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Stefan Kraft

Jean-Loup Bézy

Roland Meynart

Jörg Langen

et al.



PREMIER's Imaging IR Limb Sounder

Phase A results

Stefan Kraft, Jerome Caron, Jean-Loup Bézy, Roland Meynart,
Jörg Langen, Bernardo Carnicero Dominguez, Paolo Bensi, Pierluigi Silvestrin

Directorate of Earth Observation Programmes

ESA/ESTEC

Noordwijk, The Netherlands

Stefan.Kraft@esa.int

Abstract— The Imaging IR Limb Sounder (IRLS) is one of the two instruments planned on board of the candidate Earth Explorer Core Mission PREMIER. PREMIER stands for PROcess Exploration through Measurements of Infrared and Millimetre-wave Emitted Radiation. PREMIER went recently through the process of a feasibility study (Phase A) within the Earth Observation Envelope Program. Emerging from recent advanced instrument technologies IRLS shall, next to a millimetre-wave limb sounder (called STEAMR), explore the benefits of three-dimensional limb sounding with embedded cloud imaging capability. Such 3D imaging technology is expected to open a new era of limb sounding that will allow detailed studies of the link between atmospheric composition and climate, since it will map simultaneously fields of temperature and many trace gases in the mid/upper troposphere and stratosphere across a large vertical and horizontal field of view and with high vertical and horizontal resolution. PREMIER shall fly in a tandem formation looking backwards to METOP's swath and thereby improve meteorological and environmental analyses.

Index Terms— Explorer, atmosphere, limb sounding, imaging, Fourier Transform Spectrometer, infrared.

I. INTRODUCTION

Since the launch and operation of ENVISAT with MIPAS [1] (Michelson Interferometer for Passive Atmospheric Sounding) onboard, there is strong heritage of limb sounding in Europe. MIPAS operated since 2002 and delivered many publications in the field of atmospheric chemistry, climatology and atmospheric dynamics, thereby supporting as well operational meteorology. MIPAS covered the spectral range from 685 cm^{-1} to 2410 cm^{-1} and was designed for an unapodised spectral resolution of 0.035 cm^{-1} , which requires a maximum optical path difference of 20 cm. After the termination of the ENVISAT mission in 2012, there is no European infrared limb sounder in space.

The main challenge for PREMIER compared to MIPAS is the large increase of information, which is linked to the enhancement of the observed field. Instead of scanning the limb in elevation with a single pixel as MIPAS did at a vertical resolution of 3 km, with a single acquisition IRLS will map instantaneously a 2D-field with a 2D detector and so provide as much information as ~1800 MIPAS acquisitions at about 4 times better vertical resolution. Acquisitions will be made such

that an along-track sampling distance of between 25 and 100 km will be achieved. The resulting complexity of the sounder together with the wealth of information that becomes available through such observations will lead to strong innovations on both the technical and the scientific side. PREMIER perfectly fits the scientific research objectives of the ESA Explorer programme by means of innovative sensing.

In this overview, we will present the results of the Phase A parallel studies conducted by ESA and carried out by the IRLS instrument team of Thales Alenia Space in Cannes, France, and by the IRLS instrument team of EADS Astrium in Ottobrunn and Friedrichshafen, Germany. Each team has derived an instrument concept, which are referred to herein as Concept A and B. The complete report of the Phase A assessment including the system concept and the scientific rationale and analysis can be found on the ESA website [2].

II. OBSERVATIONAL PRINCIPLE

The IRLS is an imaging Fourier-Transform Spectrometer (FTS) combining the functions of a spectrometer and an imager with the ability to discriminate clouds. The IRLS provides two mutually exclusive measurement modes with different spatial, spectral and radiometric performance requirements (Table 1). The spectral range between 710 cm^{-1} and 1650 cm^{-1} is covered by simultaneous observation of two spectral bands with a gap of about 90 cm^{-1} . Figure 1 shows an illustration of the PREMIER observation geometry, which is based on simultaneous limb observations made by the IRLS and the STEAMR instruments. The observations are spatially and temporally co-registered with those performed by the nadir-viewing instruments on one of the MetOp satellites (either MetOp-B or MetOp-C). The IRLS acquires bi-dimensional observations of the atmosphere centred on the MetOp swath, while STEAMR acquires mono-dimensional observations centred on the IRLS swath. The along-track movement of the satellite and successive acquisitions provide the third dimension to the observations. The IRLS covers a swath of ~360 km in the across-track direction and 48 km in the vertical direction. It achieves a vertical resolution better than 900 m in the lower part of the atmosphere by sampling at ~700 m.

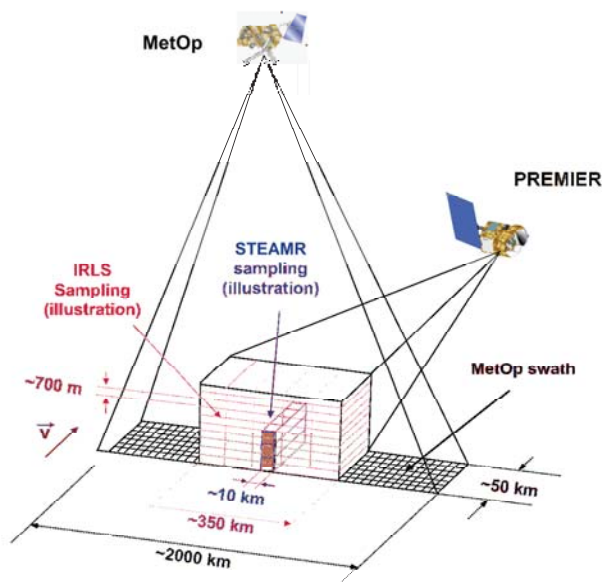


Figure 1 PREMIER observation principle.

IRLS is operated in two different modes, one dedicated to atmospheric chemistry (chemistry mode - CM) and one to atmospheric dynamics (dynamics mode - DM) providing high (CM) and medium (DM) spectral resolution. The loss of radiometric performance in CM due to the high spectral sampling is compensated by a larger across-track and along-track spatial sampling. Spatial samples at the size needed are generated from the addition of elementary sub-samples of 16 km across-track each.

Several along-track interferogram acquisitions are combined to generate an elementary along-track sample acquisition of 50 km length in both CM and DM. It should be noted that in CM the radiometric requirement is applicable for 100 km along-track distance. The acquisition of spectra at the elementary spatial sub-sampling has two main advantages: it minimises the instrument self-apodisation, so that no spectral resampling is required, and enables a cloud-imaging function to discriminate cloud-contaminated sub-samples (including contamination by thin clouds). This is achieved by a spectral analysis of the delivered sub-sample spectra on the ground with a dedicated algorithm that identifies altitude-dependent signal anomalies caused by the presence of clouds. In this way, elementary cloud-free sub-samples can be binned to create cloud-free samples at the target spatial sampling in CM and DM (see also Figure 3).

