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Radiometric Disturbances Assessment and Performance Improvement Strategies for the FORUM Sounding Instrument

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Abstract

The Far-infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission is ESA's 9th Earth Explorer, designed to provide the first comprehensive characterization of the Earth's outgoing thermal radiation in the far-infrared spectral region. This ambitious objective demands a measurement approach capable of acquiring highly accurate and spectrally resolved broadband data. To satisfy these demanding requirements, an interferometer based on Fourier-Transform Spectroscopy (FTS) has been designed. FTS instruments are sensitive to several disturbance sources, particularly speed fluctuations and detector noise. It is essential to assess and quantify the impact of these disturbances on instrument performances, to validate the instrument design or alternatively investigate improvement strategies.

Through numerical simulation and the use of experimental data sets, the robustness of the FORUM payload against such disturbances is addressed. The impact of detector noise on the total noise budget has been quantified, and improvement strategies are investigated to enhance performance and mitigate this disturbance. Furthermore, signal processing strategies are explored to account for detector noise and improve data quality in post-processing. The effect of speed fluctuations is quantified in relation to the knowledge accuracy of the detector's transfer function, demonstrating the existing correlation and the robustness of the design, provided that the transfer function is accurately characterized. Experimental speed fluctuation measurements are employed to quantify, in a representative manner, the correlation between speed instabilities and radiometric errors. This research demonstrates that the detector noise plays a dominant role in instrument data quality, while speed fluctuation effects are efficiently counterbalanced by the FORUM instrument design, constituting a minor disturbance source. Overall, the design of the FORUM instrument is proven to be robust, confirming that the ambitious research objectives of the mission are within the reach of the instrument's capabilities.

Keywords: FORUM, FTS, Interferometer, Performances, Disturbances, Radiometry.

Abstract in lingua italiana

La missione FORUM, acronimo di Far-infrared Outgoing Radiation Understanding and Monitoring, rappresenta il 9° Earth Explorer dell'Agenzia Spaziale Europea (ESA) ed è finalizzata a caratterizzare per la prima volta le emissioni terrestri nell'infrarosso. Il raggiungimento di questo obiettivo richiede un approccio di misura in grado di acquisire dati a banda larga nell'infrarosso, ad elevata accuratezza e risoluzione spettrale. Per soddisfare tali requisiti, un interferometro basato sulla spettroscopia a trasformata di Fourier (FTS) è stato progettato. Gli strumenti FTS sono sensibili a diversi fattori di disturbo, in particolare a fluttuazioni di velocità dell'interferometro e al rumore elettrico dei sensori. È pertanto essenziale valutare e quantificare l'impatto di tali disturbi sulle prestazioni dello strumento, al fine di validare il design ed eventualmente identificare strategie di miglioramento.

Attraverso simulazioni numeriche e l'utilizzo di dati sperimentali, la robustezza del design dello strumento FORUM rispetto a tali disturbi è analizzata. L'impatto del rumore elettrico del sensore sul budget totale di rumore è stato quantificato e sono state investigate strategie di miglioramento volte a mitigare questa fonte di disturbo. Inoltre, sono state esplorate tecniche di elaborazione del segnale per migliorare la qualità dei dati in fase di post-processing. L'effetto delle fluttuazioni di velocità è stato quantificato in relazione alla accuratezza di caratterizzazione della funzione di trasferimento del sensore, evidenziando la correlazione tra i due e la robustezza del design. Misure sperimentali delle fluttuazioni sono state utilizzate per quantificare in modo rappresentativo la correlazione tra ampiezza della fluttuazione ed errori.

Questa ricerca dimostra che il rumore del sensore rappresenta il fattore dominante sulla qualità dei dati acquisiti, mentre gli effetti delle fluttuazioni di velocità risultano efficacemente compensati dal design dello strumento, rappresentando una fonte di disturbo marginale. Nel complesso, il design dell'interferometro sviluppato per FORUM si dimostra robusto, confermando che gli ambiziosi obiettivi scientifici della missione sono compatibili con le correnti capacità dello strumento.

Parole chiave: FORUM, FTS, Interferometria, Prestazioni, Disturbi, Radiometria.

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1 | Introduction

The Far-Infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission is an Earth observation satellite whose primary objective is to measure Earth's top-of-atmosphere emission spectrum, closing the existing far-infrared observational gap [1]. FORUM is the 9th Earth Explorer (EE) research mission of the FutureEO Programme, established by the European Space Agency (ESA) to advance Earth science by addressing key unresolved scientific questions [2].

Each of the research missions in the EE family is characterized by the novelty of their scientific research and their complementarity with existing remote sensing capabilities. By addressing fundamental scientific challenges, while developing in parallel new Earth observation capabilities and techniques, the EEs provide the technical foundation for future operational missions.

The development of novel Earth observation capabilities is an ambitious goal that can be reached with a rigorous design process and a careful assessment of all potential disturbances and failure sources. Particular attention has to be posed on the observational performances, by verifying that the factors capable of degrading the data quality are thoroughly identified, simulated and if necessary mitigated.

1.1. The Earth Explorer Missions

To fully capture the scientific and technical aspects of FORUM, the broader context of the EE missions is required. The selection process of each EE provides a clear picture of the level of technical innovation these missions embody, underlying the necessity of accurate simulations and performance estimations. The evolution of the EE missions over time is provided, to illustrate the specific technical and scientific context from which FORUM emerged.

1.1.1. The selection process

The selection process of an EE mission is unique within the activities of the European Space Agency, due to the exceptionally broad participation of its member states. The appeal of the FutureEO program and the EE missions lies in the opportunity it offers to each participant country of significantly advancing their technical expertises, laying the groundwork for the development of higher complexity missions.

