolution using the primary scan mirror which rotates progressively to perform the south-north scan (left in Figure 1). The FES image is obtained by rotating the primary mirror from – 4.5 deg to + 4.5 deg (with respect to the position pointing at the equator) in 1249 positions. As a result a full disk SEVIRI acquisition is composed of 1249 scan lines and it is performed in 12.5 min. Once the south-north (forward) scan is completed, a retrace phase of 2.5 min repositions the mirror for the next acquisition starting at – 4.5 deg. The duration of the forward scan plus the retrace duration set the SEVIRI Repeat Cycle (RC) time to 15 min. In addition to FES, RSS is also provided. Consisting in the imaging of a portion of the full disk covering Europe, the RSS is obtained by scanning only 410 scan lines with a RC of 5 min.

SEVIRI generates images in 12 spectral channels, listed in Table 2. Here the Visible and Near-Infrared (VNIR) channels are also named “warm” or “solar” channels, while Infrared (IR) channels are named “cold” or “thermal”. The imaging resolution is 3 km at sub-satellite point for all channels except for the HRV one that has 1 km and observes only a portion of the SEVIRI field-of-view (FOV).

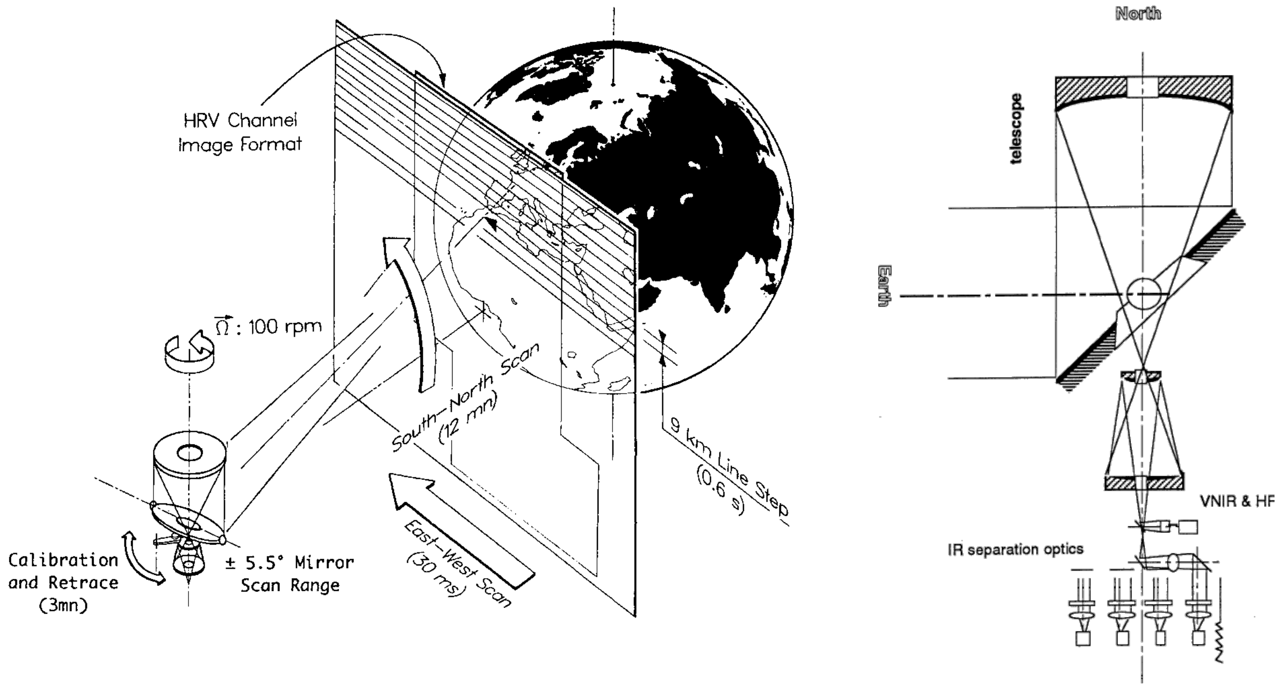


Figure 1. SEVIRI Earth imaging principle (left) and telescope overview (right).

Table 2. SEVIRI channels spectral and spatial resolution

Channel type	Channel	Central wavelength and range [µm]		Spatial resolution at SSP [km]
warm/solar	HRV	0.75	[0.3; 1.30]	1
	VIS 0.6	0.635	[0.56; 0.71]	3
	VIS 0.8	0.81	[0.74; 0.88]	3
	NIR 1.6	1.64	[1.50; 1.78]	3
cold/thermal	IR 3.9	3.92	[3.48; 4.36]	3
	IR 6.2	6.25	[5.35; 7.15]	3
	IR 7.3	7.35	[6.85; 7.85]	3
	IR 8.7	8.7	[8.30; 9.10]	3
	IR 10.8	10.8	[9.80; 11.80]	3
	IR 12.0	12	[11.00; 13.00]	3
	IR 9.7	9.66	[9.38; 9.94]	3
	IR 13.4	13.4	[12.40; 14.40]	3

C. SEVIRI Characterisation and Calibration

Characterization and calibration of the SEVIRI instrument are performed in three main phases, namely, (i) pre-launch characterisation, (ii) post-launch calibration, and (iii) on-ground processing with the aim of enabling the correct conversion from Digital Counts (DC) to radiances for each pixel imaged by an instrument. This conversion is performed by means of calibration coefficients (or calibration equation (1)):

$$\Delta C = \frac{G}{1 + BL} L \quad (1)$$

where C is the DC value, ΔC the count with offset removed and L the input radiance. This function represents the calibration model transforming the input radiance into digital counts. For the solar channels $B = 0$ so that the calibration is linear.

At any instant of the Earth imaging (or blackbody measurement, see below), the instrument collects a flux determined by the radiance of the current target which is distributed to each detector. This flux also includes any parasitic radiation and the instrument thermal emission (affecting only IR channel). The signal offset, including the instrument background and the detection dark signal, is measured at each line scan during the viewing of deep space and removed from the detector output signal via the Dark Current Removal (DCR) function. From orbit, the raw digital counts in the down-linked SEVIRI image data represent the numerical difference between the measurement and an observation of deep space plus a numerical offset. Hence, ΔC can be easily calculated from equation (1) by subtracting the known numerical offset.

As the launch conditions, operational scenarios, contamination, and ageing will inevitably affect the instrument performances, the periodical updating of the calibration coefficients is necessary to guarantee the radiometric quality of both images and products along the entire life period of the instrument.

Because the gain of the detection chains varies with the instrument ageing and thermal variations, it is also necessary to calibrate the channels using a well characterised radiance source in order to maintain the required absolute radiometric accuracy. The SEVIRI instrument has been equipped with a blackbody radiance source (of accurately measured temperature) which is periodically brought into the optical path to perform the calibration of the IR ("cold") channels. The blackbody is operated at two temperatures allowing for determining a gain (G, eq. (1)) correction but not a measurement of the non linearity (B), so that the ground characterised value is used.

In the absence of on-board SEVIRI solar band calibration mechanism, the operational calibration of the SEVIRI VNIR (solar) bands is based on a vicarious calibration technique using stable desert scenes as transfer targets[6].

The calibration information is then used to calculate the incoming radiance from the digital counts. The radiance is used to populate the level 1.5 image product. Here, a fixed scaling is used to map the radiance value to the integer level 1.5 image counts:

$$Physical\ Units = Cal_{Offset} + \left(Cal_{Slope} \times Level\ 1.5\ Pixel\ count\right) \quad [\mathrm{mWm^{-2}\ sr^{-1}\ (cm^{-1})^{-1}}] \tag{2}$$

II. The MSG System Commissioning Image Verification and Validation

The Image Verification and Validation (IVV) aims to provide proof of the fidelity of the SEVIRI-derived level 1.0 images and the IMPF-derived level 1.5 images, and compliance with EUMETSAT system requirements. Also, the functionality and performance of the IMPF with real MSG data for the new S/C will be verified. This verification and validation is achieved using a combination of image inspection and interrogation of image content. It consists of a set of tests performed during the satellite commissioning (post-launch calibration). Among them, a special relevance is to be given to the tests involving the acquisition of Deep Space, Sun and Moon. The objective of scanning these different sources is to use the resulting images so as to:

i. Deep Space – derive the signal to noise ratio for all channels;
ii. Sun – characterise the impact of stray light on Level 1.0 images, to use the stray light characterisation to set-up the IMPF stray light correction model and to assess the performance of the IMPF stray light correction model;
iii. Moon – calibrate VNIR channels.