The provision of spectra with a sub-sample size of 16 km facilitates the processing, since the self-apodisation function is weak enough so that no spectral resampling is required. Further processing on ground of the along-track change of the interferogram DC-level allows the identification of along-track variations of the signal generated by cloud presence with the subsequent possibility to flag the anomaly.

The STEAMR instrument provides spatially resolved information (vertically 1.5–2 km and horizontally 50 km in the

along-track direction) on the atmospheric constituents by means of observations in the 320 to 360 GHz range. The STEAMR measurement concept is based on multi-beam limb sounding in the orbital plane using Schottky-diode heterodyne receivers. The instrument limb view follows a staring concept, observing simultaneously an altitude range of 22 km with 14 beams spaced vertically: every 1.5 km in the lowest 12 km and every 2 km in the highest 10 km. For a description of the STEAMR configuration, see [2].

III. IRLS OVERVIEW

The infrared limb sounder, IRLS, is an imaging FTS with heritage from previous instruments such as MIPAS [1], IASI [3] and GOSAT[4]. One of the main advances of the IRLS with respect to similar currently-operating limb sounders, such as MIPAS, is the extended FOV. This creates a very large volume of data, which must be pre-processed on board. The amount of spatial and spectral samples drives the detector readout frequency, the number of video acquisition chains and finally the data volume.

The IRLS provides the two mutually-exclusive measurement modes (CM, DM) by making use of a single interferometer (IFM) operated at two different strokes and by adapting the acquisition times accordingly. The stroke requirements are well adapted to operate the IFM in a two-sided interferogram acquisition mode. The core of the instrument is the IFM mechanism, which benefits from technology heritage from IASI and GOSAT. The spectrum is acquired by scanning the optical path difference of the two split beams and by recording the interferogram generated by the two-beam interference. The scan is performed during an observation time in the order of one to several seconds. This means that the spectrum, which is derived on the ground by Fourier transformation of the interferogram, is an average of the scene radiance acquired during the interferogram dwell time. Figure 2 shows the functional block diagram of the IRLS.

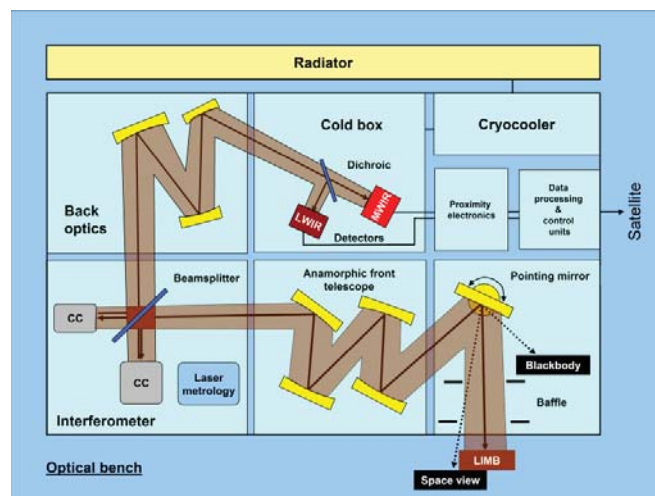


Figure 2 Concept of the Imaging FTS.

The radiation emitted by the atmosphere is collected at the entrance of the instrument, which is protected by a baffle or by

the entrance aperture to minimise the collection of unwanted radiation from Earth. The pointing mirror reflects this limb signal towards the anamorphic front optics, which provides a uniform and almost rectangular beam (Concept A) or a circular beam (Concept B) at the entrance of the IFM. The beam is then split by the beam splitter of the IFM and reflected by the corner cubes to generate interference between the reflected beams.

The light is then imaged by the back optics onto the focal plane inside the cryostat, cooled by active cryocoolers. Before the light reaches the detectors, it is split into two bands by a dichroic beam splitter. The cryostat may contain further optical elements or even a complete reimaging optics. The interference signal is recorded by two-dimensional detectors, one per band. The detectors instantaneously gather the full image of the limb scene for each interferogram scan position. The acquisition and the processing of the interferograms are performed by the data processing system.

Parameter	Requirement	
Geometric requirements	Dynamics Mode (DM) Chemistry Mode (CM)	
Vertical coverage	48 km (4-52 km @ poles, 8-56 km @ tropics)	
Horizontal coverage	360 km [240 km]	
Vertical sampling distance	0.6 km [0.8 km] lower half of altitude range 1.2 km (0.8 km in DM) [1.6 km] upper half	
Horizontal sampling distance	72-96 km	24-32 km
Horizontal sub-sampling dist.	12-16 km (can be relaxed in upper half of atmosphere)	
Along-track sampling distance	50 km [100 km]	50 km
FWHM of vertical PSF	700 m [900 m]	
Vertical width increase of FWHM	<5% [$<10\%$] over 240 km of swath	
Spatial cross-talk (vertical)	1 st neighbour <5% [15%], 2 nd neighbour <2% [7.5%] 3 rd neighbour <1% [4%], 4 th neighbour <1%, 5 th neighbour <0.5%	
Spectral requirements		
Wavenumber range	710 cm ⁻¹ [730 cm ⁻¹] to 1650 cm ⁻¹	
Band gap	Up to 90 cm ⁻¹ in the range 980 cm ⁻¹ to 1100 cm ⁻¹	
Spectral resolution	0.25 cm ⁻¹ [0.27 cm ⁻¹]	1.58 cm ⁻¹ [1.73 cm ⁻¹]
Spectral accuracy	0.008 cm ⁻¹	0.01 cm ⁻¹
ILS characterisation	1% of width, 1% of ILS maximum value	
Radiometric requirement		
Noise Equivalent Delta Radiance (NEdL) @ Zero input Band A	2 [4.0-6.5] nW/(cm ² sr cm ⁻¹)	0.8 [1.5-2.5] nW/(cm ² sr cm ⁻¹)
NEdL @ Zero input Band B	1.5-2.0 [4.0-6.5] nW/(cm ² sr cm ⁻¹)	0.4-0.8 [1.5-2.5] nW/(cm ² sr cm ⁻¹)
Radiometric accuracy	$< [NEDL^2 + (\text{radiometric offset})^2 + (0.015 \text{ meas. radiance})^2]$	
Spectrally varying radiometric error (ghost)	< 4 nW/(cm ² sr cm ⁻¹)	< 1.5 nW/(cm ² sr cm ⁻¹)
Radiometric scaling error	0.15% [0.25%] (spatially and/or spectrally uncorrelated) 1% (spatially and spectrally correlated)	
Radiance range (blackbody radiance equivalent)	133 K to 240 K	143 K to 240 K
Geo-location, LOS stability and spatial co-registration		
Vertical knowledge	750 m for a wavenumber range up to 710 cm ⁻¹	
Vertical co-registration	75 m [150 m] intra-band, 250 m inter-band; Knowledge: 25 m [50 m] intra-band, 100 m inter-band	
Vertical geolocation stability	60 m [100 m] (within interferogram acquisition time) 75 m [150 m] (within horizontal sampling time)	

Table 1 Overview of the PREMIER IRLS requirements. Threshold requirements are in brackets.

