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Introduction to the Novel Verification Concept of the Instrument Performances for the Meteosat Third Generation Infrared Sounder Instrument (MTG-IRS)

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I. INTRODUCTION

The Meteosat Third Generation (MTG) Programme will ensure the future continuity and enhancement of meteorological data from geostationary orbit as currently provided by the Meteosat Second Generation (MSG) system. The industrial prime contractor for the space segment is Thales Alenia Space (France), with a core team consortium including OHB System AG (Germany). This contract includes the provision of six operational satellites, four Imaging satellites (MTG-I) and two Sounding satellites (MTG-S).

MTG-S carries the Infrared Sounder (IRS), which is based on an imaging Fourier Transform Spectrometer (FTS). OHB System AG is the prime contractor for this complex instrument and the associated development is concentrated at its new site in Oberpfaffenhofen (Munich, Germany). The IRS will deliver spectroscopic data in the Mid-Wave-Infrared (MWIR) and Long-Wave-Infrared (LWIR) bands. A scanning mirror will be used to cover the full earth disc within an hour and allows a repetition cycle of 15 minutes over Europe. For the on-ground verification of the stringent optical performance requirements, a novel concept was developed. This concept allows measurement and verification of all optical performances (spectral, spatial and radiometric) of the IRS within a single test campaign. The main benefit is the reduction in time, effort and risk which can be achieved by combining all performance tests. An additional advantage by combining the test is that the obtained results during the radiometric tests ensure a radiometric calibrated instrument beneficial for all other tests. In the following paper the individual performance testing including sophisticated OGSE required for the various performance verifications will be presented.

II. IRS PERFORMANCES

The IRS instrument is an imaging Fourier Transform Spectrometer and will deliver hyper spectral sounding information in two bands, a Long Wave InfraRed (LWIR: 700 - 1210 cm-1) and Mid Wave InfraRed (MWIR: 1600 - 2175 cm-1) band with a spectral resolution of better than 0.625 cm-1. The spatial sampling distance is 4 km. The IRS converts the input spectral radiances to interferograms, which are processed on-board for data rate reduction and then transmitted to ground as compressed interferograms. For each of the two bands, there is a detector of 160 x 160 pixels, leading to more than 50,000 interferograms which are provided every 10 seconds for further on-ground processing. In addition, high resolution images (integrated spectra) composed of 9 subpixels per pixel are sent to ground to support the image navigation and registration process. [1]

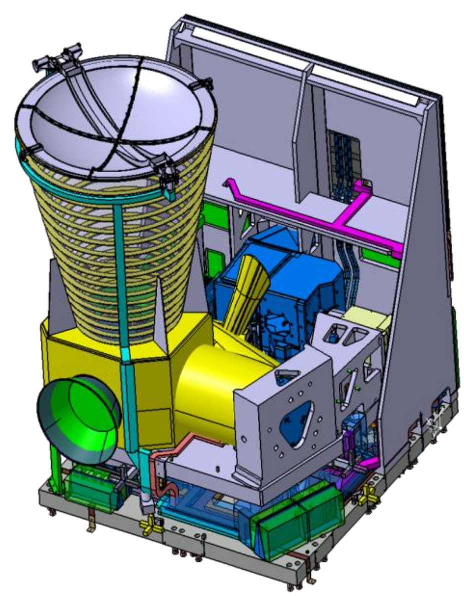

Fig. 1 Overview of IRS

III. OVERVIEW OF VERIFICATION CONCEPT

For the on-ground verification of the stringent optical performance requirements of the IRS, a dedicated OGSE is being developed. This OGSE consists of two main subsystems, the Geometrical and Spectral Test Assembly (GESTA) and three Black Bodies (BBs). A sketch with the layout of the test setup and the OGSE is shown in Fig. 2 below. In order to accommodate all the BBs and GESTA together into the vacuum chamber and execute all performance measurements in a single campaign, an exchange mechanism is used to place either the GESTA or BB in front of the IRS instrument.