1. Signal to Noise Derived from Deep-Space Scans

The noise levels of all channels are comparable to those obtained from the space corner statistics and within specification. This test aims to detect low frequency noise problems such as pink noise 1/*f* that can cause stripes in the image. To perform this test SEVIRI needs to scan the empty space, i.e. no Earth, Moon, Sun nor bright stars are allowed in the FOV. As the celestial bodies cannot be removed from the FOV, the FOV is moved to scan the empty space using a special trick at DHSS level. The start of the EAW is calculated by the SEVIRI Functional Control Unit (FCU) based on the reception from the Data Handling Sub-System (DHSS) of three signals: the converter synchronisation signal, the Start Of Line (SOL) signal and the Master Clock (MCLK) signal. Processing the signals the FCU produces several outputs among which the SCAN-START signal which is transmitted to the Main Detection Unit (MDU) for the image acquisition. It is possible to "corrupt" the SOL at DHSS level via commanding a time offset from ground. This time offset will be translated by the FCU into an offset in the start of the EAW, meaning the FOV is being moved. With the right time offset, the SEVIRI FOV will be pointing the dark space. The scan type selected for the test is FES. A custom manual stack commands setting the same MDU output gain to all channels is uploaded to the S/C for the test. Nominally, this test is performed prior Sun images acquisition applying the same scan settings described in the next session. This is standard operations for the IVV commissioning testing.

2. Stray light Characterisation

The IMPF stray light model aims to describe the stray light content in an image as a function of the angular distance from the Sun. The compensation is only applied when the Sun is within a configurable angular distance to the pixel and is not covered by the Earth disk. The stray light model is 1-dimensional polynomial giving radiances of stray light [$mWm^{-2}sr^{-1}(cm^{-1})^{-1}$] as a function of distance in pixels from the Sun centre. This stray light contribution is then subtracted from the Level 1.5 image. A stray light compensation is only derived for the IR 3.9 channel, as the stray light levels (outside the image of the Sun) are negligible in the longer wavelength channels and the warm channels are not usable at all, being night.

The 1-dimensional polynomial straylight model is created from a fit of an image of the empty space and the Sun, similar to the Deep Space Scans described above. The SEVIRI Earth Acquisition Window (EAW) is moved away from the Earth towards the Sun and kept fixed for several repeat cycles as the Sun transits over the SEVIRI field of view (FOV).

During the test, performed on 27 August 2015 following deep space acquisitions, the SEVIRI EAW (i.e. the FOV) was moved away from the Earth towards the Sun and kept fixed for several repeat cycles as the Sun transited over the field of view. The Sun was at elevation β of 11.95 deg at 11:00 UTC and at 11.92 deg at 13:00 UTC. This elevation is high in the SEVIRI FOV and therefore SEVIRI was configured to complete forward scanning with scan mirror at 1560 scan lines above limit switch L1. This is as well a standard operation for IVV commissioning test.

3. Moon Observations and the Calibration of the SEVIRI Solar Channels

In the absence of on-board SEVIRI solar band calibration mechanism, the operational calibration of the SEVIRI solar bands is based on a vicarious calibration technique using stable desert scenes as transfer targets[6]. Such a method provides the calibration coefficients for each band and allows one to monitor the band temporal drift. However, several years are required to derive reliable drift estimates and to reduce the uncertainties caused by seasonal variations and changes in surface properties of the desert targets. To overcome these limitations complementary targets can be employed for drift monitoring. Currently EUMETSAT employs two complementary calibration targets: Deep Convective Clouds, and the Moon. Here we will focus on the Moon calibration target. Moon acquisitions are nominally part of the IVV tests performed during commissioning. This one in particular, conducted during MSG4 commissioning is a special custom test exceptional by means of operation preparation and duration/moon-phase acquisition.

III. The Lunar Calibration System

The Moon is a target whose surface properties are exceptionally stable in time[7], and since it crosses the SEVIRI field of view it can be used as a radiometric reference by means, for example, of a lunar irradiance model. Since 2014, EUMETSAT is in charge of implementing, developing and maintaining the GIRO (GSICS Implementation of the ROLO model[8]). The GIRO is currently the international reference for lunar calibration and it is traceable to the ROLO model and has a reproducibility of 1%, allowing it to be used to accurately track calibration changes.

This model allows computing the total irradiance from the Moon disc for a given position of the observer and observation time. It can reproduce the combined effects of the lunar phases (illumination), the non-Lambertian reflection on the surface of the Moon, and the lunar librations. Due to the stability of the lunar surface properties, the GIRO model can be used as radiometric reference for observations made at any time. The GIRO is part of the offline operational Lunar Calibration System (LCS) of EUMETSAT which analyses Meteosat Second Generation operational data for drift monitoring of SEVIRI solar bands. This is composed of two modules: (i) the Moon identification and extraction module, and (ii) the calibration module, i.e. the GIRO.

The Moon identification is done via Connected Component Labelling (CCL) analysis by using the functionalities of the ITK package[9]. This allows one to label connected patches in binary images and to get geometrical properties of such patches. By creating a binary image from one of the Level 1.0 IR channels of SEVIRI and by using the number of pixels composing each patch identified by the CCL analysis, one can identify and distinguish the patch associated to the Earth, i.e. the largest patch in the image, and the patch associated to the Moon, i.e. the second largest patch in the image. The reason why the binary image is created from one of the IR channels is that in this spectral range the Earth has always a circular shape, independently of the illumination condition. Using this extraction method a Moon observation database has been created in EUMETSAT as summarized in Table 3.

Table 3. Number of Moon observation produced by the Moon identification and extraction module.

	MSG1 (2003 – 2015)	**MSG2** (2006 – 2015)	**MSG3** (2013 – 2015)
Phase angle range [deg]	[-150,152]	[-147,150]	[-144,143]
VIS006	507	490	119
VIS008	499	481	116
NIR016	519	489	125
HRV	68	83	26

For the first three MSG operational satellites, the LCS is able to measure the drift of the analysed bands with an accuracy of 0.01 % starting from the second year of accumulated Moon. The annual drift of all the solar bands of MSG1, 2, and 3 is between 0.5 % and 1 % per year, i.e. well within the 2 % long term drift requirement.

In preparation of the MSG4 commissioning, the idea of using the LCS for monitoring the medium-term performances of the SEVIRI solar bands was put forward. In fact, it is not possible to find on Earth a stable target that allows the verification of the SEVIRI solar bands medium-term drift requirement (0.1% over 24 hours). For this reason, the possibility to use the Moon as a stable target was explored. In order to do so, a lunar irradiance model with a relative accuracy better than 0.1% is required. Therefore, Moon observations cannot be used to verify the requirement on the medium-term drift. However, it is still possible to use those observations to:

i. provide some insight on the daily stability of the SEVIRI solar bands, and
ii. Provide some insight on the performances of the GIRO calibration reference when employed for the monitoring solar bands over one day.

For these reasons, dedicated Moon observations were acquired during MSG4 commissioning. Performing dedicated Moon observations allows one to maximize the data for the medium-term drift analysis. Thanks to the possibility of using RSS acquisition during a Moon transit taking place either north or south of the Earth limb, the acquisition of up to 17 Moon observations in all the SEVIRI solar bands over a time interval of about 1.5 hours was achieved. The planning of such acquisitions required the support of predictions from the Flight Dynamics team who performed a dedicated analysis for the test.