IV. OBSERVATIONAL REQUIREMENTS

The key IRLS observational requirements are summarised in Table 1. The following sections summarise the impact of the main Level-1b requirements on the instrument design.

A. Geometric requirements

PREMIER requires a maximum across-track view (swath) of ~360 km. The swath and the spatial sampling of the observed field drive the amount of data generated. The vertical coverage at any point of the swath is 48 km from a reference minimum altitude tangent point that varies with latitude from 4 km at the poles to 8 km at the equator.

Since the vertical coverage is much smaller than the horizontal one, it is convenient to adapt the magnification of the front-optics in both directions. This measure rectifies the beam, allowing the use of conventional optics (corner cubes, beam-splitter and detector formats) and simplifying both the IFM and detector configuration. The vertical resolution drives the vertical extent of the aperture, which is much larger than the horizontal one where the required sampling is 16 km only. The swath width and the vertical resolution define the complexity of the optics. This is because the swath width determines the range of field angles that must be handled by the instrument optics, and the vertical resolution drives the maximum aperture extension and the magnification range of the optics. The IRLS concepts must comply with the required spatial sampling and resolution in both DM and CM (Table 1). The higher vertical-heterogeneity of the atmospheric constituent in the lower half of the altitude range compared to the upper one leads to a different vertical resolution and sampling in the lower and upper halves of the FOV in CM. The broadening of the instantaneous FOV at the edge of the swath owing to Earth's curvature also affects the vertical resolution.

With a sub-sampling size of 15 km, for example, a FOV of 360 km by 52 km can be made up of 24 across-track sub-samples by 80 vertical samples, resulting in 1920 sub-samples. The target across-track sampling between 72 km and 96 km in CM and between 24 km and 32 km in DM can be achieved by spatial binning of the sub-samples. A picture of one possible configuration is shown in Figure 3.

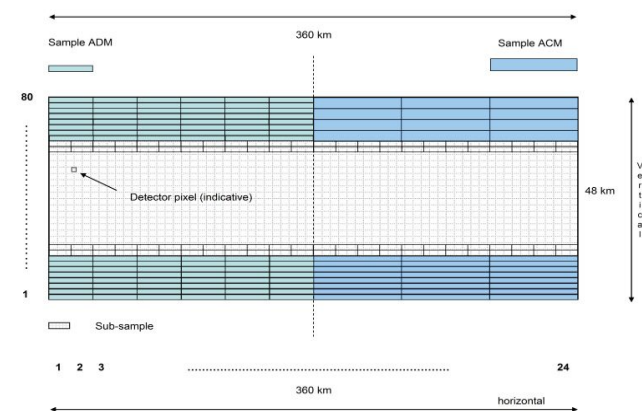


Figure 3 The sample and sub-sample concept. The (atmospheric) CM and DM samples are generated by co-addition of several sub-samples. The left and the right part of the field are identical and have only been split here to show the configuration in DM and CM (exclusive modes). For CM and in band B, two vertical samples may be binned in the upper part of the atmosphere.

B. Spectral requirements

For an imaging FTS, the spectral resolution defines the Maximum Optical Path Difference (MOPD) and the degree of acceptable self-apodisation, and therefore the required level of pixel granularity. The IRLS optical design is optimized such that the beam divergence variation within the IFM is very small, which makes the self-apodisation function almost negligible. Given the expected self-apodisation, MOPDs of ~ 2.5 cm and ~ 0.4 cm are required to achieve spectral resolutions of 0.27 cm^{-1} and 1.73 cm^{-1} in CM and DM, respectively. The spectral accuracy is also demanding and requires a state-of-the-art thermally-stable IFM concept, a stable instrument line shape across the FOV, high optical-axis stability and accurate measurement of the variation in Optical Path Difference (OPD) during scanning.

The spectral range from 710 cm^{-1} to 1650 cm^{-1} is covered by two spectral bands (Bands A and B) with an intermediate gap of 90 cm^{-1} located in the spectral range between 980 cm^{-1} and 1100 cm^{-1} . The cross-over of the dichroic beam splitter requires this spectral gap to enable the separation in two bands. The splitting is beneficial for the radiometric performance, because it limits the spectral range of each band and thereby relaxes the requirements on key detector/focal plane characteristics (e.g. detector coating, detector charge handling capacity, signal band width, straylight separation). On the other hand, it requires a careful thermo-mechanical focal plane design to meet the interband co-registration requirement.

C. Radiometric requirements

The dynamic range to be covered by the IRLS must be compatible with the radiance emitted by the atmosphere in the relevant spectral bands within the observed altitude range. Representative atmospheric radiance spectra are shown in Figure 4. The scene radiance levels can vary by two orders of magnitude within the observed spectra. The dynamic and spectral ranges are directly linked, since the FTS is exposed at zero OPD to the radiation present within the full spectral range. The larger the dynamic and spectral ranges, the larger the charge handling capacity and the detection noise of the detector. The effective dynamic range requires detectors with large charge handling capacity operating at high readout frequencies.

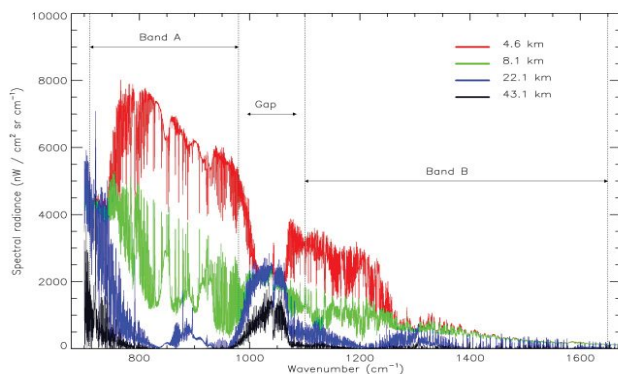


Figure 4 Atmospheric radiance spectra at four altitudes as expected to be observed by the IRLS.