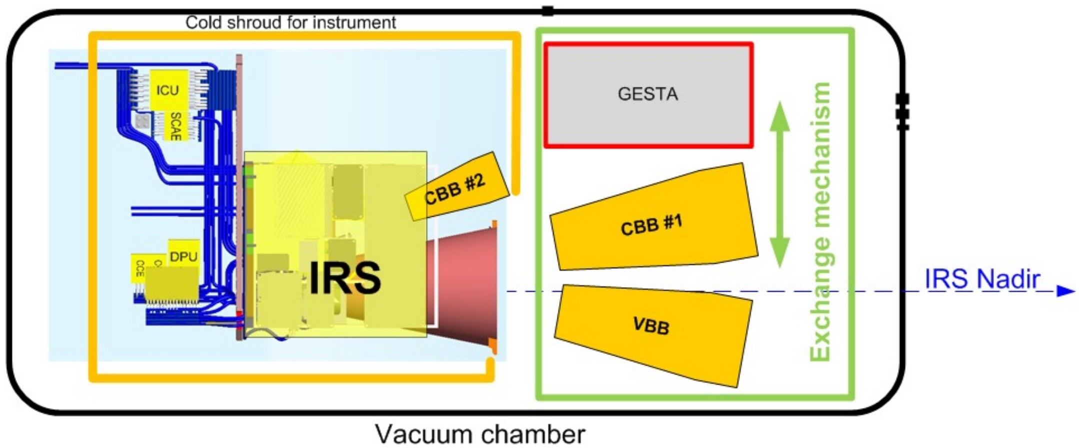

Fig. 2 Performance Test overview

The GESTA is used for the verification of the spatial, spectral and straylight performance requirements of the IRS and is based on three different configurations. The optical beam in each configuration is projected into the IRS entrance pupil by collimator optics with a squared Field-of-View (FoV) of 1.2x1.2deg and a pupil diameter of 320mm. To achieve the geometrical and optical quality requirements, the collimator optics consist of four mirrors building an off-axis telescope close to the diffraction limit and having very low optical distortion.