IV. Flight Dynamics Moon Acquisition Determination

The Moon periodically crosses the SEVIRI field of view for Earth acquisition. In order to define the best intervals by means of Moon illumination and duration of the acquisition, a study was conducted using the Analysis of Attitude Dynamics and Disturbances tool[5] of the EUMETSAT Flight Dynamics team. Based on a predefined orbit scenario, the tool computes the angle between up to 3 instruments (modelled as the boresight of their reference axis) and the Moon, Sun and Earth. The celestial bodies' motion is modelled according to Chebyshev polynomials of the NASA JPL Ephemerides DE-405. The instrument field-of-view is assumed to be conical or pyramidal with square section. The tool detects intrusions of Sun/Moon/Earth as seen from the spacecraft (see Figure 2) given by the angle from the instrument axis to the limb of the body. Here, only results related to Moon are taken into consideration. To identify blinding and occultation, specifically for Moon and Earth, their phase is also computed. The Sun lid percentage is a function of the angle between Sun and body ζ (see Figure 3), defined as (2):

$$P_{\mathrm{Moon}}(\zeta) = \frac{\pi - |\zeta|}{\pi} \tag{3}$$

A full Moon corresponds to 100% while 0% is a new Moon.

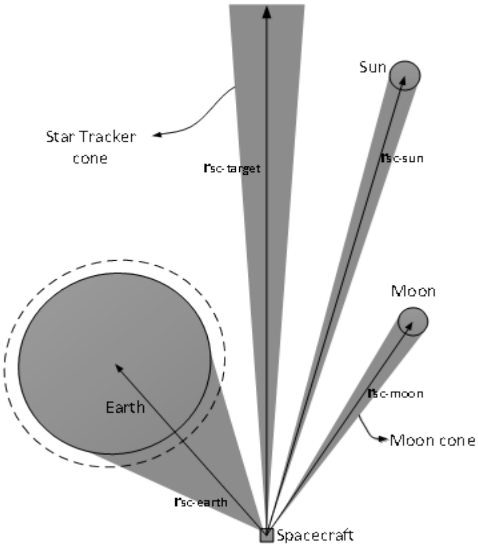


Figure 2. Simplified geometric representation for determination of Sun/Moon/Earth intrusions in the instrument's Field of View.

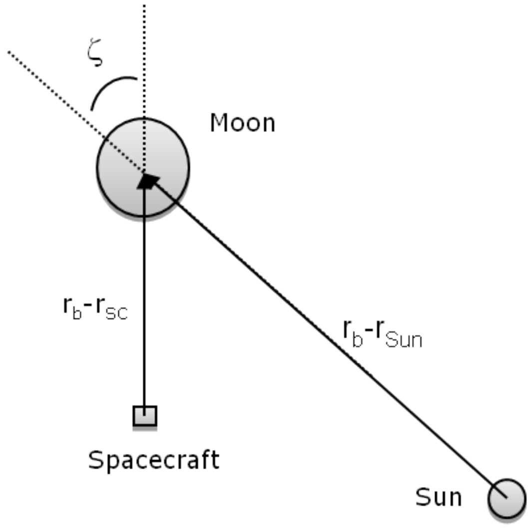


Figure 3. First approximation of Sun lid percentage with angle between Sun and body.

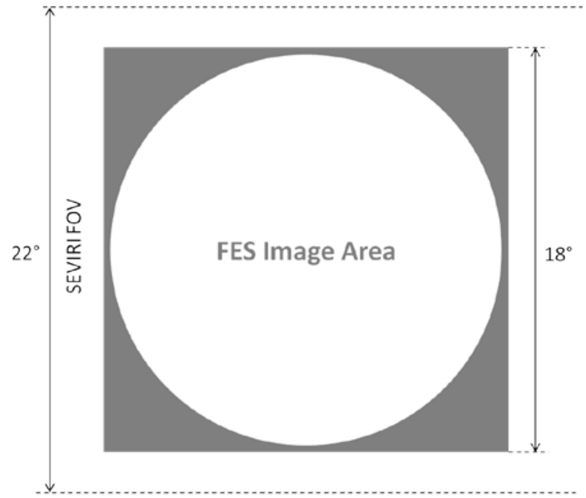
The orbit scenario was prepared ad-hoc, using the Station-Keeping Analysis Tool[6], based on the assumptions for MSG4 commissioning of: (i) launch not earlier than 15 June 2015, (ii) commissioning slot at longitude 3.4 W and (iii) initial inclination of 3.1°. The assumed dead-band for the longitude control is similar to the one used for MSG operations at 0° longitude (Full-Earth Scan service). The simulated time-span covered 365 days.

Assuming a triad rigidly fixed with the spacecraft main body, the attitude is assumed to be geocentric pointing. This is equivalent to assume the spin axis is parallel to the North-South direction. For nominal imaging, considering the limited scan range of SEVIRI, an Earth Aspect Angle allowed range can be identified. Summing up all the main components of the FOV range total budget of 22°, the spin-axis to orbit-pole alignment should be always maintained within 1° (in terms of Earth Aspect Angle: 89° < EAA < 91°).

At beginning of the MSG4 mission, main requirements on the attitude was to have the mean spacecraft spin axis aligned at 1.0° from the instantaneous orbit normal, within a tolerance of 0.1°, and as close as possible to the North-South direction, and the orbit normal inclined up to 3.1° with respect to the equatorial Earth plan, due to in orbit storage initial period[3]. To ease the reading, the simulation results are reported as a function of the angular separation from an instrument boresight pointing the Earth. Thus, the FOV has ±9° angular length in vertical (Y) direction, when considering the instrument relative field of view, with Y-axis parallel to the orbit normal.

The Earth full disc is acquired by SEVIRI in 1249 scan lines, corresponding to 14.412 millideg per line for a total FOV of 18° (see Figure 4).

The threshold on the Moon phase to classify the Moon intrusion as useful for calibration is 55%. The assumed SEVIRI FOV is 18.4° (±9.2°) in X, while for Y an extended FOV is considered of 25° (±12.5°), to cover also potential marginal missed detections. The simulation was then narrowed once launched the S/C, in line with the actual commissioning scheduled activities. Moon intrusions were predicted in the useful interval between 5 August and 2 September 2015. The results of the sumulation are listed in Table 4 and depicted in Figure 5. The optimum interval was spotted on 29 August starting at 11:13 UTC, when the Moon would have crossed the SEVIRI FOV for 85.5 min with 96% phase angle.



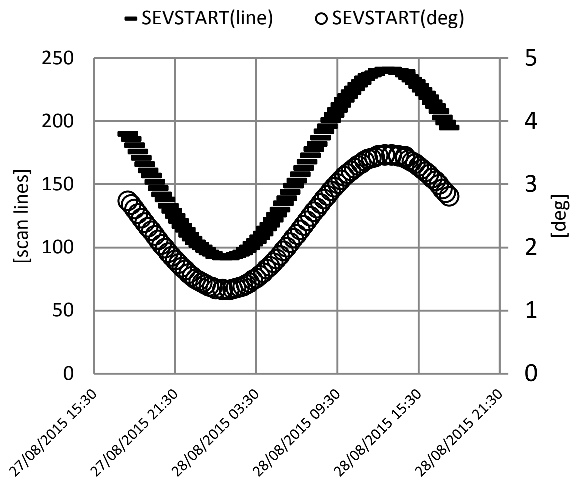


Figure 4. SEVIRI nominal Field-of-View (FOV) definition (left) and SEVSTART (SEVIRI start of line) variation (right). *SEVIRI acquires the Earth full disk in 18 deg FOV. The scan module allows a total scanning range of 22 deg. This is relevant due to the variation of the Earth N/S position respect to the SEVIRI FOV. Therefore, the start line of the scan varies over time with a magnitude that is proportional to the spacecraft attitude angular deviation from the orbit normal. On the right, the variation of the start of line for the Earth acquisition is represented over 24 hours for MSG4 (number of lines is counted from SEVIRI lower limit switch L1).*

Table 4. Moon intrusions in the SEVIRI FOV during MSG4 commissioning.
Data provided by the EUMETSAT Flight Dynamics team.