The absolute radiometric accuracy is defined as the quadratic sum of the actual Noise Equivalent Delta Radiance (NE Δ L), the radiometric offset error and 1.5% of the measured radiance. This requirement limits the total gain error to 1.5% at the top of the dynamic range (low altitudes). For the low radiance observations (deep space or high altitudes), the absolute radiometric accuracy is determined by the offset and NE Δ L characteristics.

D. Line of sight stability

Instability in the pointing of the instrument's vertical LOS generates pseudo noise and a broadening of the FOV. Pseudo noise is understood in this context as a noise equivalent disturbance of the interferogram signal, and finally of the spectrum disturbance, which is generated by the modulation of the signal in the case of observing non-uniform scenes. A random oscillation of the LOS generates random noise that can be of the same magnitude as the instrument noise [5]. Depending on their frequency, periodic oscillations will generate either line broadening or ghost lines.

A vertical LOS stability between 60 m and 100 m within one interferogram dwell time, which is of the order of 1 s to 7.5 s, is required to minimise the pseudo noise. The instrument is susceptible to pseudo-noise in a specific frequency range. As a result, micro-vibration and any other perturbation at frequencies between 0.2 and 500 cycles per interferogram in CM and between 0.2 and 2000 cycles per interferogram in DM is considered as critical and must be minimised by design.

A vertical LOS stability between 75 and 150 m within one horizontal along-track sample acquisition, which is of the order of 7.5 s, limits the FOV broadening. The requirement is not restricted to any frequency range, although the FOV broadening is mostly sensitive to low frequencies.

V. INSTRUMENT SUBSYSTEMS

A. Mechanical and thermal architecture

The accommodation is driven by the high geometrical and thermal stability performance required to meet the pointing knowledge requirement. For both concepts, the instrument includes: (1) A very stable optical bench to minimise thermo-elastic distortions supporting all the optical elements, the pointing mechanism, the IFM and corner cubes and the cryostat. The optical bench is isostatically mounted on the PIP (Payload Interface Plate) in Concept A and on the top structure panel of the satellite in Concept B. The optical bench is kept at ~ 240 K for Concept A and at ~ 293 K for Concept B. (2) An entry baffle minimising illumination of the instrument from the Sun and Earth. (3) A blackbody accommodated close to the entrance. (4) A secondary structure made of aluminium panels supporting the cryocooler, which prevents the propagation of micro-vibrations to the optical bench. This secondary structure also supports parts of the electronics, which are covered with MLI. (5) A top cover of the instrument that serves as a radiator.

The optical bench is made of aluminium for Concept A and of an aluminium honeycomb core with Carbon Fibre Reinforced Plastic (CFRP) skins for Concept B, which is a design inherited from IASI. The dimensions (height \times width \times

depth) of Concept A are $0.6 \times 1.15 \times 0.8 \text{ m}^3$ and $0.55 \times 1.65 \times 1.0 \text{ m}^3$ for Concept B. The eigen-frequencies of the structures (first mode 35 Hz laterally and 75 Hz axially) are well above the requirements for both concepts. The thermal control relies on passive cooling and on heating by thermistor lines, with the exception of the Focal Plane Assembly, where a cryocooler is needed to keep the temperature of the detectors in the cryostat at $\sim 55 \text{ K}$. The cryocooler has a dedicated radiator to evacuate several hundred mW of thermal power to cold space. In Concept A, almost all of the electronics are accommodated in the service module, whereas in Concept B the signal processing, the IFM and the cryocooler control electronics are attached to a secondary structure of the payload module. The electronic modules are thermally isolated with MLI.

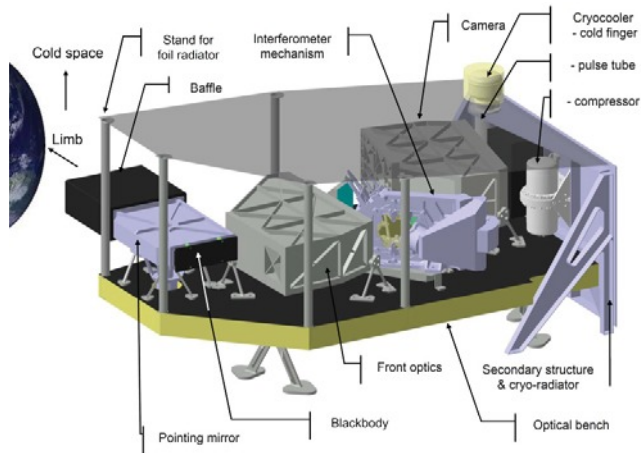


Figure 5 General overview of Concept A.

The instrument is operated at a temperature of about 240 K (Concept A) or at ‘room temperature’, i.e. 293 K (Concept B). A cold instrument generates little background radiation, but requires a more complex assembly, integration and testing. Concept A is based on an athermal aluminium design to prevent deformation when cooled from room temperature to $\sim 240 \text{ K}$. The thermal control is based on an MLI tent with foil radiators supported by a tubular structure, which guarantees survival of the launch. A second radiator dedicated to the cryocooler is accommodated on the zenith side. Concept B is kept at 293 K with the exception of the entrance cavity so that the blackbody can be operated at a temperature of $\sim 240 \text{ K}$. A segmented radiator on top of the secondary structure is connected by heat pipes to the sub-units to enable the thermal control of the various subsystems, including the cryocooler. Both thermal control concepts benefit from extensive flight heritage. The instrument mechanical and thermal architectures are outlined in Figure 5 for Concept A and in Figure 6 for Concept B.

B. Entrance aperture and pointing mirror

The instrument entrance aperture is not symmetrical since the required spatial resolution is more stringent in the vertical direction. A vertical aperture of at least 150 mm is needed. The horizontal aperture, between 25 and 40 mm, is not critical and

determines the aperture area required to achieve sufficient signal throughput.

The pointing mirror is used to enable pointing to (i) the limb in normal acquisition mode, (ii) deep space, for radiometric calibration including offset determination and (iii) a blackbody, for radiometric calibration. These pointing directions can be realised either with a one-axis or a 2-axes gimbal pointing mirror. The geolocation knowledge and the minimisation of LOS jitters require a highly repeatable, accurate (to few arcseconds) and stable mirror pointing. The blackbody is accommodated in the entrance cavity and is maintained at a constant temperature of 240 K to provide a known reference radiance.

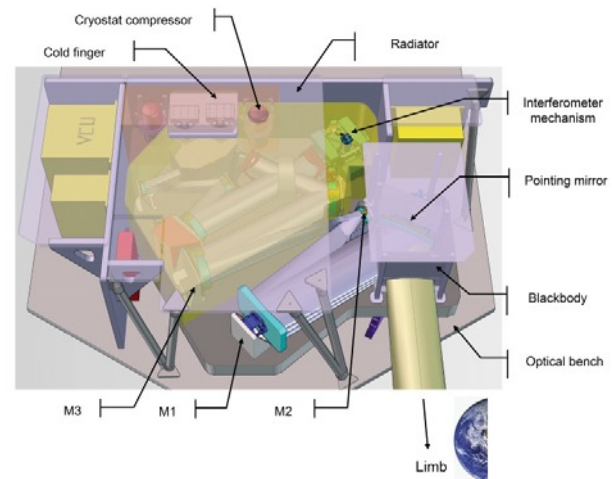


Figure 6 General overview of Concept B.