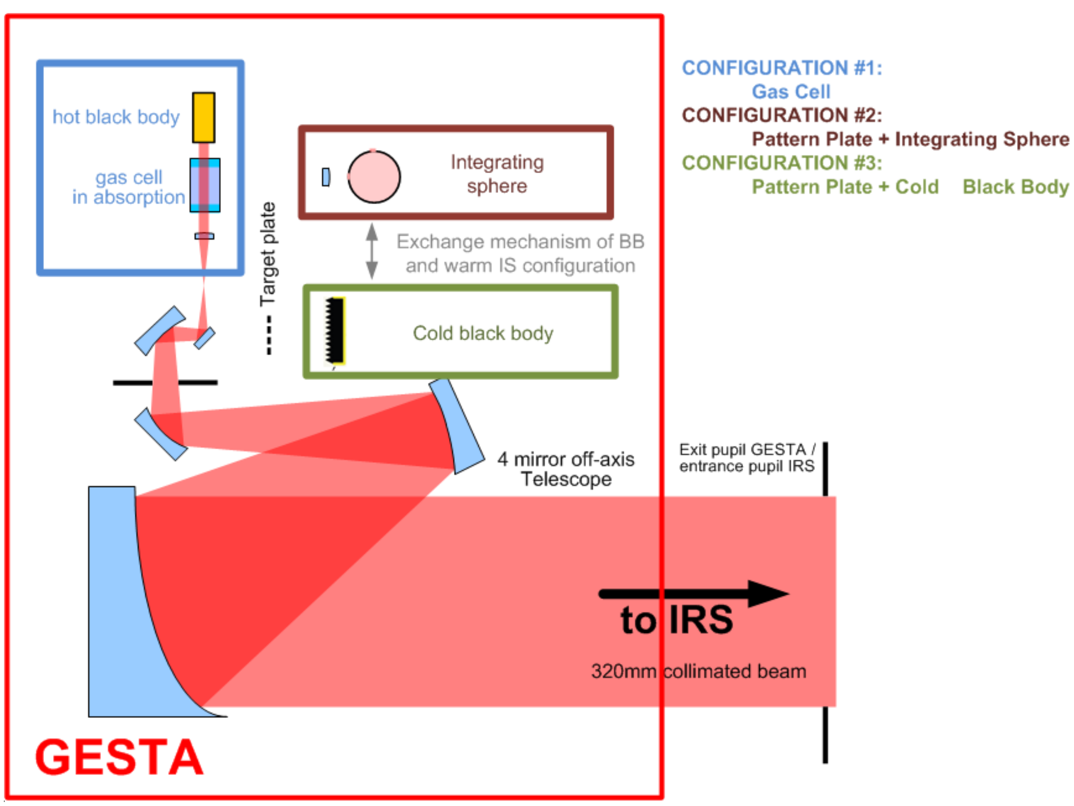

Fig. 3 Overview GESTA configurations

The configuration #1 of the GESTA consists of an absorption gas cell, which is illuminated by a hot black-body to support the high-precision spectral calibration of the IRS. This is visible in Fig. 3 above; it is the configuration marked in blue. The absorption spectra of the gas cell provide discrete narrow absorption features in the MWIR (4.6µm-6.25µm) and LWIR (8.26µm-14.29µm) spectral bands using several exchangeable gases. This allows very accurate determination of any effects on spectral scale shift.

Configuration #2 (see Fig. 3 above) is used for the characterisation of the Instrument Line Shape (ILS). In this configuration, the complete FoV and pupil are illuminated with a monochromatic laser line in the MWIR and LWIR spectral band, by using an integrating sphere. Furthermore, in this configuration a knife-edge can be introduced to measure the straylight performance at these two discrete laser lines.

Finally, the spatial performance, such as Integrated Energy and Spatial Sampling Distance, straylight in the complete spectral range and the co-registration of the two bands, will be verified with the third configuration (see configuration #3 in Fig. 3). These measurements are enabled by moving a heated and very precisely positioned pattern plate in the focal plane of the collimator. The cold background is realized by a cooled black-body.

The second main OGSE consists of three BBs at different temperatures for the characterisation and calibration of the instrument radiometric performance, as visible in Fig. 2. A Cold Black Body (CBB#1) and a Variable Black Body (VBB) are placed in front of the IRS, covering the entire entrance pupil. By use of the IRS scanner the instrument can switch between CBB#1 to VBB. An additional Cold Black Body (CBB#2) is placed in front of the deep space calibration port, which is used for in-flight calibration of the IRS.

IV. SPATIAL AND SPECTRAL VERIFICATION

The spectral and spatial verification is separated into several individual measurements which are described in the following subchapters, and all conduced in the same vacuum test campaign using the GESTA.

A. SPECTRAL CALIBRATION

For the spectral characterization of the instrument, two measurements are used. The first is to characterize the Instrument Line Shape (ILS). This is done by using two narrow Laser lines, one in the LWIR and one in the MWIR spectral region. The spectral width of the laser lines is less than 1/100th of the instrument ILS. To illuminate the full FoV, the GESTA configuration #2 is used, as shown in Fig. 4.