Intrusion start UTC	Duration [min]	Phase [%]	X-start [deg]	Y-start [deg]	Scan Line [-]
2015-08-05T16:10:34Z	7.73333	60.9559	-9.19869	4.54197	940
2015-08-05T17:27:15Z	8.28333	59.5951	7.40346	4.73261	953
2015-08-06T17:02:46Z	31.8667	53.4922	-9.19901	8.51444	1216
2015-08-06T17:54:59Z	32.7333	52.5696	2.10865	8.52862	1217
2015-08-07T17:54:58Z	84.9667	46.1683	-9.19829	11.9136	1452
2015-08-14T23:49:11Z	84.0167	3.17049	-9.19845	11.6647	1434
2015-08-16T00:34:00Z	31.8833	8.50252	-9.19734	8.68894	1228
2015-08-16T01:26:38Z	31.1667	9.28925	2.3556	8.464	1212
2015-08-17T01:17:21Z	10	14.5643	-9.19859	5.36967	998
2015-08-17T02:31:30Z	9.5	15.716	7.10841	5.16756	984
2015-08-18T01:59:45Z	2.75	20.6694	-9.19804	1.85073	753
2015-08-18T03:20:44Z	2.58333	21.9406	8.62919	1.65258	740
2015-08-19T02:41:48Z	2.65	26.7815	-9.19739	-1.73389	505
2015-08-19T04:02:33Z	2.83333	28.0607	8.57555	-1.9249	491
2015-08-20T03:24:10Z	9.78333	32.9273	-9.19861	-5.25638	260
2015-08-20T04:37:35Z	10.2833	34.105	6.93836	-5.39364	251
2015-08-21T04:07:35Z	32.5667	39.1526	-9.19637	-8.58779	29
2015-08-21T04:58:09Z	33.3167	39.9762	1.89149	-8.57968	30
2015-08-22T04:52:43Z	84.1833	45.5106	-9.19806	-11.5895	-179
2015-08-29T11:13:41Z	**85.6333**	**96.4457**	**-9.19778**	**-10.2715**	**-88**
2015-08-30T12:10:51Z	13.6167	94.5111	-9.19878	-6.24561	192
2015-08-30T13:23:28Z	12.8667	93.2769	6.42664	-5.99233	209
2015-08-31T13:06:51Z	2.75	86.6266	-9.19858	-1.79501	500
2015-08-31T14:29:39Z	2.55	85.1241	8.64975	-1.54069	518
2015-09-01T14:01:49Z	3.91667	78.6891	-9.1976	2.72847	814
2015-09-01T15:22:46Z	4.28333	77.2113	8.2737	2.9607	830
2015-09-02T14:56:04Z	17.85	70.8814	-9.19646	6.99501	1110
2015-09-02T16:02:35Z	18.65	69.6702	5.1691	7.10448	1118

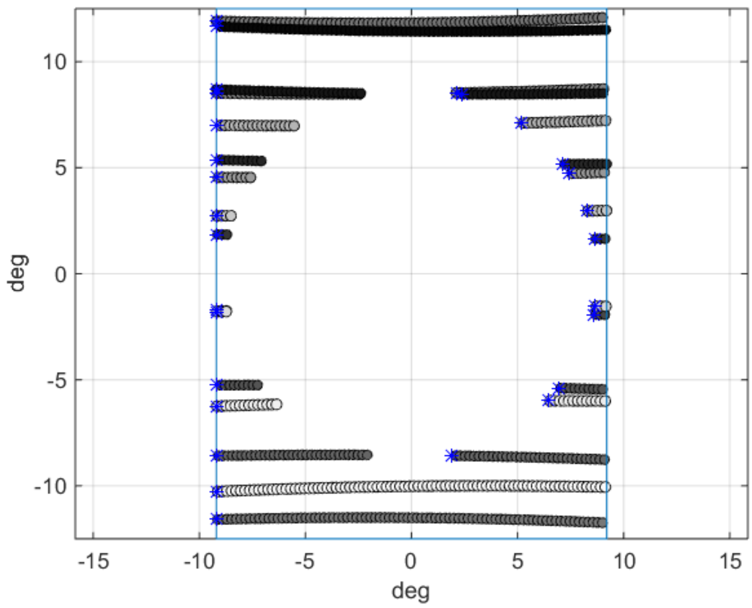


Figure 5. Representation of the Moon intrusions in the SEVIRI FOV listed in Table 4. *Results based on EUMETSAT Flight Dynamics predictions over the commissioning time frame.*

V. Operational Planning and Schedule for Moon Acquisition

The target interval for the custom Moon scanning was decided based on the FD predictions and the on-going MSG4 commissioning schedule. The designated slot was on Saturday 29 August 2015. On that date, the Moon with a phase of 96% was predicted to pass below the Earth starting at 11:13 UTC for duration of 85.5 min. The slot was then exceptional for high Moon illumination and duration of the acquisition. The planning of the test was developed along the following salient points:

i. Maximisation of the number of acquisitions during the interval;
ii. Usage of the HRV channels;
iii. Image layout including the Earth.

To accomplish point (i), RSS was selected as scan type. Nominal rapid scanning consists in mini scans of the duration of five minutes and they are nominally applied for routine RSS service over Europe. This way the triple of images and therefore Moon acquisitions could be obtained respect to a generic 15 min full disc scan.

Point (ii) required a customised moving of the HRV window. The SEVIRI HRV detectors have a different design respect to the VNIR and IR channels. The acquisition window of the HRV is half of the full disc, i.e. it has a width of 15 msec. Therefore, for routine operations the HRV window is moved during the day following the Sun illumination. At the time predicted for the test, the HRV would have been on the right hand side respect to the Earth acquisition window (EAW), away from the Moon during the first half of its acquisition. This led to shifting the HRVW three times during the test.

The RSS has a total duration of 5 min where 4 min and 10 sec are forward scanning and 50 sec retrace. In terms of scan lines, the RSS image consists of 410 lines (1230 detector lines for VNIR and 3690 for HRV). The Moon can be acquired in about 35 scan lines which give enough margin to the acquisition of the Earth that needs to occupy a bigger portion respect to the Moon to enable the Moon identification and extraction. For this reason and due to the fact that SEVIRI scan range, and therefore FOV, is limited by mechanical stops positioned at ± 5.6 deg respect to the neutral position pointing at the centre of the Earth, it was decided to start scanning at 50 above lower limit switch L1, 180 line below the Earth's lower limb. The plots below (Figure 6) show the position of the Moon in terms of scan lines from L1: the centre of the Moon is at about 130 lines from L1, about 100 lines from the Earth's lower limb. With this configuration, the Earth occupies half of the RSS image in compliance with point (iii).

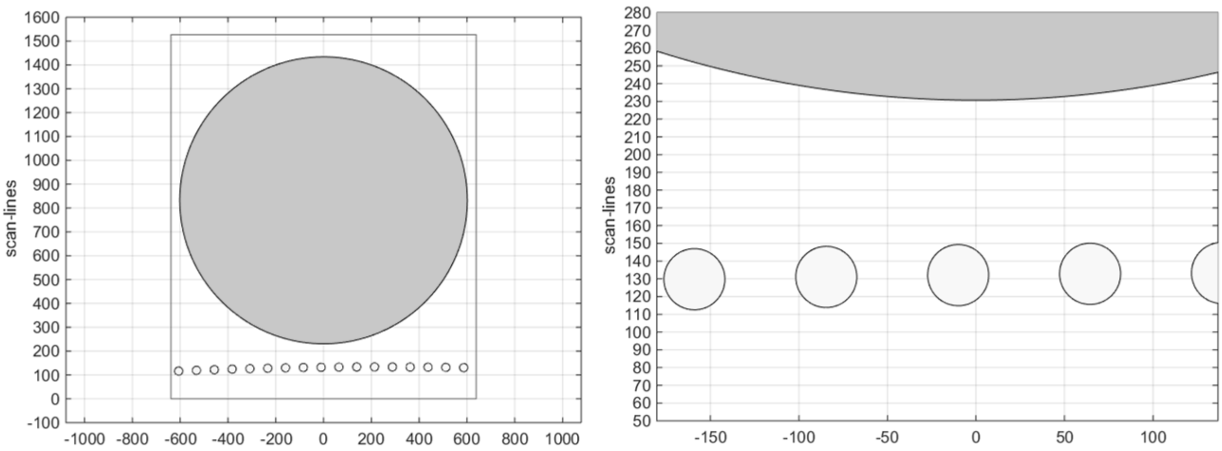


Figure 6. Moon position during the transit on Saturday August 29th 2015 in SEVIRI nominal field of view. *The image is zoomed-in on the right to show the ratio between Moon and Earth respect to the RSS image. As the RSS image is 410 scan lines above L0 (50), the Earth occupies exactly half of the RSS image.*

Decision was made to perform the test using the MSG Mission Planning Schedule (MPS), i.e. using routine automated procedures nominally used for FES and RSS with customised procedure arguments for the test. As MSG4 was performing FES, a transition from FES to RSS and back was required. FES-RSS transitions are nominally performed as part of routine operations. It is in fact a health requirement of the SEVIRI manufacturing industry to interrupt RSS once per month for the duration of two days and once per year for the duration of one month. The operations of the instrument are defined through a set of operation parameters loaded by means of a memory load commands. The relevant ones in terms of scan transitions are parameters “N” number of forward scan lines and “K3” number of retrace scan lines. These two parameters allow to increase/decrease the number of scan lines during the phases of forward scan and retrace, so to station the SEVIRI scan mirror at the right position for the acquisition target. For the lunar scan, N and K3 were customised to first lower the FOV from the nominal FES to RSS 50 scan lines above the scan mechanism mechanical stop L1. During the test, the ops parameters were kept unchanged so as to keep constant the FOV. The HRVW was moved at the beginning of the test to the left hand side respect to the EAW, and moved during the test to acquire the Moon also with the HRV. At the end of the test, the ops parameters were changed again to restore nominal FES. The ops parameters values driving this operation are listed in Table 5 and represented in Figure 10. Figure 11 shows the mirror position during the test.