C. Front optics

The front optics are designed with an anisotropic magnification such that the rectangular field is transferred into an almost square (Concept A) or circular shape (Concept B) at the IFM entrance. The anamorphic optical design reduces the beam divergence, distributing it almost equally within the IFM. This allows the use of existing IFM mechanisms and maintaining corner cube configurations and sizes. IASI, for example, uses corner cubes compatible with beams with a diameter of 80 mm, which is the selected size for the IRLS Concept B. GOSAT accommodates 70 mm beams, which is slightly larger than for the IRLS configuration in Concept A.

D. Interferometer (IFM) mechanism

Double pendulum (as GOSAT, Concept A) and linear (as IASI, Concept B) IFM mechanisms have been identified as suitable candidates, because both can provide the required stroke and beam diameter. A double pendulum enables, using a rotational mechanism, the displacement of both corner cubes instead of only one as in the linear mechanism. The corner cubes move in opposite direction, so that the resulting path difference corresponds to two times the effective displacement. Both IFM mechanisms are of similar complexity, with respect to IASI or GOSAT, and need adaptations to fulfil the performance requirements, in particular for corner cube speed, trajectory and the related control accuracy.

A single-point laser metrology system, which is used to determine the OPD, uses a sine and cosine interference signal to avoid fringe losses. It is based on a laser source providing a highly stable signal in the near-infrared spectral domain. Fibre optics collimate the laser beam and send it through the IFM. The IFM (corner cube) movement generates interference, which is measured by two photodiodes, and is then used to derive the actual OPD. Depending on the concept, a three-point measurement system can be considered to reduce the effect of lateral jitter that causes ghost lines in the generated spectra.

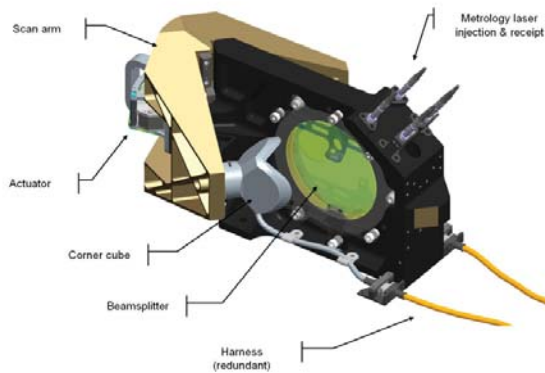


Figure 7 IRLS IFM mechanism of Concept A, including the two corner cubes, the beam splitter and the IFM mechanism.

The stroke of the IFM varies with the operating mode and hence the dwell time of the interferogram. In CM, the IFM operates with a stroke of 2.5 cm leading to a dwell time of about 7.5 s for 50 km along-track sampling. In DM, a stroke of 0.4 cm leads to a dwell time 6.25 times shorter than in CM, assuming that the IFM velocity remains constant. Since the along-track sample acquisition may be composed of several interferograms, the dwell time can be reduced if the IFM operates at higher speed. The IRLS may then acquire and co-add several interferograms within one along-track acquisition period. This option leaves some freedom for the choice of the instrument configuration and the operational concept, since either constant or variable IFM velocities can be selected. The two IFM mechanisms identified as baseline for the two concepts are shown in Figure 7 and Figure 8.

E. Back optics and cryostat

The back optics consists of a set of mirrors imaging the object into or onto the cryostat. The optics combination plus some compensation elements in the cryostat generate an image of quality close to the diffraction limit, which means that IRLS has good imaging performance and relatively low spatial cross-talk. The back optics generates an image matched with typical squared IR array detector formats. The cryostat subsystem provides the thermal isolation of the detector compartment, which must be kept at ~55 K. Optical elements inside the cryostat, such as the dichroic beam splitter, are thermally isolated from the cryostat housing. The mounting structure and the wiring of the detectors are designed to minimise the heat load of the cryocooler.

F. Detectors

Suitable detectors are mercury cadmium telluride (MCT) complementary metal oxide semiconductor (CMOS) detectors similar to those currently under development for the MeteoSAT Third Generation (MTG) programme. The typical pixel pitch is 30 μm . The IRLS detector array format is significantly smaller than for MTG. Also the 'macro-pixel' configuration and the charge handling capacities are different. A macro-pixel is a subset of detector pixels having a combined integration capacity which is read out as a single entity. For the IRLS, the macro-pixel is the set of detector pixels required to form the elementary spatial sub-sample (compare also Figure 3). As a consequence, detector pixel defects have limited impact on the performance of a complete sample and allow to maintain good data quality. The signal from a set of about 20 to 30 pixels is then combined and the charge is collected by a single charge capacitor for each sub-sample. Each single detector pixel can be switched on and off, as required to perform health checks, to remove malfunctioning pixels and to implement special operating modes of IRLS.

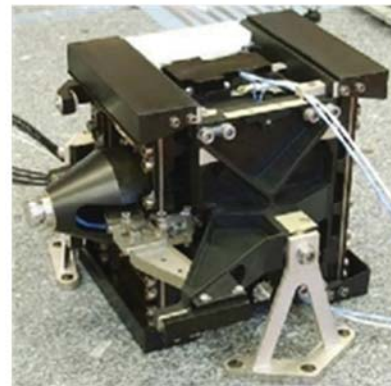


Figure 8 IRLS IFM mechanism of Concept B.

The detectors will have to be customised by changing the detector mask and by redesigning the detector ROIC. Assuming 24 horizontal sub-samples and 80 vertical sub-samples, the IRLS requires 1920 sub-samples. If each sub-sample is made up of 30 detector pixels, then in total 57 600 detector pixels are required. As a consequence, the detector array has an area of less than 50 mm^2 , about four times smaller than the MTG detectors. The cut-off wavelengths are 14 and 10 μm for Bands A and B, respectively. Both detectors are operated at about 55 K in order to limit their dark current contributions (driven by Band A).

G. Cryocoolers

The detectors' required low temperature can only be achieved by active cooling. Stirling or Pulse Tube are possible cryocooler options, but must be optimised with respect to their operation to minimise power consumption and exported microvibrations. Coolers meeting the IRLS requirements are available from other programmes (e.g. MTG, Sentinel-3); the MTG cooler is considered as baseline. The cryostat accommodation requires careful thermal interfacing of the detector with the instrument structure to minimise thermal conductance.