The Call for Proposal: the selection process starts when a Call for Proposal for the implementation of an EE is issued by ESA. This call contains the guidelines that each proposed mission has to follow [3]. The main aspects covered are:

- Scientific area of research: the selection committee, according to the current needs of the scientific and global community, identifies the main research areas to be investigated.
- Scientific Readiness Level (SRL): the SRL measures the maturity of a scientific objective and research method. In the call for proposal, a minimum threshold is specified for the submission. This ensures that only sufficiently mature scientific concepts are taken into consideration. An SRL of 4 to 6 is usually specified, to encourage the research of novel scientific issues [4].
- Technology Readiness level (TRL): the TRL measures the level of development of a technology. Similarly to the SRL, a minimum threshold is specified. To favour both maturity and innovation, a minimum level of TRL 4 is typically requested [4].
- Technical recommendations: depending on the specific call, technical recommendations on the mission design are issued, depending on the currently available Earth observation techniques and the desired capabilities.
- Cost and launch period: the cost at completion is specified, along with the envisaged launch period.

Review of the proposals: each candidate is evaluated based on its scientific and technical maturity. The scientific content is assessed through a peer-review process, conducted by the global scientific community, while ESA focuses on both the technical and programmatic feasibility of the proposal.

Selection for feasibility study: depending on the call, a limited number of candidates are selected for the Phase A study. Each mission has to refine the initial proposal through cooperation with industry partners.

At the end of Phase A, each candidate must provide a Report for Mission Selection with:

- Scientific justification, research objectives, observational requirements.
- Mission elements identification (architecture, space and ground segments, concept of operations, programmatics).
- Scientific data processing and validation.
- Mission performances estimation.

Final selection for implementation: the candidates submit the outcome of the Phase A study to an internal committee for the evaluation of the technical aspects of the mission proposal. The scientific aspects are presented at a User Consultation Meeting, an open forum where the scientific community, i.e. the end users of the mission, are asked to provide their feedback on the scientific maturity and effectiveness of the mission. According to the outcome of the technical and scientific review, the Earth Explorer mission is selected for implementation [5].

1.1.2. Scientific and technological trends of the EE missions

Within the EE research missions family, reported in Figure 1.1, specific trends in the scientific focus and technological development can be identified.



Figure 1.1: *The Missions of the EE family [2].*

At the beginning of the EE program, ESA's Earth observation capabilities were limited to a small number of dedicated missions. Consequently, the first EE were conceived as stand-alone projects, each dedicated to addressing a specific and unexplored scientific question.

Their research topics were selected to fill critical gaps in Earth science knowledge, while also establishing reference measurements for future missions.

Today, the Copernicus programme and the Sentinel series, paired with the Meteorological Operational satellite programme (MetOp) provide a much broader range of observation capabilities [6]. Therefore, the selection of research areas has become more strategic, taking into account both the most pressing needs of the scientific community and the compatibility with existing and forthcoming missions. In recent missions, emphasis is placed not only on the uniqueness of the measurement but also on its complementarity with currently available datasets. FORUM, being one of the most recently selected EEs, embodies this duality in its observational spectral band, providing unique measurements in the Far-Infrared and complementarity with currently available Medium-Infrared datasets [1].

From a technological standpoint, the most recently selected missions show a growing emphasis on formation flying and collaboration with other operational missions. Enhancing the synergy between different missions allows for improved data quality and broader scientific outcomes, with cross-calibration being a notable example of this advantage. FORUM fully embraces this cooperative approach, through formation flying with the MetOp-SG(A) satellite, which will acquire similar data in a partially overlapping spectral band. This configuration will enable valuable cross-calibration opportunities, further enhancing the scientific return of both missions [1].

1.2. Motivation and Outline of this document

In the previous sections, it was shown that an EE mission embodies a balance between innovation and scientific and technological maturity. FORUM concretizes this balance, as it relies on flight-proven technologies for infrared spectral measurements, while being the first mission to extend their application to the Far-Infrared region. The novelty of the scientific research and the extension of the measurement band implies additional challenges for the mission and instrument design. Representative simulations of the instrument behaviour are fundamental to aid the design process and mitigate the mission risks.

This document provides a comprehensive overview of Fourier-Transform Spectrometry (FTS), the observational principle adopted for FORUM, establishing the necessary technical foundation for the simulations presented later in this document. A broad description of the FORUM Sounding Instrument (FSI) design is reported, illustrating the state-of-the-art implementation of a spaceborne interferometer. Finally, the operational simulator developed to model the FSI's in-orbit behaviour is introduced, serving as the basis for the analyses implemented for this document.

Among all aspects requiring thorough simulations, the observational performances demand a high priority. The mission success, in particular in the case of a first-of-its-kind like FORUM, is related to the ability of delivering the measurements with a sufficient quality to secure their relevance for the upcoming decades. Researches have been performed to study the impact of several disturbance factors on the instrument performances. The analyses and simulations presented in this report were conducted to verify the robustness of the current design and to further strengthen confidence in the mission's success.

Within this framework, the primary objective of this thesis is to quantitatively assess the impact of radiometric disturbances on the FORUM Sounding Instrument. Through simulations and thanks to experimental data, this study aim is to characterize how critical perturbations degrade the measurements' quality. A secondary goal of this thesis is to evaluate the effectiveness of disturbance mitigation strategies and correction algorithms, verifying that residual errors remain within the stringent margins required for the achievement of FORUM's scientific goals.

This document is structured as follows:

- Chapter 1 provides the context of the Earth Explorers missions and outlines the scientific and technological trends that brought to the FORUM Mission.
- Chapter 2 is dedicated to an overview of the FORUM Mission and Fourier-Transform Spectrometry. The scientific rationale and observation requirements are presented, along with the selected measurement technique, instrument architecture and operational concept. The simulator used for the analysis of Chapter 3 is introduced, along with the estimated performances of the instrument.
- Chapter 3 is an in depth analysis on the impact of several disturbance sources on the observational performances of the mission. The role of the detector noise and the interferometer speed fluctuations are assessed. Improvement strategies are investigated and their effectiveness is quantified. The results of each assessment are presented in this Chapter.
- Chapter 4 offers a discussion based on the results reported in Chapter 3, evaluating the relevance of each disturbance, the robustness of the current instrument design and the effectiveness of improvement strategies.
- Chapter 5 draws conclusions relative to the technical studies reported and offers considerations about future developments.