Table 5. Mission planning Ops parameters for Moon scan on DOY241 (29/08/2015)

Start of RC [UTC] (DOY241)	SEVSTART	N	K3	HRV DELAY (ClkP)
11:00	50	410	400	55808
11:15	50	410	400	55808
11:30	50	410	400	55808
11:45	50	410	400	28672
12:00	50	410	400	28672
12:15	50	410	400	0
12:30	50	410	400	0
12:45	50	410	400	0
13:00	50	410	400	0

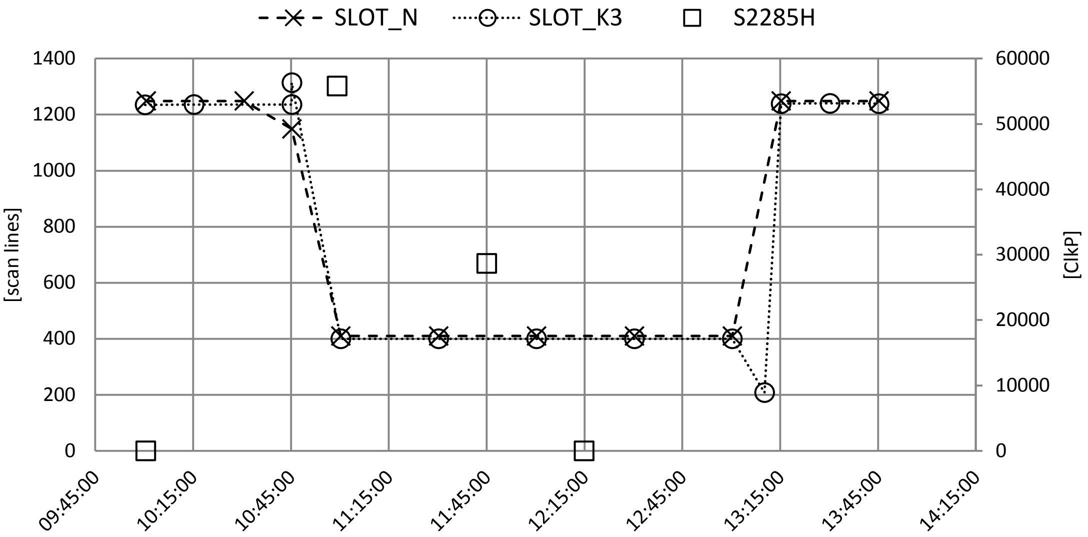


Figure 7. SEVIRI Sequence Manager Ops Parameters. *Representation of Table 6, where N is the number of forward scan lines, K3 is the number of scan lines for retrace and S2285H is the telemetry associated to the HRV window shift.*

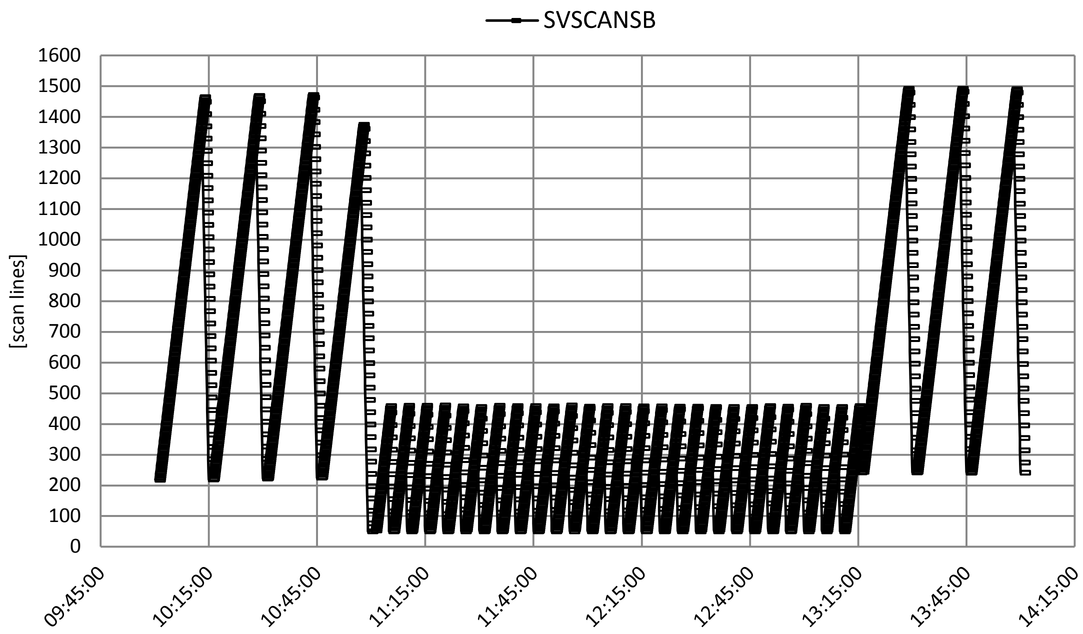


Figure 8. SEVIRI scan mirror position

VI. Test Results

A. Signal to Noise Derived from Deep Space Scans

The test was performed on 27 August 2015. No significant "features" in the images could be identified. Figure 9 and Figure 10 show test results respectively for channels VIS 0.6, IR 12.0, WV 7.3 and WV 6.2. Some occurrences of weak telegraph noise (visible as lines) were observed, but this is not expected to affect image quality. There is no apparent low frequency noise problem. It can be concluded, that the space scans show the same noise values as during normal scan.

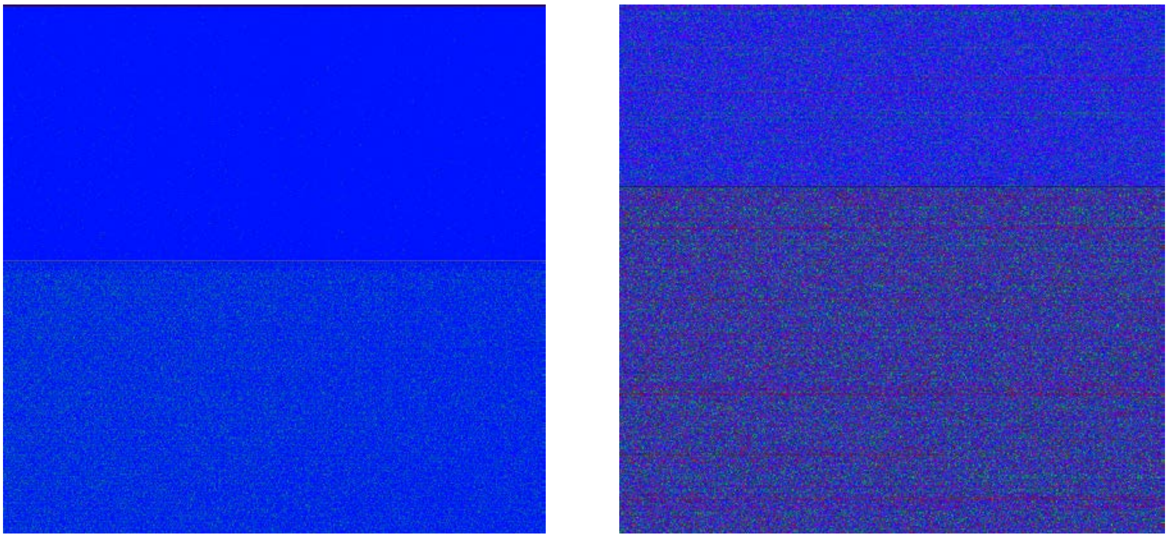


Figure 9. Space Scan from Channels VIS 0.6 (left) and IR 12.0 (right). *Repeat cycles starting 09:15. The mean value is 51 counts, as expected.The noise is enhanced because of setting the MDU output gain q=1. The ColouringScheme is enhancing the noise. During retrace, in the upper part of the panel, the gain is reset to q=0*