H. Instrument electronics

The electronic architecture for Concept A is shown in Figure 9. The figure also shows the distribution of the functionalities within the optical and the service module. The architecture of Concept B is similar except that the Signal Processing Unit (SPU) is located in the optical module. The detectors signals from both bands are distributed by the Focal Plane Electronics (FPE), which contain mainly the detector Read Out Integrated Circuits (ROICs). The signal is further pre-amplified by Front End Electronics (FEE) before it is sent to the SPU, where the analogue to digital conversion takes place. The IRLS performance relies on a 16 bit Analog to Digital Converter (ADC) with low noise characteristics, operated at a sampling frequency of 2 to 4 MHz.

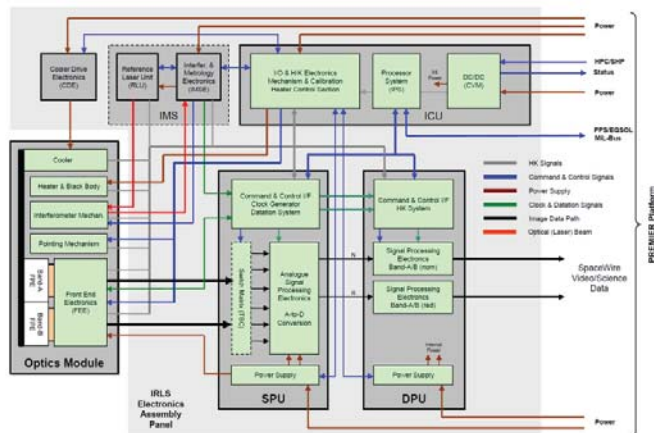


Figure 9 The electronic sub-units of the IRLS as derived within Concept A, SPU and DPU part of the service module.

There are multiple solutions that are compatible with the required performance of the video signal processing. The Data Processing Unit (DPU) performs the onboard processing. The Instrument Management System (IMS) controls the metrology system. The Instrument Control Unit (ICU) distributes the command signals and the power to the electrical sub-units and is in charge of the instrument thermal control. The IMS and the ICU are implemented in separate units to enable independent development and testing.

I. Onboard processing chain

The IMS takes care of the time sequences (synchronisation) and execution of all processing tasks. The IFM metrology system and the two detectors' readouts need to be clocked synchronously and read out at a frequency of 4 kHz. The analogue signals are then digitised and transferred to a buffer for further processing in the DPU. The pixel readout rate is about 8 MHz, which requires using at least two output ports for each detector chain. The proximity electronics needs to be located close to the detectors to shorten the signal lines, which are sensitive to noise from the environment. Other control and processing electronics can be physically placed in the service module. The exact split between the service and the payload module can be either before or after the video processing.

J. Onboard data processing

The large data flow (~200 Mb/s) generated at the output of the detector chains is transferred to the DPU, where the following processing steps are performed: (1) Detection of cosmic rays or electrical anomalies, which cause a strong signal change. (2) Non-linearity correction and bad pixel identification through look-up tables. (3) Binning of sub-samples to restrict the data volume (e.g. upper part of the atmosphere). (4) Interferogram resampling to transfer constant time-sampling on a fixed spatial reference grid. (5) Interferogram filtering and decimation to reduce the amount of data e.g. by a finite impulse response filter. (6) Data compression. (7) Provision of DC level for cloud detection and discrimination.

The data will be provided with a sufficient number of bits so that the radiometric information content is maintained. The onboard processing approach has heritage from previous missions (IASI and MIPAS). It is further assumed that fringe loss detection is not required since the metrology is based on a sine and cosine signal acquisition. The application of all these onboard processes will reduce the onboard data production rate from ~200 Mb/s to ~28 Mb/s in Concept A and ~18 Mb/s in Concept B. The onboard processing chain generates compressed interferograms for each sub-sample, which are then downlinked for further processing on the ground.

VI. INSTRUMENT ON-GROUND CHARACTERISATION AND IN-FLIGHT CALIBRATION

A. Spectral and spatial response on-ground characterisation

The spectral and spatial parameters that have to be characterised on the ground are the instrument line shape (ILS) and the point spread function (PSF).

The ILS must be characterised to an accuracy of better than 1% of its maximum. The ILS accuracy depends on the determination of the optical axis, the corner cube trajectory and the PSF knowledge. The characterisation can be performed on the ground using a gas cell and lasers by comparing the instrument response to the input spectrum line shape. A similar process is performed in-flight by analysis of atmospheric emission lines and by the use of an ILS model.

The PSF determines the instrument spatial response to the observed target. Since the signal level varies drastically along the altitude range, a good knowledge of the PSF shape, up to ~100 km from its central peak, is required. The knowledge of the PSF shape has to be such that the integral outside ±5 Full Width at Half Maximum (FWHM) is known with an accuracy better than 0.1% for PSF error contributions, which are uncorrelated between spatial samples. The shape of the PSF depends on the diffraction pattern, the detector convolution and the in-field/far-field scattering. To minimise scattering, an instrument providing a high level of cleanliness throughout the mission lifetime is required. The PSF shape must be characterised on-ground.

B. Spectral calibration

The spectral calibration consists of the characterisation of the instrument line shape, which depends on the knowledge of

the trajectory of the corner cube, the shape of the PSF and the shift of the optical axis.

The IFM metrology system is used to determine the on-axis position and trajectory of the corner cube, whereas the PSF shape is known by pre-launch on-ground characterisation.

The shift of the optical axis is determined by exploiting the imaging properties of the FTS through the analysis of the distribution of the spectral positions of one or several atmospheric emission lines (e.g. CO₂ line at 951.2 cm⁻¹ as shown in the left of Figure 10) in every sub-sample across the observed field. The shift of the optical axis is retrieved by making a fit to the distribution of the line positions within the field (see Figure 10).

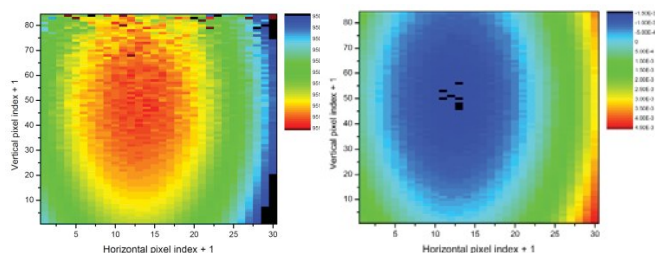


Figure 10 Result of a fit to the spectral positions of the CO₂ line at 951.2 cm⁻¹ (left). Residual error after correction of the shift of the optical axis as derived from the fit to the distribution shown on the left (right).