2 | The FORUM Mission

This chapter provides a comprehensive overview of the FORUM mission, establishing the technical and scientific context required to interpret the analyses in Chapter 3. Section 2.1 introduces the mission’s scientific objectives, which drive the observational requirements detailed later in Section 2.3; these requirements are fundamental as they define the performance targets against which the disturbance analyses in Chapter 3 are benchmarked. To ensure a solid technical understanding of the instrument’s operation, Section 2.2 describes the working principles of Fourier Transform Spectrometry (FTS), laying the necessary foundation for the analyses and trade-off studies that follow. Section 2.4 then presents the design of the FORUM Sounding Instrument (FSI), offering a system-level view of the key components involved in the trade-offs of Chapter 3. This is complemented by Section 2.5, which outlines the acquisition and calibration strategies, explaining how the scientific data products, i.e. the subjects of the data quality analyses of Chapter 3, are generated. Lastly, Section 2.6 introduces the operational simulator developed to model the FSI’s behaviour, serving as the primary tool for assessing instrument performance and the impact of disturbances. The FORUM mission patch is shown in Figure 2.1.



Figure 2.1: *The patch of the FORUM Mission [7].*

2.1. Scientific Rationale and Mission Objectives

FORUM, short for Far-infrared Outgoing Radiation Understanding and Monitoring, is an Earth observation mission whose objective is to characterize for the first time Earth's emissions in the far-infrared. FORUM scientific products will fill an important knowledge gap in the current comprehension of Earth's climate and will contribute significantly to climate models, increasing the current weather prediction capabilities.

2.1.1. Earth's thermal radiation in the far-infrared

Earth climate can be described as a complex system of interconnected phenomena all simultaneously interacting. The Global Climate Observing System (GCOS), a world recognized system for climate observations, has defined a list of this interconnected components, called the Essential Climate Variables [8]. This comprehensive list collects 55 physical, chemical or biological variables that critically contribute to the characterization of Earth climate. Among these variables, the Earth Radiation Budget (ERB) stands out for its significant impact and relevance on Earth's weather. The FORUM mission objective is the accurate characterization of this Essential Climate Variable.

The ERB describes the balance between the incoming energy of the sun irradiation and the outgoing thermal emission of the Earth. Considering a multi-annual scale, these components are normally in equilibrium; if this balance is perturbed, for example due to an increase of greenhouse gases in the atmosphere, this will cause a climate adjustment that will modify the temperature of the Earth, until a new equilibrium is reached. Therefore, a direct measurement of the ERB will provide important information to address the present and future heating and cooling rates of the Earth.

The energy emitted by Earth that is dispersed into space is commonly referred to as Outgoing Longwave Radiation (OLR). Due to the average Earth temperature, 97% of the OLR occurs in the 4-100 μm wavelength range. In this spectral region, several greenhouse gases have strong absorption bands, therefore their concentration significantly impacts the OLR [1]. Highly accurate OLR measurement will allow to link changes in the planetary energy balance to the mechanisms behind the alteration, such as the modification of concentration of a greenhouse gas. The current knowledge of the OLR is limited to the mid-infrared (4-15 μm), where continuous and global observations exist [9]. In the Far-Infrared Region (FIR, 15-100 μm), no recent and comprehensive measurement is recorded. A large portion of the effects resulting from a climate balance modification occurs in this region. Therefore, due to the relevance of this spectral band, a measurement of the OLR in the FIR is needed, to fill the knowledge gap and improve climate models [1].

H₂O vapour role and the necessity of spectrally resolved measurements

The dominant role of the FIR in Earth's OLR is mainly due to water vapour absorption lines [10]. To address the effect of water vapour in the FIR, it is necessary to define what constitutes a feedback mechanism in climate science. Climate feedbacks are processes that can either amplify (positive feedback) or diminish (negative feedback) the effect of an initial climate forcing, such as increased greenhouse gas emissions. Water vapour is linked to a positive feedback mechanism, where the increase of the temperature leads to higher water evaporation, causing itself a temperature increase due to its powerful greenhouse effect, thus repeating the cycle.

Enhanced sensitivity in the FIR to small changes of water vapour concentration can be exploited to link directly, for the first time, water vapour greenhouse effect with its associated radiative signature. The dominant role of H₂O vapour in the infrared region is presented in Figure 2.2.