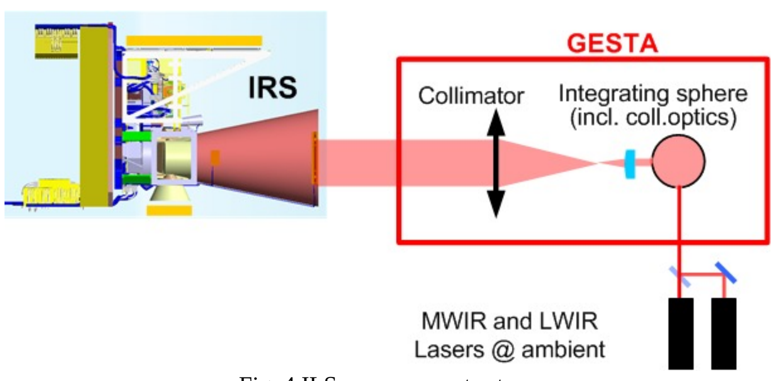

Fig. 4 ILS measurement set-up

The second spectral test is a gas cell test, using the GESTA configuration #1. With this test the spectral scale shifts depending on the pixel position in the FoV to be measured. The gas cell parameters, e.g. gas composition, pressure, and temperature, are accurately monitored to be able to precisely predict the absorption spectrum of the gas cell. To cover the entire spectral bands, several gases are used at a pressure of a few mbar. These are for the MWIR band: nitrogen monoxide (NO); Carbon monoxide (CO); and, water vapour (H2O). To cover the LWIR band, Ammonia (NH3) is used. To produce an absorption spectrum, the gas cell temperature will be below 300K and the black body will be at a temperature of around 330K. To allow measuring the thermal background of the GESTA, the gas cell can also be evacuated. A sketch of the set-up is given in Fig. 5.

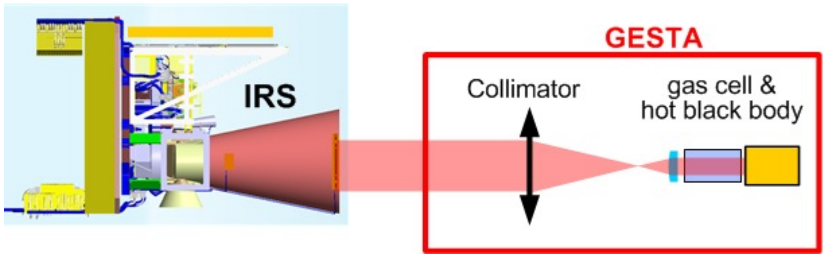

Fig. 5 Gas Cell measurements

B. INTEGRATED ENERGY MEASUREMENT

The IRS Integrated Energy (IE), which is the signal reaching the detector pixel from the area of a projected pixel on ground, will be retrieved and assessed by performing Knife-Edge (KE) measurements. To achieve a sharp edge input signal, a heated KE (blackbody-like source), which is part of the pattern plate, will be placed at the focal plane of GESTA's collimator in front of a cold blackbody. This generates adjacent, uniform dark and bright fields. This pattern plate will be moved across the focal plane in several directions and cover the complete IRS FOV. The measurement set-up is illustrated in Fig. 6.

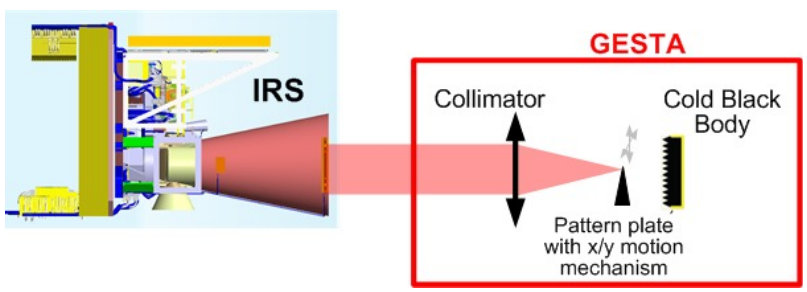

Fig. 6 Knife Edge Measurement set-up

For each KE position, a full set of interferograms will be acquired for all pixels. The signal acquired when the KE is fully retracted (only the cold blackbody is visible) will be employed as the background signal and consequently subtracted from all measurement. The scene that will be seen for one spectral channel is illustrated in Fig. 7. In order to achieve a sufficient contrast, the temperature of the KE plate will be set to roughly 330 K, whereas the cold blackbody will be set to a temperature lower than 240 K.