The determination of the shift of the optical axis is performed using a statistically representative set of five consecutive observations in CM (CM because of the higher spectral resolution of this operation mode compared to DM). Successful spectral calibration requires a relative spectral stability ($\Delta\nu/\nu$) better than 2.3×10^{-7} during the calibration sequence, which is achieved with a stable focal plane together with a high stability of the laser wavelength of the metrology system. The total residual error after spectral calibration (e.g. corner cube trajectory, the PSF and the shift of the optical axis) is $\sim 5 \cdot 10^{-6}$ and meets the spectral accuracy requirement. Spectral calibration must be performed once per orbit given the expected high spectral stability of the instrument. The spectral calibration performed in CM is also applicable to the DM.

C. Radiometric calibration

The radiometric calibration consists of the determination of the radiometric offset and gain errors, both required to establish the relationship of the instrument radiometric response to the signal.

The main contributor to the radiometric offset error is the instrument background thermal emission generated by variations of its internal temperature. The offset error is determined by periodic observations of cold space, which is a target providing close to zero radiometric signal. The radiometric gain error is determined by observing a radiation source at a reference temperature. The IRLS observes periodically a blackbody at a temperature of 240 K, which provides a signal corresponding to the maximum of the dynamic range. The radiometric offset calibration has to be performed several times per orbit to keep the radiometric offset error below $\sim \text{NE}\Delta L/4$, as required.

D. LOS calibration

The main contributor to the LOS knowledge is the misalignment produced during launch and thermo-elastic distortions in the instrument/optical bench. An initial onboard altitude knowledge of ~ 750 m (i.e. about one vertical SSD) is required to obtain a vertical knowledge of the LOS better than 200 m by on-ground analysis of the atmospheric pressure and temperature information carried in the retrieved altitude dependent spectra. The requirement of 750 m is achieved by performing an inflight calibration of the LOS using the Moon as pointing target. The calibration is performed when the Moon's path crosses the PREMIER orbital plane by letting the Moon transit across the IRLS FOV.

VII. PERFORMANCE

A. Geometric performance

All the geometric requirements are met at or below the threshold value (compare Table 1). The horizontal FoV the goal value of 360 km or at least close to it is foreseen.

B. Coverage and sampling

PREMIER IRLS will observe the same range of altitudes (48 km corresponding to 4–52 km at the poles and 8–56 km at the equator) throughout the entire swath. This requires slightly oversizing the instrument FOV in the vertical direction to take account of the effect of Earth's curvature. As a result, the total vertical coverage achieved is in the range of 50 to 52 km.

A vertical sampling distance of better than 800 m will be realised by the optics magnification, and by a corresponding match of the detector configuration. Horizontal sampling distances are multiples of 15 km or 16 km corresponding to the smallest detector macro unit. The along-track sampling distance of 100 km in CM and less than 50 km in DM will be realised by an adaptation of the interferogram acquisitions and subsequent on-track binning.

C. Spatial resolution and PSF

A vertical resolution of less than 900 m is achieved by a vertical sampling of about 700 m, an aperture with a vertical extension in the order of 150 mm, and an optical design such that the imaging performance is close to the diffraction limit.

The PSF will change slightly with the field location (altitude). The basic shape is determined by the diffraction limit and the detector response. Mirror roughness and contamination affect the near- and far-field contribution in a similar manner and generate an almost flat contribution to the PSF. The baffle scattering and other effects such as ghosts from the optics, which can deteriorate the PSF, have been minimised in the optical designs.

D. Spatial cross-talk

Assuming that the instrument is exposed to a black-and-white (illuminated / not illuminated) scene with the edge between white and black placed in the middle of a pixel '0', then the spatial cross-talk is defined as the percentage of radiation, which is seen by the pixels that are not illuminated, compared or normalised to a fully illuminated pixel. The cross-

talk is calculated by the convolution of the PSF with this step-function and the corresponding analysis of the true instrumental step-function to derive the signal (cross-talk) seen by the neighbouring pixels.

The cross-talk computation is further illustrated in Figure 11, where the simulated PSF is convoluted with an ideal step-function. The resulting cross-talk values up to 35 km away are plotted in the figure. According to current assumptions, the cross-talk requirements are fulfilled as can be seen in Figure 11 by comparing the instrument response to the step-function with the green dots/line, which corresponds to the goal requirements.

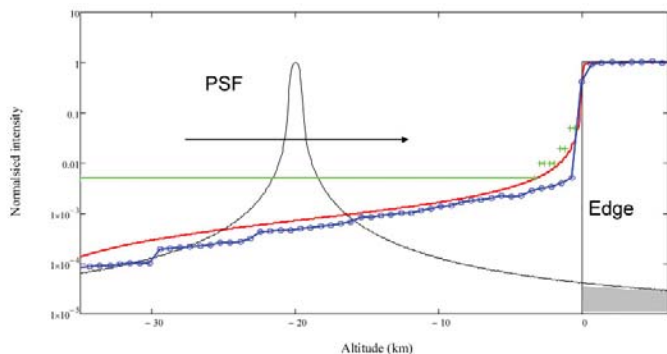


Figure 11 The convolution process and resulting instrument response to a stepfunction located at the centre of pixel 0 (red). The PSF is convoluted across the edge and the overlap with the edge step is integrated across a field of ± 40 km. The edge-function is compared to a ray-tracing simulation, which shows the contribution from light scattering (blue). Cross-talk requirements are indicated by the green dots and line.

E. Interband/intraband spatial co-registration

Spatial co-registrations are formulated as interband and intraband co-registration, ensuring that the registrations of different spectral features are related to the same target.

Intraband co-registration (between two spectral channels of the same band) depends on the capability of the instrument and its optics to propagate the radiation independently of its wavelength. Aberrations alter the image formation and prevent perfect co-registration. The optical designs have been analysed with respect to their susceptibility to aberrations, and it has been shown that they are compliant with the intra-channel requirements as given in Table 1.

Interband co-registration (between two spectral channels of different bands) requirements are more difficult to meet than the intraband co-registration. It is affected by the misalignment between the focal plane assemblies of Band A and Band B, and the back optics located after the dichroic beam splitter inside the cryostat. An interband co-registration of 25 m corresponds to a focal plane misalignment of the order of 3 μm . Concepts A and B are both expected to meet the threshold knowledge requirement of 50 m by means of a high thermal and mechanical stability for the focal plane and by performing in-flight observations with both bands of well-structured targets such as the Moon, so that correlation between the obtained images in both bands can be revealed.

F. Spectral performance

A wavenumber range down to 710 cm^{-1} has been implemented. The band gaps are slightly different for the two concepts. The transition range is limited to about 70 to 90 cm^{-1} , which is considered small but feasible. A deeper analysis is required on the spectral band splitting properties of the dichroic beam splitter to investigate and predict the expected performance in more detail.