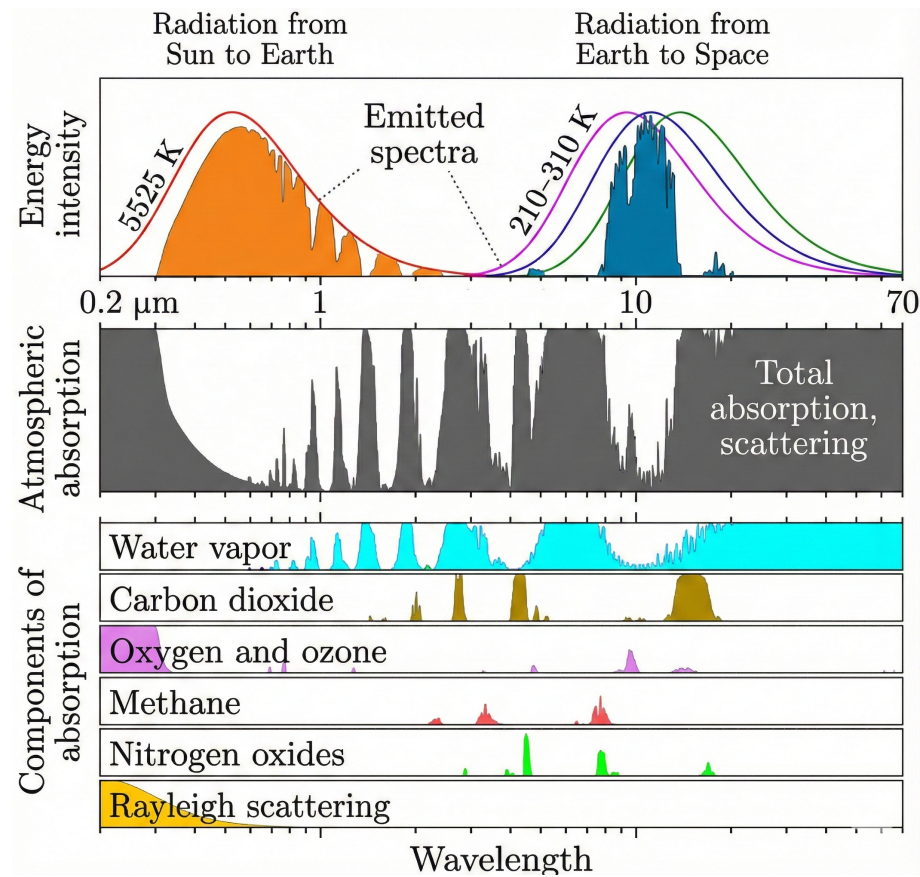


Figure 2.2: The Earth emissions (blue spectra, top plot) in the infrared compared to the downgoing solar radiation (orange spectra, top plot) and the main radiance absorption gases (bottom plots). Adapted from [11].

Every greenhouse gas is associated with specific absorption bands. For example, the greenhouse effect of CO₂ in the IR is mostly centred around a wide absorption band at 15 µm, while water vapour has numerous absorption bands with a very narrow width. As a consequence, to properly assess the impact of each greenhouse gas and atmospheric constituent on the OLR, spectrally resolved measurements are required.

FORUM Scientific goal

As demonstrated in the previous sections, FIR radiation has a fundamental role in modulating the climate and holds critical information about key climate processes. Therefore, the overall scientific goal of the FORUM mission can be summarized as follows [1]:

The FORUM Mission scientific goal is to evaluate the role of the FIR in shaping the current climate, to reduce the uncertainty in predictions of future climate change.

2.1.2. Mission Objectives

The scientific goal of FORUM is addressed through primary and secondary objectives.

Primary Objective

The primary objective of the FORUM mission is [1]:

The FORUM mission will observe, for the first time, the distribution of Earth's OLR in the IR spectrum, encompassing FIR. These measurements will:

- Assess the underlying spectroscopy in the FIR.
- Tie the radiative signatures to variability of greenhouse gases, clouds and surface properties.
- Provide an evaluation of radiative processes in climate models.

Hence, the primary goal of FORUM is to enable these measurements to be made with sufficient spectral coverage and resolution, and with high enough radiometric accuracy that each of these goals can be met.

To satisfy the primary objective, the spectral coverage must be large enough to encompass a significant portion of Earth's OLR. The observation bandwidth selected for the FORUM mission ranges from 6.25 µm to 100 µm (in wavenumbers¹ this corresponds to 100-1600 cm⁻¹), where 95% of OLR is expected to be emitted [12].

¹Wavenumber = 1 / wavelength, expressed in [cm⁻¹]

To accurately distinguish the fine spectral signatures of greenhouse gases, particularly water vapour, whose absorption and emission lines in the far-infrared are narrow and densely spaced, a spectral resolution of at least 0.5 cm^{-1} is required; this ensures precise identification of individual spectral features. Any coarser resolution would result in the merging of adjacent water vapour lines, degrading retrieval accuracy [12].

Due to the exploratory nature of the mission, an emphasis is posed on the measurement accuracy and not on instantaneous noise, to minimise measurement bias. For climate studies purposes, it is possible to average multiple measurements to reduce the effects of noise up to the level of the measurement accuracy. The targeted performance for the radiometric accuracy is 0.1K (from 300 to 1100 cm^{-1} , most stringent value), while the required radiometric noise is $0.4 \text{ mW}/(\text{m}^2 \text{ sr}^{-1} \text{ cm}^{-1})$ (from 200 to 800 cm^{-1} , most stringent value) [12]. A detailed explanation of the observational performance requirements is available in Section 2.3.

Secondary Objectives

The FORUM mission has several secondary objectives [1]:

- FIR surface emissivity retrieval.
- Assess FIR additional benefits in H_2O retrieval compared to MIR.
- Detection of thin cirrus clouds.
- Detection of ice-cloud optical depth.

Each of these secondary objectives requires instantaneous radiance observations and is not achieved with measurement averaging, therefore an emphasis is placed also on the radiometric noise of the mission.

2.2. Fourier Transform Spectrometry

The observation method selected for the FORUM mission is based on Fourier Transform Spectrometry (FTS). This section offers an overview of this measurement technique, along with a description of typical architectures, working principle and data processing techniques to obtain the desired scientific products. Further advantages of FTS instrumentation over dispersive spectrometers are detailed in Appendix A. While these merits complement the current discussion, they are not a prerequisite for interpreting the core analyses presented in Chapter 3.

In brief, a Fourier Transform Spectrometer is an instrument that generates the spectrum of a radiation source, by modulating the collected radiance in time domain through an interference process. The interferogram of the observed scene is Fourier transformed to obtain the frequency distribution of the acquired signal. FTS is a common measurement technique for spectrally resolved infrared measurements, with significant advantages compared to dispersive spectroscopy [13]. It provides accurate, spectrally resolved and broadband measurements, all desired qualities for FORUM science products.