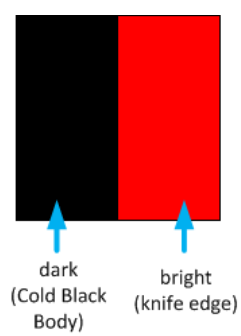

Fig. 7 Knife Edge's plate (black: cold blackbody, red: heated KE)

The KE will be moved over the IRS FOV at steps of 1/10th of an IRS detector pixel size. When the KE is moved across a dedicated pixel, the intensity of the scanned pixel is raising with each step of the edge. Fig. 7 shows how the signal of one pixel is raising for the moving KE, which is the so-called Edge Spread Function (ESF). The mathematical expression, that is often used to approximate the shape of a typical ESF from a KE measurement, is the error function. [2]

The derivative of the ESF is called Line Spread Function (LSF), which also corresponds to the integration of the corresponding Point Spread Function (PSF) in the direction perpendicular to the scan direction: [3]

$$LSF(x) = \frac{d[ESF(x)]}{dx}, \;\; LSF(x) \in \mathbb{R} \quad (1)$$

$$LSF(x) = \int_{-\infty}^{+\infty} PSF(x,y)dy, \;\; PSF(x,y) \in \mathbb{R}^2 \quad (2)$$

A simulated KE measurement and the retrieved LSFs are shown in Fig. 8.

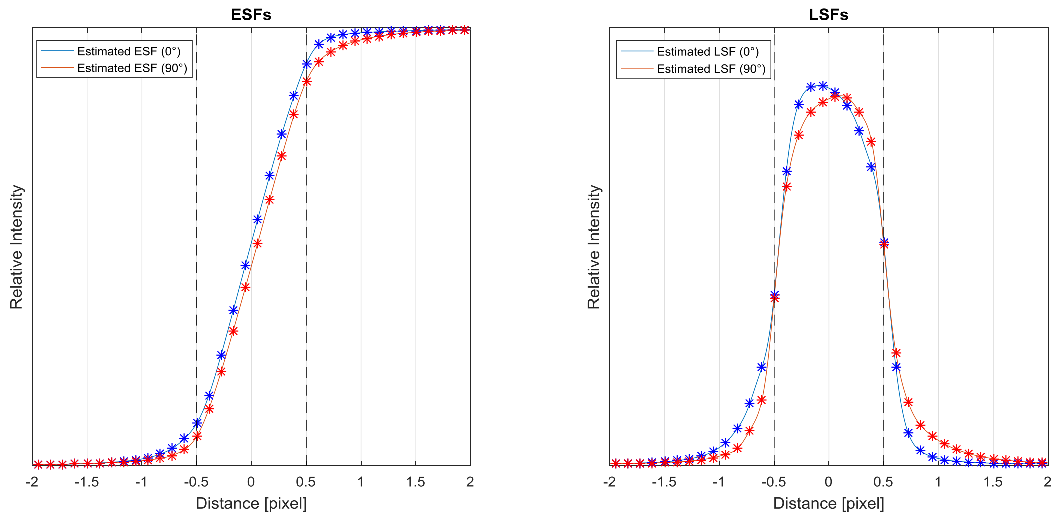

Fig. 8 Non-symmetric signal from KE measurements (left: ESF, right: LSF; for two scanning directions)

The IE is evaluated by integrating the Instrument PSF (which is normalized, so that the summation of samples is equal to 1) over the SSD (pixel size on ground):

$$IE\,[\%] = 100 \cdot \int_{-\frac{SSD}{2}}^{\frac{SSD}{2}} \int_{-\frac{SSD}{2}}^{\frac{SSD}{2}} PSF(x,y)\;dx\,dy \quad (3)$$

Due to wavefront aberrations of the optics and additional instrument contributions (e.g. micro-vibrations, scanner jitter, etc.) the PSF shape will not be symmetric. To obtain the two-dimensional PSF and the Integrated Energy, KE measurements will be performed in four different motion directions to cope with those asymmetries and to restore, more accurately, the PSFs: 0°; 90°;, 45°; and -45°. A sketch of the pattern plate used for these measurements can be found in Fig. 10. An estimation of the two-dimensional PSF of one pixel is shown in Fig. 9.