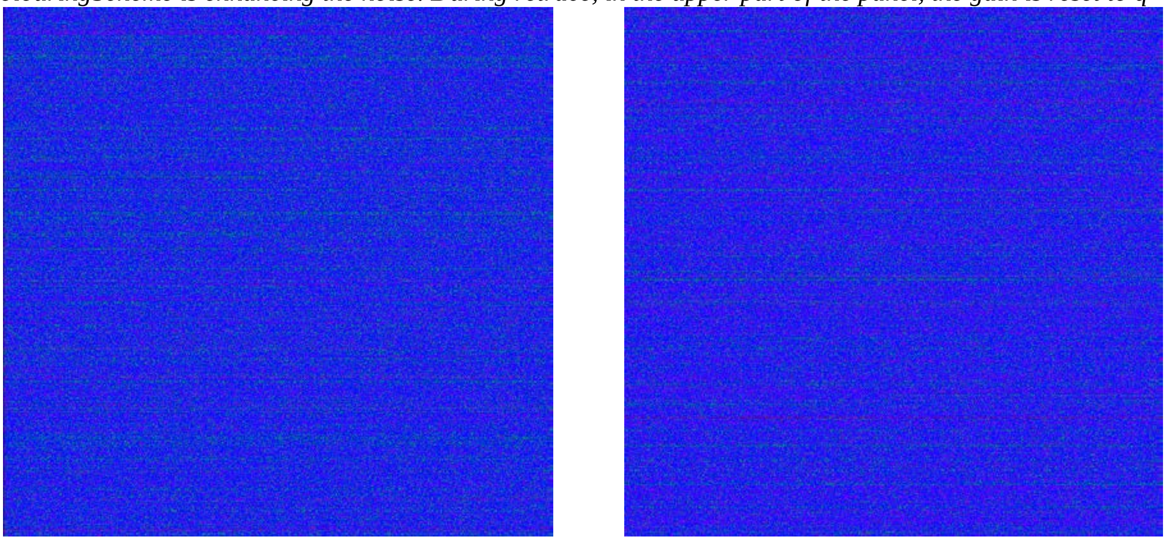


Figure 10. Space Scan from WV Channels WV 7.3 (left) and WV 6.2 (right). *Same setting as channels 0.6 and 12.0 are applied except that In this case q was not changed.*

B. Stray Light Characterisation

Figure 11 shows the images collected during the stray light characterisation test. As depicted, the Sun was just outside FOV (about 30 scan steps North). During this time of the year, the scan range is not sufficient to capture the Sun. This is acceptable, as the data close to the Sun is not usable. The Sun moved from left to right across FOV and finally moved out towards right. Sun scans were performed using nominal earth gains.

Only the solar channels (VIS 0.6, VIS 0.8, NIR 1.6 and HRV) and the IR 3.9 channel are affected when the Sun is close to the Field of View of the instrument. This is only the case for a few hours around midnight during or close to eclipse season. Although the effect is larger for the solar channels, the illuminated part of the Earth is minimal and hence the usefulness of the solar channel data collected during this period is low. Therefore, stray light correction is disabled for the solar channels and only enabled for channel IR 3.9.

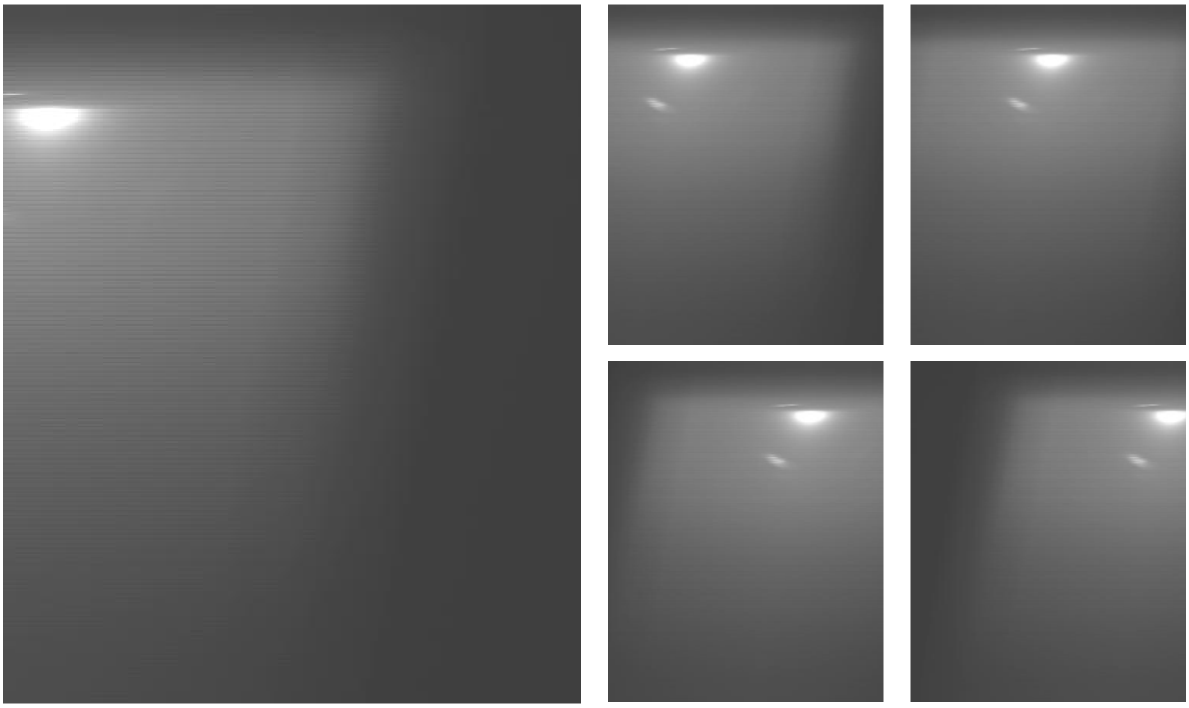


Figure 11. Sun scanning images for the stray light characterization. *Sun transition in FOV during deep space scans for channel VIS 0.6. From left to right and top to bottom: repeat cycle starting at 10:30z, 10:45z, 11:00z, 11:15z and 11:30z, 27th August 2015.*