2.2.1. Principles of Fourier Transform infrared Spectrometry

FTS instruments are optical spectrometers, thus they are capable of decomposing an incoming electromagnetic radiation into its components across the observed spectral band. There are several techniques that can be used to decompose light, such as dispersive or filter based spectrometry, where light is optically separated into its constituents depending on its interaction with a material (e.g. a prism).

In an FTS instrument, light is not separated optically, since the signal it is collected altogether by a detector and then spectrally decomposed with signal processing techniques. Ideally, by Fourier transforming the signal collected by a detector, it is possible to extract its frequencies components. However, no detector currently exists capable of measuring the extremely rapid oscillations of light in the infrared region ($5 \cdot 10^{13}$ Hz for light at $6\mu\text{m}$) [13]. FTS instruments exploit an interferometer, that encodes the spectral information into an interferogram. The Michelson's interferometer is the simplest example of this technology [14]. It consist of an instrument with a beam splitter, two mirrors and a detector. Of these two mirrors, one is capable of translating over the optical axis and one is fixed, as shown in Figure 2.3.

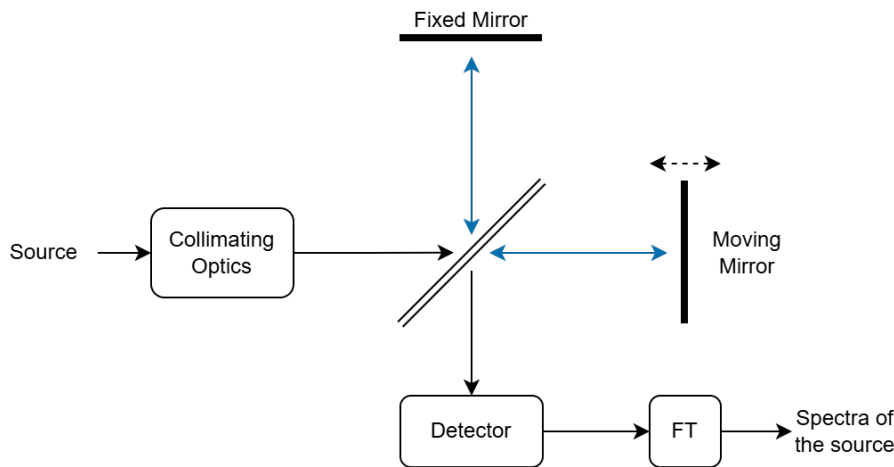


Figure 2.3: *FTS instrument with Michelson Interferometer.*

Light first passes through a set of collimating optics that produce a parallel beam. The beam splitter then divides the collimated light into two perpendicular beams of equal amplitude. Each beam is reflected by a mirror and subsequently recombined at the beam splitter. With the recombination, a constructive or destructive interference is generated. Typically, one of the two mirror moves to create a time dependant variation of the interference; the signal recorded by the detector with this time varying interference constitutes the interferogram. A Fourier Transform routine is then applied to extract the frequency distribution of the incoming radiation source. In an ideal FTS instrument, the interferogram is symmetric and the cosine Fourier Transform is used.

$$C(\nu) = \int_{-\infty}^{\infty} I(x) \cos(4\pi\nu x) dx \quad (2.1)$$

where $C(\sigma)$ is the spectral distribution function, σ the wavenumber, $I(x)$ the interferogram and x the difference in distance travelled by the two beams [13].

At first glance, it is not straight forward to understand how the spectral information is encoded in the interferogram. A simplified explanation is provided as follows. When one of the two mirror moves, the two beam of light will cover a different distance. This introduces a phase difference δ between the two signals at recombination, expressed as:

$$\delta = \frac{2\pi x}{\lambda} \quad (2.2)$$

where x is the difference in distance travelled by the two beams and λ the wavelength [13]. At recombination, this phase difference results in a constructive or destructive interference. In the interferogram, these interferences are recorded with respect to the movement of the mirror, allowing to associate maximum and minimum points (respectively fully constructive or destructive interferences, $\delta = 0^\circ$, $\delta = 180^\circ$) to the associated mirror position x . Subsequently, from Eq 2.2, the wavelength is extracted and the spectral information is retrieved. This simplified explanation demonstrates how an interferogram is able to embed the spectral information of the input signal.

This represents the simplest configuration of an ideal FTS instrument. A real FTS instrument, such as the one designed for the FORUM mission described in Section 2.4, includes several additional components to ensure the correct functioning of the instrument, although the working principle is the same.

Interferometer motion and the Metrology

To complete the description of the FTS operating principle, it is necessary to outline the fundamentals of interferometer motion and interferogram sampling.

Optical Path Difference (OPD) is the difference in the distance covered by two beams of light travelling through an interferometer before they recombine. A variation of the position of one mirror of x cm will result in an OPD of $2x$, due to the reflection. When the length of the two arms is the same, then the interferometer is at Zero optical Path Difference (ZPD). To generate the interferogram, the interferometer moves up to the Maximum optical Path Difference (MPD).

Depending on the selected interferometer motion, two types of interferograms (IGM) can be generated [14]:

- Single sided: the moving mirror moves from MPD to ZPD or from ZPD to MPD.
- Double sided: the moving mirror moves from -MPD to +MPD.

In both types of interferogram, at ZPD the phase difference between the signals at recombination is null (see Eq 2.2) and a peak in the interferogram is recorded, due to strong constructive interferences. This peak is often referred to as centreburst. With a polychromatic input signal, when the mirror moves away from ZPD, destructive interferences rapidly increase, quickly bringing the recorded signal to zero.

The interferogram is usually recorded in time and then resampled on the OPD domain. To ensure the correct movement of the mirror with a feedback control loop and to accurately resample, the OPD over time must be correctly measured, by a system of components referred to as Metrology [14].