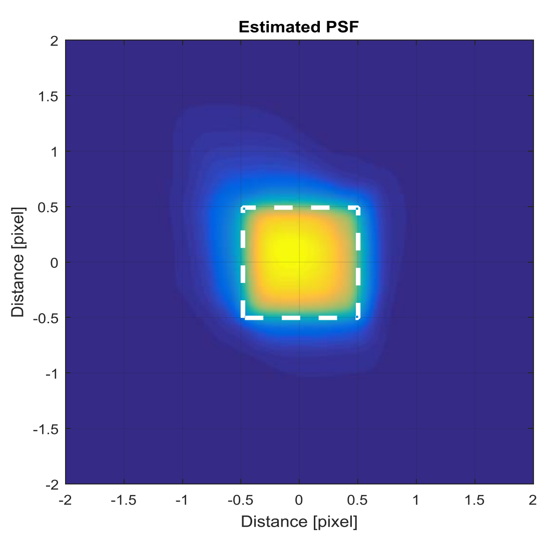

Fig. 9 Non-symmetric PSF of one pixel

C. PREDICTION OF DISTORTION GRID

Since the Spatial Sampling Distance (SSD) is given in kilometres on-ground, the parameter to be characterized with the OGSE is actually the Spatial Sampling Angle (SSA). The SSA between any two adjacent spatial pixels is determined based on the data that has been acquired from the 2D PSF characterization. After each adjacent instrument PSF has been determined, its spatial centroid position is computed. The distance between the centroids can be related to the SSA. Additionally, the large-scale optical distortion over the entire FoV of the IRS will be measured with a dedicated distortion target in the focal plane of the GESTA collimator. The derived Spatial Sampling Grid is used for post processing the Instrument data on ground.

The distortion target (left, top corner of Fig. 10) has 21 over 21 circular spots regularly distributed over the FoV.

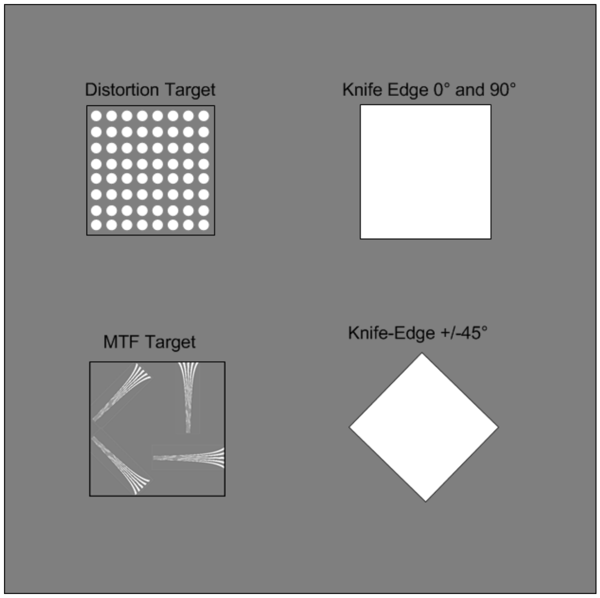

Fig. 10 Pattern Plate

The co-registration between the two spectral bands will be obtained from the knife-edge measurements, which are described in section B above. To allow the simultaneous acquisition of spectra in both bands, the temperature of the target plate will be adjusted to within a narrow range, Additionally, different integration times of the detector, as compared to in-orbit, will be used.

D. STRAYLIGHT CHARACTERIZATION

To assess in-field straylight performance and obtain characterization data that can be used in correction algorithms, a combination of two individual tests is done.

For the straylight determination with the required high contrast, a combination of a knife edge with a laser is used. The employed laser has a very narrow spectral width which is much smaller than the instrument resolution. Therefore, the signal of the laser will be detected in one spectral channel of the instrument, resulting in a high contrast, without saturating the detector. The set-up is shown in Fig. 11.