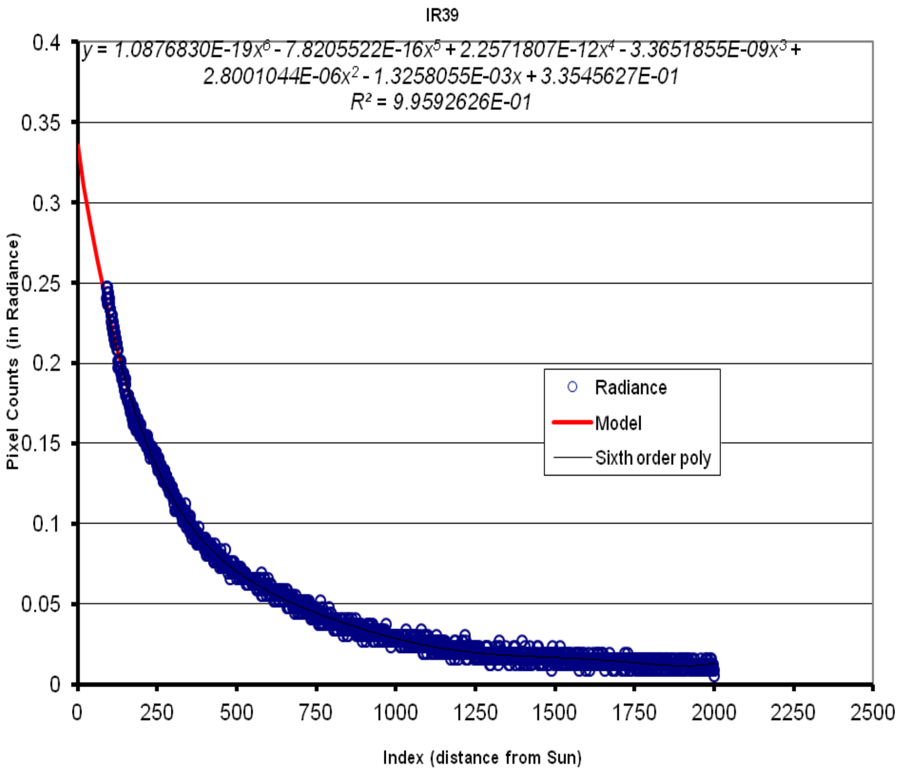


Figure 12. Stray light characterisation as a function of the angular distance from the Sun. *Only the solar channels (VIS 0.6, VIS 0.8, NIR 1.6 and HRV) and the IR 3.9 channel are affected when the Sun is close to the Field of View of the instrument. This is only the case for a few hours around midnight during or close to eclipse season. Although the effect is larger for the solar channels, the illuminated part of the Earth is minimal and hence the usefulness of the solar channel data collected during this period is low. Therefore, stray light correction is disabled for the solar channels and only enabled for channel IR 3.9.*

Offline analysis of the data has been done and Chebyshev coefficients derived for the Sun scan images. Following, the stray light from the Sun is modelled by a Chebyshev polynomial of angular distance from the Sun. The radiance has been derived as a function of the angular distance from the sun by creating vertical profiles through the space. Figure 12 shows the final result with the stray light as a function of the angular distance from the Sun.

C. Extraction of the Moon images and calibration results

The analysis via the EUMETSAT Lunar Calibration System (LCS) of the dedicated Moon scans performed on 29 August 2015 was successful. The calibration tool succeeded in the extraction and calibration of a total of 17 Moon observations in the VIS0.6, VIS0.8, NIR1.6 and HRV channels. The sequence of Moon acquisitions covers a total time interval of 1 hour 20 minutes. With the aim of complementing the results derived from the dedicated Moon scans, further data acquired during nominal FES imaging within 24 hours from the first acquisition. On 30 August 2015 the Moon was acquired again inside the nominal SEVIRI FOV (i.e. without custom observation) and the images were analyzed. These new data consist of two acquisitions in the low resolution channels and one in the HRV. Table 6 summarises the observation conditions of all Moon observations extracted and calibrated by the LCS. In this table the "phase angle" is the angle between the vector identifying the position of the Earth and the vector identifying the position of the Sun in the Moon fixed "mean-Earth" reference frame for the different observation times. This angle measures as well the illumination of the Moon but in this case a phase angle equal to zero indicates a full Moon (opposite to the 100% Moon phase mentioned in Section IV). This convention is the one used in the framework of the LCS and therefore is the one used hereafter. Figure 13 provides a composed image of all the observations extracted on the 29th August 2015 in the HRV channel.

Table 6. Acquisition times, illumination conditions, and availability in SEVIRI channels. *Moon observations in MSG4 data during the dedicated Moon scans of the 29 August 2015 and on 30 August 2015 full-disk mode.*

#	Time [YYYY.DD.MM.hh.mm.ss]	Phase angle, *g* [deg]	Available channels, scan mode
1	2015.08.29.11.16.06	- 6.23	
2	2015.08.29.11.21.09	-6.14	
3	2015.08.29.11.26.11	-5.98	
4	2015.08.29.11.31.13	-5.82	
5	2015.08.29.11.36.14	-5.67	
6	2015.08.29.11.41.15	-5.51	
7	2015.08.29.11.46.16	-5.36	
8	2015.08.29.11.51.15	-5.21	
9	2015.08.29.11.56.14	-5.06	All, RSS
10	2015.08.29.12.01.13	-4.91	
11	2015.08.29.12.06.14	-4.76	
12	2015.08.29.12.11.14	-4.61	
13	2015.08.29.12.16.15	-4.47	
14	2015.08.29.12.21.16	-4.32	
15	2015.08.29.12.26.17	-4.18	
16	2015.08.29.12.31.18	-4.04	
17	2015.08.29.12.36.18	-3.91	
18	2015.08.30.12.17.03	10.10	Low resolution, FES
19	2015.08.30.13.32.10	12.41	All, FES

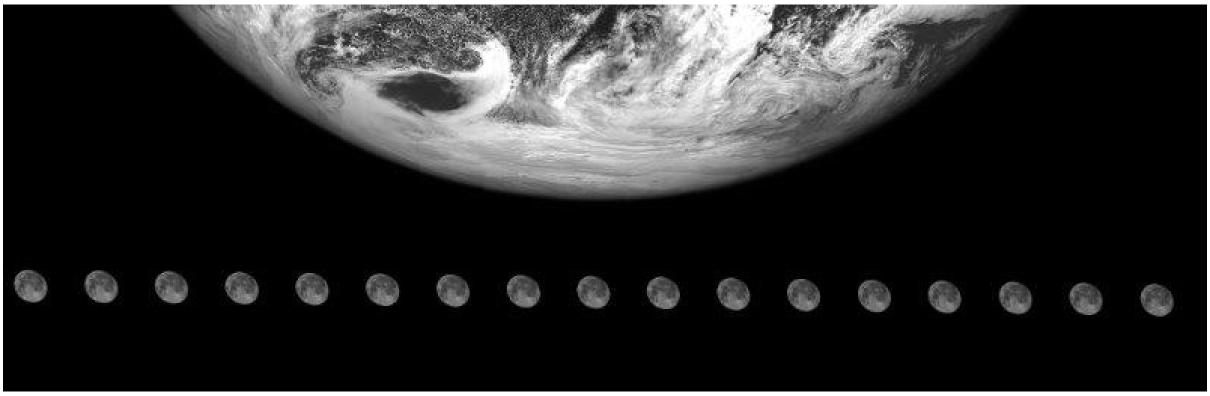


Figure 13. Composit image of the Moon observations in the HRV band. *Image shows the 17 cases extracted on 29 August 2015 (listed in red in Table 6).*

All observations are very close to full-Moon illumination and are all analyzable by the LCS. The LCS has an applicability range of phase angle in the range [2, 92] deg in absolute value. The analysis of the calibration results was focused on the study of the short term stability of the VNIR channels of MSG4.

For this purpose the following quantities have been studied:

i. The quantity *Obs*

$$Obs = \sum_{i=1}^{N_{PIX}} (DC_i) - N_{PIX} Off_{DC} \text{ [DC]} \tag{4}$$

In this definition, the sum is performed over the NPIX pixels above a specific threshold used for the analyses of MSG data, and the OffDC is the imagette offset derived as average over a five-pixel-wide region along the imagette border.

ii. The calibration coefficient Cf at the scale of the GIRO reference derived as:

$$Cf \propto \frac{Irr_{GIRO}}{(Obs)} \text{ [W m}^{-2}\text{ µm}^{-1}\text{ DC}^{-1}\text{]} \tag{5}$$

The temporal variation of the quantity introduced in eq. (5) is a measure of the degradation of the monitored radiometer, while the temporal variation of the quantity in eq. (4) shows the variation of the observed integrated signal in Digital Counts from the Moon imagettes. Both temporal variations are expressed in percentage with respect to the value of the observation #1 in Table 6 (named the REF case).

Figure 14 shows in the same plot the variation of C_f and *Obs* as a function of time for a direct comparison with the outcome of the calibration (magenta content of the plots). From the plots, one can make a clear distinction between the observations on 29 August and the ones on 30. Plots are split in 2 parts showing on left the observations on 29 August characterised by positive *Obs* values and on the right the observations on 30 with negative values. The reason for such difference can be found into the Moon illumination conditions. In fact, during the acquisition interval, the illumination of the Moon goes from waxing to waning. The illumination condition determines an observed Moon irradiance that is lower in the waning observations respect to the waxing ones, as confirmed by the negative values of *Obs* variation for the two observations of 30 August due to the larger absolute values of the phase angle reached during this date opposite to the ones observed on 29. The variation of the *Obs* is similar in magnitude for all the four warm channels (the reader can refer to the horizontal magenta dotted lines in the plots in Figure 14).