The OPD measurement is achieved with the addition of a laser source in the interferometer: a monochromatic beam travels through the interferometer and is measured by a dedicated detector. The relative displacement of the mirror is measured by counting the sinusoidal pulses (alternation between constructive and destructive interferences); the velocity of the mirror can be extracted from the frequency of these sinusoidal pulses [13]. This technique as it is cannot determine the interferometer's scan direction. Since some FTS instruments exhibit direction-dependent behaviour, identifying the motion direction is necessary for accurate data calibration, thus requiring a more advanced optical configuration. Additional elements introduce a phase delay, to generate a circularly polarized metrology beam, which passes through the interferometer and is later split into horizontal and vertical components, that are detected by two dedicated sensors, as in Figure 2.4.

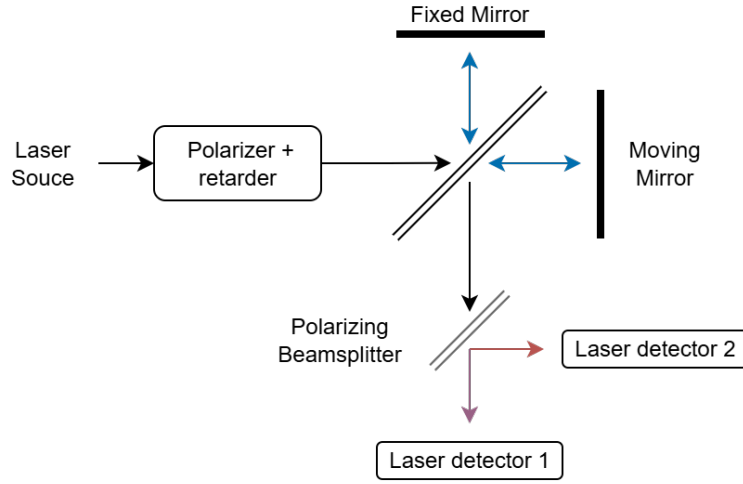


Figure 2.4: *The Metrology system of an FTS instrument.*

It is possible to associate the direction of movement with the derivative of the phase of the horizontal and vertical components, thus extracting the desired motion information [13].

Instrument Line Shape and Spectral Resolution

An FTS instrument is capable of recording spectrally resolved measurements thanks to the Fourier Transform routine. The theoretical maximum value of the spectral resolution is related to the Instrument Line Shape (ILS) and the OPD range.

The Instrument Line Shape can be defined as the resulting output spectrum of a purely monochromatic input signal [14]. If the instrument is ideal, a monochromatic input with infinitesimal thickness yields the same line as output. This is achieved only if an ideal cosine Fourier transform is performed (Eq 2.1). In a real instrument, the integration limits are truncated at $\pm$ MPD (for a double sided IGM).

$$\text{ILS} = \int_{-\text{MPD}}^{\text{MPD}} I_{\text{monochromatic}}(x) \cos(4\pi\nu x) dx \quad (2.3)$$

The Fourier Transform of a delta function (monochromatic signal) with finite integration limits yields a sinc function. This sinc function is the Instrument Line Shape.

The spectral resolution $\Delta\sigma$ is directly proportional to the Full-Width Half-Maximum (FWHM) of the ILS. For example, two closely spaced monochromatic signals as input will yield two closely spaced sinc functions as output. The two signals are spectrally resolved only if the ILS is narrow enough to avoid superpositions of the first lobe of the sinc function, as in Figure 2.5.

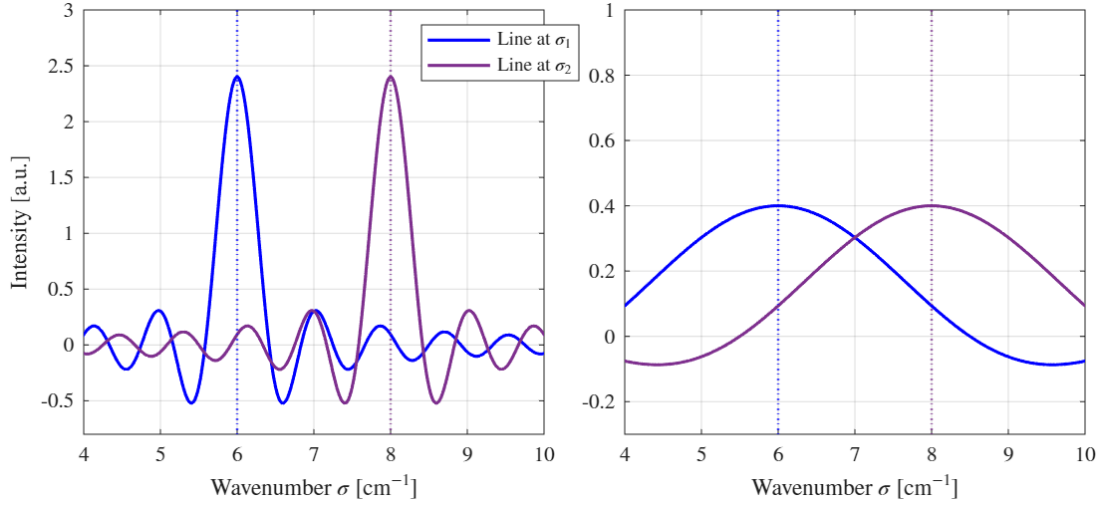


Figure 2.5: Simple example of two monochromatic signals sampled with two different ILS: left figure represent an FTS with narrow ILS and spectrally resolved measurement, right figure represent a wider ILS and unresolved measurement.

The theoretical maximum value of the spectral resolution $\Delta\sigma$ is expressed by Eq 2.4 [15].

$$\Delta\sigma = \text{FWHM(ILS)} = \frac{1}{2 \text{ OPD}} \quad (2.4)$$

Therefore, the wider the movement range of the mirror, i.e. the OPD, the higher the resolving power of the instrument. Other additional factors, such as the self-apodisation discussed in Section 2.2.2, will degrade the ideal performance of Eq 2.4.