The CM drives the spectral performance requirements. The spectral resolution is not seriously compromised by the instrument self-apodisation and the target value of 0.27 cm^{-1} in CM can be met even with a stroke less than 2.5 cm. The spectral sampling interval will be slightly above 0.2 cm^{-1} in CM. A comparison of the ideal ILS of a sub-sample at the location of the optical axis compared to the ILS that is effectively generated by a sub-sample of 0.8 km by 15 km at the edge of the field is illustrated in Figure 12. The simulation assumes an ideal detector response.

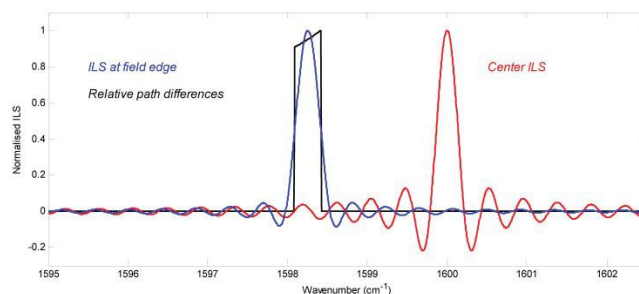


Figure 12 Comparison of the normalized ILS for a centre sub-sample and an edge sub-sample. The relative path difference contributions for a sub-sample (distribution within the sub-sample area) also are shown.

According to the analysis taking all known error contributors into account, the ILS width and asymmetry, and the ILS knowledge are expected to be compliant with the requirements. Changes of the ILS generated by malfunctioning detector pixels, which will be switched off, can be compensated by modelling. It is noted that, due to the relatively large sub-sample being composed of more than 20 detector pixels, the sensitivity to pixel losses is relatively low. The spectral characterisation accuracy is expected to be well below 1%. The spectral accuracy is better than 0.008 cm^{-1} in CM, and better than 0.01 cm^{-1} in DM.

G. Radiometric performance

The Noise Equivalent Radiance (NE Δ L) is computed using detailed and mature radiometric noise models developed during Phase-A [5]. The instrument noise levels depend mostly on the instrument pupil size, its total spectrally dependent transmission, the operational temperature, the dynamic range of the signal, and on the noise of the instrument detectors and electronics. The instrument operational temperature plays a key role in the NE Δ L performance, since emission from the instrument can generate a dominant noise contribution to the NE Δ L. If the temperature is 240 K instead of 293 K, the NE Δ L improves considerably. The evaluation in Phase-A concluded

that both concepts, which operate at 240 K and 293 K respectively, are compliant with the NEdL requirements.

The NEdL, the radiometric offset and the scaling error contribute to the radiometric accuracy. The NEdL has been discussed above. Offset errors can be corrected by measuring the offset through deep space calibration. Therefore, the dominant error for the radiometric accuracy is the scaling or gain error, for which a dedicated requirement has been formulated. Scaling errors are due to changes in the instrument radiometric response or inaccuracies in the calibration sources. They alter the instrument radiometric response depending on the input radiation level. Scaling errors can be classified in spatial, spectral and temporal errors, and can also either be correlated or uncorrelated.

Spatially correlated errors are the blackbody (BB) temperature measurement error, the absolute temperature knowledge and the knowledge of the emissivity. Spatially uncorrelated errors are the detector non-linearity and the gain variation of the amplification chain, which can vary randomly pixel by pixel

Temporally varying errors can potentially be corrected during the retrieval process if the change induced in the instrumental response is not random (i.e. they are correlated). Therefore, the tolerance to correlated errors is much higher than to uncorrelated errors. The error analyses, including all known contributors, led to the conclusion that the goal requirements can almost be fulfilled.

Spectrally-varying radiometric errors are errors generated from ghosts appearing in the ILS as a result of modulations during the IFM scan. Such modulations can be caused by micro-vibrations and a corresponding lateral movement of the corner cube(s). The effect is similar to the LOS jitters and will cause pseudo-noise. Analysis of the requirements shows that the lateral shift must be limited or measured and corrected to achieve knowledge of the corner cube lateral jitter of about 5 nm. This can be achieved with a three-point metrology; however the performance and degree of compliance of a simpler single point metrology still has to be investigated in more detail.

VIII. INSTRUMENT PRE-DEVELOPMENTS

The design activities and the associated technical risk analyses performed during the Phase-A led to the definition of risk areas, which can be mitigated by the early breadboarding and performance evaluation of the following sub-systems and functionalities: The interferometer mechanism, its control electronics, metrology, the front and back-optics, the pointing mirror, the cryostat and focal plane implementation, the detectors, the impact of micro-vibrations on performance, the complexity and performance of the processing chain, and the integration of critical instrument subsystems.

A representative instrument breadboard shall serve as a demonstration of the working principle of the IRLS and can be used for the confirmation of the compliance to critical performances as estimated by analysis during the Phase A. The early development and testing of a representative and complete IRLS breadboard (BB) is therefore considered as a high

priority activity to mitigate development risks and to secure the instrument concept and expected performance.

It is therefore planned to build for both concepts a IRLS BB which shall consist at least of the IFM mechanism with two Corner Cubes, a beamsplitter, and the laser metrology system. It shall include a front optics and a camera or reimaging system and a detection system with OGSE and EGSE. All items except for the detection chain, the OGSE and EGSE shall be representative in function and performance for the PREMIER IRLS configuration. The objectives of the IRLS BB are to demonstrate compliance to the relevant instrument requirements. The expected performance evaluations or verifications are:

- Characterisation of the IFM performance by measurement of the field dependant ILS in both operating modes,
- Investigation of the influence of the IFM lateral jitter on the ILS and the degree of compliance to the ghosting requirement,
- Investigation of the sensitivity to micro-vibrations within the applicable frequency range (for the micro-vibration effects see also [5]),
- Verification of the spectral calibration, its transfer from CM to DM, and investigation of the achieved spectral stability,
- Demonstration of the resampling strategy (constant time sampling),
- Demonstration of the feasibility of the data acquisition in PREMIER operating conditions,
- Verification of the data quality,
- Measurement of the IFM and instrument field dependent transmission or vignetting,
- Characterization of the instrument's PSF within the applicable field of view and verification of the analytical model for the PSF,
- Measurement or verification of the WFE,
- Establishment of straylight sensitivity,
- Demonstration of the feasibility of the PSF knowledge,
- Investigation of instrument stabilities in general (spectral, spatial, IFM jitter as function of time), and
- Verification of the emissivity / radiometric model.

The IRLS BBs may be used as well to investigate other system related aspects..

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