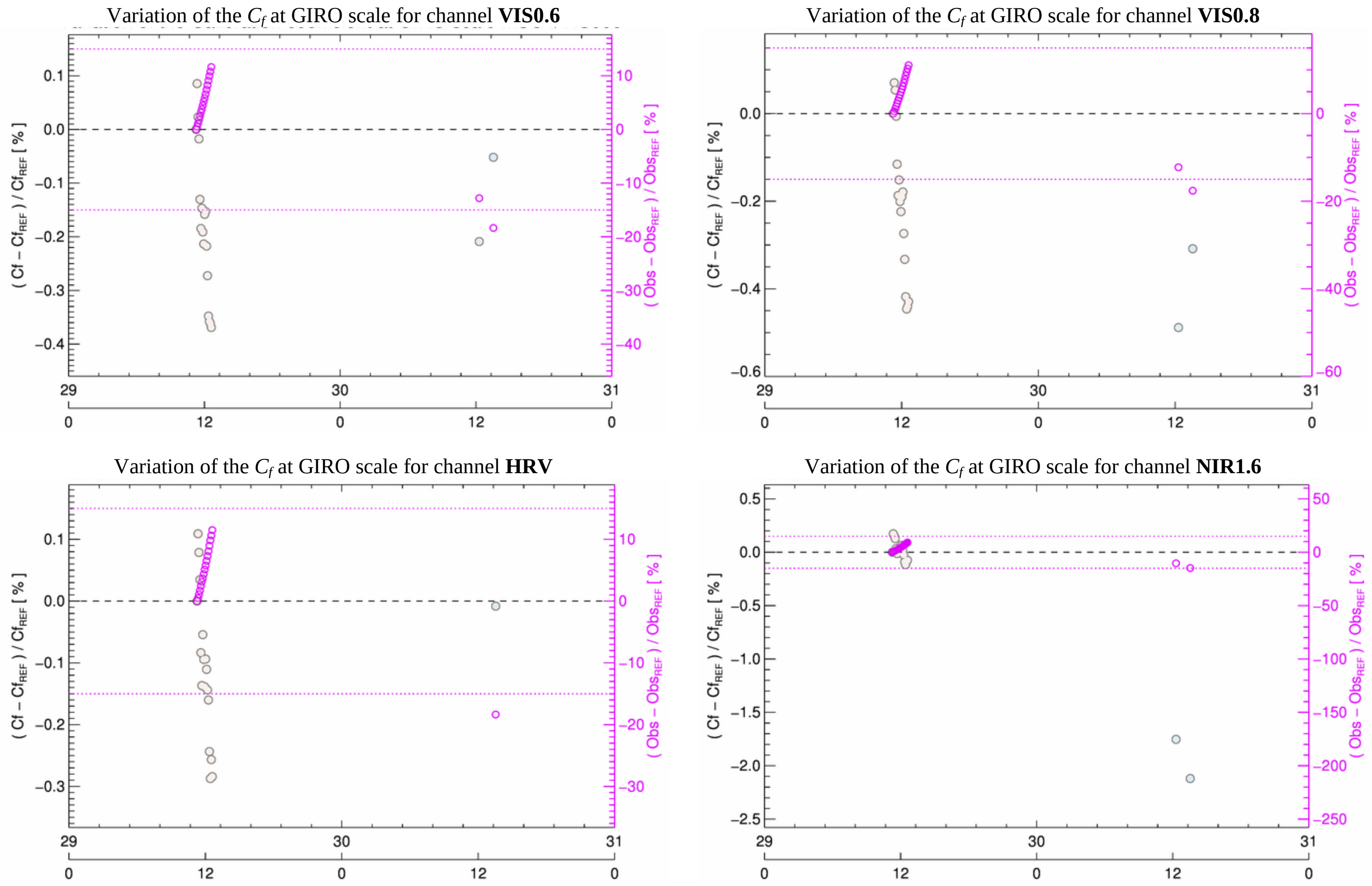


Figure 14. Results of the LCS calibration applied to the four warm channels of MSG4. *In each panel: variation of both Cf (coloured dots) and Obs (purple dots) as a function of time; the Cf points are coloured according to the phase angle colour bar in Figure 14 and their variation is referred to the left-side Y axis, the Obs purple circles refer to the right-side purple Y axis (the two horizontal purple dotted lines mark the ±15% variation range of Obs for a comparison between the different plots).*

The variation of C_f is a measure of the *Obs* variation compared to the GIRO reference (see equation (4)). In fact, C_f is derived from the ratio between the GIRO disk-integrated Moon irradiance and the *Obs* (multiplied by a constant). The relative accuracy of the GIRO reference radiance is of 1%. From this it stems that a relative variation of C_f below 1% indicates a stable behaviour of the instrument. This is the case for three of the four warm MSG4 channels here analyzed: for the VIS0.6, VIS0.8, and HRV the relative variation of C_f is within 0.5% (peak-to-peak). A different result is found for the NIR1.6 channel where a variation of about -2% is measured over a period of one day (from 29 August to 30). This variation can be explained by a known deficiency of the current version of the GIRO model which has been shown to have some phase dependence residual which introduces a phase-dependent bias in the comparisons with observations. This effect is visible for the MSG1, MSG2 and MSG3 time series, and it is known to be particularly strong in the NIR1.6 band. Specifically, NIR1.6 is affected in the order of 10% in C_f when calibrating observations whose illumination varies in the applicability range of the GIRO, i.e. [2, 92] degrees in absolute value for the phase angle. The important difference with respect to the results obtained so far for MSG1, MSG2, and MSG3 is that for these three missions the phase dependence has been measured by observations extracted from data acquired over many years, and this implies that the phase dependence is super-imposed to the degradation of the instrument. From the MSG4 results (shown in Figure 15), it is reasonable to assume that the instrument is not degrading during one day (as found for the VIS0.6, VIS0.8, and HRV). Therefore, the result in the bottom panel represents clear evidence that the GIRO is unable to accurately reproduce the observations in the NIR1.6 channels while it works properly in the other channels. The GIRO phase-dependence issue is currently under investigation within the GSICS community.

Finally, the results here presented show that:

i. The LCS succeeded in the extraction and calibration of Moon observations from dedicated Moon scans during the MSG4 commissioning.
ii. The VIS0.6, VIS0.8, and HRV channels are stable within the GIRO reproducibility (i.e., 1%).
iii. The NIR1.6 cannot be analysed properly due to well known limitations of the GIRO calibration reference. The results here presented provide further proof of such limitations.

VII. Conclusions

The results presented in this paper reflect the calibration performed on the SEVIRI instrument with the aim of obtaining images with the appropriate radiometric accuracy. Custom tests are performed during the spacecraft commissioning as part of the EUMETSAT IMPF IVV. Thanks to these tests the presence of anomalous behaviour introduced by 1/f noise can be detected and the effect of the stray light compensated for the IR 3.9 channel. The use of different radiative sources is made to achieve these results, and for the cases above mentioned, the deep space and Sun are acquired for the analysis. Furthermore, the acquisition of another source is very beneficial to the calibration of the visible channels, the Moon. This study reveals the potential and the efficiency of planned dedicated Moon observations for calibration purposes. Provided that a dedicated mission planning schedule is prepared based on available flight dynamics predictions, including the synchronisation of the SEVIRI HRV window with the Moon movement, a total of 17 images of the Moon in 1.5 hours can be acquired using rapid scanning. This number can be compared against the number of HRV observations extracted from the complete archive of MSG1: 60 usable observations over more than 10 years. Dedicated Moon observations would allow one to monitor the HRV channel with a much higher accuracy. The same applies to the low resolution channels even though the amount of observations in these channels is much higher than in the HRV. Finally, performing dedicated Moon observations for different illumination conditions would allow one to improve the characterization of the phase-dependence of the GIRO and therefore would allow the possibility to implement systematic corrections leading to an increase of the accuracy of the medium-term and long-term drift estimate.

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