Interferogram digital pre-processing

Once the interferogram has been acquired, a few basic operations are performed before the Fourier Transform [13] [16].

1. Apodisation: this refers to a mathematical processing applied to the acquired interferogram to modify the ILS. It consist of a multiplication of the interferogram with a shape function (triangular, Gaussian, ecc...), resulting in the reduction of the side lobes and an increase of the FWHM of the ILS, thus improving the signal quality at the cost of a spectral resolution degradation.
2. Zero Path difference estimation: the process of identification of the ZPD position in the recorded interferogram. It is a necessary step to guarantee accurate resampling of the interferogram from time domain to OPD domain.

3. Phase errors correction: phase errors arise when the interferogram is not sampled at exactly the peak of the centreburst (at ZPD). If not corrected, this causes distortions in the amplitude and asymmetries of the spectrum [17]. These errors are corrected by including a correction factor for the displacement, or by computing the complex Fourier transform (and not the cosine FT of Eq 2.3). The Phase correction is particularly relevant when dealing with single sided IGM [13].

Additional operations are required depending on the precise architecture of each FTS instrument. A breakdown of the data processing for FORUM is reported in Section 2.6.2.

2.2.2. Main Disturbances in FTS instruments

FTS instruments are subject to several disturbance factors that degrade their theoretical performance and increase the complexity of design and signal processing methodologies. A detailed analysis of these effects for FORUM is presented in Chapter 3. The purpose of this section is to provide a concise qualitative overview of these disturbances, establishing the background knowledge for Sections 2.3 and 2.4.

Detector noise

The electrical noise of the detector is one of the most impactful sources of errors for FTS instruments [13]. The disturbance is quantified through the Noise Equivalent Power (NEP), describing the minimum power within a specific bandwidth required to produce a SNR of one, thus representative of the smallest detectable signal.

In an FTS where the detector noise is the dominating factor, i.e. detector noise limited, the noise of the collected signal is independent from the intensity of the input signal. With a FIR observation, where the input signal is faint, the detector selection will be a driving factor for the design and the instrument will likely be detector noise limited. Several analyses of the effects of this disturbance and possible improvements for the FORUM mission are reported in Section 3.1.

Radiometric errors and calibration necessity

FTS instruments measure a scene emissions passively, like a radiometer. The collected signal is composed of the radiation emitted by the observed scene and the additional contribution of the instrument self-emissions, in the bandwidth of observation. To this measurement, other disturbance sources such as detector noise are added.

As a first approximation, considering that an FTS is collecting signals as a radiometer, its behaviour can be described as linear with Eq 2.5.

$$\text{Retrieved Spectra} = \text{Gain} \cdot \text{Input Spectra} + \text{Offset} \quad (2.5)$$

To correct the radiometric errors and retrieve the Input, the Gain and Offset must be characterized. This is often done with a two point calibration, with two calibration bodies at well known temperatures.

Self-apodisation

In Section 2.2.1, the apodisation effect was described as a method to modify the ILS of the instrument. Self-apodisation consist of an additional apodisation effect caused by the optics of the instrument.

In a perfect FTS, the input beams enters the interferometer perfectly collimated; in a real instrument, an angle of divergence with respect to the propagation axis is expected. This divergence angle causes a reduction of the OPD covered by the beam, with the cosine of the angle. This effect is accentuated when the moving mirrors is at the extreme positions of its movement range ($\pm$ MPD) due to the destructive interference contribution. According to Eq 2.4, a reduction of the OPD implies a broadening of the ILS of the instrument. The self-apodisation causes the same effect as applying an apodisation function during post-processing. The difference is that the effect is intrinsic of the optics and geometry of the instrument and cannot be fully removed.

The self-apodisation is the main source of spectral resolution deviation from the maximum theoretical value, given by Eq 2.4, as discussed in Section 2.3.

Interferometer speed fluctuations

As described in Section 2.2.1, a relative movement of the interferometer mirrors is required to create the desired interferogram. In a real FTS instrument, the movement can be influenced by external vibrations, resulting in speed fluctuations. The direct consequence is an undesired amplitude and phase modulation of the input signal [17]. Due to the random nature of this disturbance, a loss of repeatability of the measurement occurs, i.e. an increase in the radiometric noise. The effects of speed fluctuations for the FORUM payload are described in detail in Section 3.3.

2.3. Observational Requirements and Performances

To achieve the mission objectives outlined in Section 2.1, a comprehensive set of mission requirements has been defined. For the purpose of this document, emphasis is placed on the radiometric, spectral, and geometric requirements; accordingly, this section presents the primary requirements for the FTS instrument of the FORUM mission. The performance parameters to be investigated through the studies of Chapter 3 are specified together with their corresponding requirements and their current status.

It must be noted that, as described in Section 2.4, FORUM carries both an FTS instrument (FORUM Sounding Instrument, FSI) and a thermal camera (FORUM Embedded Imager, FEI). The performance requirements presented here focus on the FSI, being the primary payload. The specifications and role of the thermal camera will be addressed in Appendix B, at a lower level of detail, due to its complementary role in the measurements.

2.3.1. Spectral Range

Earth's Outgoing Longwave Radiation has to be measured over the full spectral range where significant emissions occur, from the FIR to the MIR. To achieve the desired synergy with the IASI instrument MetOp-SG(A) mission, described in Section 1.1.2, an overlap of the observation bandwidth is also required.

The selected spectral range is expected to contain 97% of the total FIR energy and is partially overlapping in the MIR region with the IASI instrument MetOp-SG(A) [1, 12].