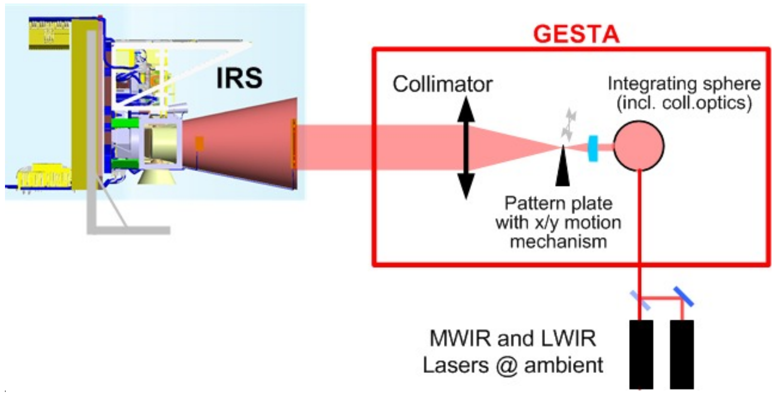

Fig. 11 Overview Straylight Test with Laser

As visible in Fig. 11 this measurement will be performed in GESTA configuration #2. The pattern plate is illuminated from the backside with the laser light using a collimator optics. Observing only the spectral channel of the laser light the area covered by the pattern plate is dark, as compared to the area which is illuminated by the laser light. To be within the dynamic range of the instrument the integration time will be reduced accordingly. The achieved high contrast will provide data to verify the straylight performance for the two laser wave numbers.

In order to verify the straylight performance over the complete spectral range, the broad band measurements in GESTA configuration #3 obtained for the Integrated Energy characterization will be used.

V. RADIOMETRIC CALIBRATION AND CHARACTERIZATION

The main purpose of the on-ground radiometric calibration and characterization (C&C) is the assessment of IRS verification of the in-flight calibration approach and characterization of radiometric performances and parameters used in L1 processing. As mentioned, the radiometric C&C will be performed together with the spatial and spectral tests (see chapter IV) within one campaign. The radiometric C&C uses the three previously named BBs CBB#1, CBB#2 and VBB. A sketch of the test set-up can be found in Fig. 2.

In principle, the radiometric C&C can be split in two test parts. The first part, radiometric calibration, is to perform on-ground an Instrument calibration and thus verify the in-flight calibration concept. The other part, radiometric characterization, assesses radiometric characteristics across the IRS radiometric range.

The IRS in-flight calibration is based on three different IRS calibration configurations. One is to stare with the IRS into deep space, the other two use a special flip-in mirror (FIM) switching to an on-board blackbody or to a dedicated calibration port observing deep space. To calibrate the IRS on-ground, and thus verify the in-flight calibration concept, two cold OGSE BB are used. The cold BB CBB#1 is placed in front of the IRS instrument and simulates the IRS staring into cold space. The other cold BB CBB#2 is positioned in front of the IRS calibration port. Both BB are cooled down to less than 100K.

In order to achieve the radiometric characterization, the Variable BB (VBB) simulates the range of Earth's radiances during earth observation. It has a controlled temperature in the range of 100K-330K and is placed in front of the IRS so that the IRS scanner can stare at it. Therefore, it is used as a reference scene for the radiometric characterization. Various radiometric performance parameters such as radiometric accuracy, medium term radiometric stability, non-linearity correction and end-to-end noise performance, are characterised across the whole IRS dynamic range with this test.

VI. CONCLUSION

The novel verification concept presented in this paper allows measurement and verification of all optical performances of the IRS on-ground. To achieve this a sophisticated OGSE, consisting of the GESTA and three Black-Bodies, is being developed. This OGSE will include several configurations and functions. Furthermore, to fulfil the tight testing requirements, corresponding tight performance requirements are applicable for the OGSE.

In order to cover the large variety of tests, an integrated verification campaign was developed, closely matching the functionality of the OGSE to the testing needs, and to allow covering all the verification activities in a single test campaign. This has without doubt several benefits. A first commercial and programmatic reason is the reduction in time and effort which can be achieved by combining the radiometric and GESTA (spectral and spatial) tests. An additional benefit is the significant reduction in risk for damaging or contaminating the IRS instrument through the avoidance of an extended campaign duration and additional integrations activities.

Since the results obtained during the radiometric tests are required for the processing of the data from the spectral and spatial performance tests, combining the two tests ensures the same radiometric behaviour of the instrument. This further improves the confidence and quality of the results obtained during the characterization and verification campaign of the IRS instrument.

VII. ACKNOWLEDGEMENT

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