MR-OBS-160: The FSI shall provide spectrally resolved measurements between 100 and 1600 cm^{-1} (100 – 6.25 μm).

2.3.2. ARA: Absolute Radiometric Accuracy

ARA stands for Absolute Radiometric Accuracy. It is defined as the unknown systematic measurement error of the radiometrically calibrated spectra of Earth's emissions; it represents how much the FSI is able to approximate the "real" value of the observed scene. Climate is by definition a statistical description of weather events, therefore spatial and temporal averages are necessary operations to perform statistical studies [1]. When different measures are averaged, the instantaneous noise is strongly reduced (since random noise between different measurements can be considered uncorrelated [12]) and the only source of error left is the Absolute Radiometric Accuracy. Therefore, the ARA is of crucial importance to establish a highly accurate dataset of FIR radiances that can serve as benchmark for present and future climate models, thus satisfying the goal of FORUM.

ARA: Requirement

The required Absolute Radiometric Accuracy of the FSI is:

MR-OBS-290: The Absolute Radiometric Accuracy shall allow determination of equivalent brightness temperature with the following accuracy:

< 1.0 K in 100-200 cm^{-1} and 1300-1600 cm^{-1}

< 0.2 K in 200-300 cm^{-1} and 1100-1300 cm^{-1}

< 0.1 K in 300-1100 cm^{-1}

The requirement is specified at 3σ confidence level. The ARA is expressed as brightness temperature, and not radiance, due to the relevance of the former for climate studies [12]; the ARA can be converted to radiance units ($\text{W}/\text{m}^2 \text{ sr cm}^{-1}$) via the Planck Law.

ARA: Contributors

In the observational band of FORUM, the instrument is itself a large source of signal, due to its thermal self-emissions. The accuracy of an FTS instrument, i.e. the ARA, relies mainly on the effectiveness of the radiometric calibration and correction, discussed in Section 2.6.2, i.e. the ability of the instrument to remove undesired signals from the measurements, such as the thermal self-emissions. Table 2.1 summarizes the main ARA contributors. The calibration components mentioned (reference black body, baffles) and the calibration procedure are described respectively in Section 2.4.1 and Section 2.5.1.

Contributor	Description	Cause
Baffle emissions	Earth measurements and calibrations are not performed observing through the same baffle, leading to different and uncompensated self-emission signals.	Different baffle temperatures, emissivities and view factors.
Uncertainty of the reference black body radiance	A blackbody with a known temperature and emissivity is measured for calibration purposes. The uncertainties in the knowledge of both quantities lead to a loss of accuracy.	Blackbody characterization and temperature monitoring.
Detector responsivity and self-emissions	The detector responsivity and the self-emissions are dependent on the orbital temperature change. Between calibration events there is a systematic error in the knowledge of both quantities.	Thermal fluctuations between calibration events.

Table 2.1: ARA Contributors [1].

ARA: Current status

The ARA performance, according to the current estimates [18], is presented in Figure 2.6.

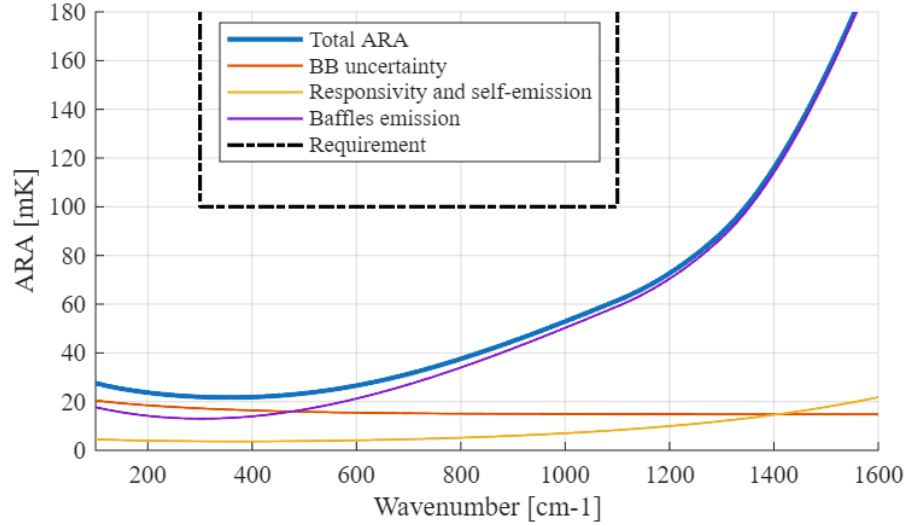


Figure 2.6: Estimate of Total ARA (Earth @ 190K) - Zoomed view at 0-180 mK.

The impact of the contributors on the total ARA is dependant on the temperature of the observed scene. For the FSI, the worst ARA performance is registered with a scene at 190K. At this temperature, the unbalanced baffle self-emission is dominating the ARA, in particular at high wavenumbers. Nevertheless, the estimated ARA is currently fully compliant with the mission requirements.

2.3.3. NESR: Noise-Equivalent Spectral Radiance

NESR stands for Noise-Equivalent Spectral Radiance. It is defined as the standard deviation of a time series of radiance measurements for a specific spectral channel, with a constant spectral source as input. It represents the precision of the instrument and the instantaneous noise level of a measurement.

The NESR requirement is essential for climate studies, where spatial and temporal averages are performed. Due to the random nature of the instantaneous noise, the NESR will be attenuated when averages are performed. Therefore, the lower the NESR, the lower the amount of averages necessary to bring the noise level to a desired threshold [12]. This is the primary driver for the NESR performance.

The secondary driver is the desire of performing low noise measurements of events that will not be subjected to averages. For example, surface emissivity is planned to be retrieved with a single measurement. Therefore, the NESR should be low enough to guarantee the quality of both instantaneous measurements and long term averages.

NESR: Requirement

The required Noise-Equivalent Spectral Radiance is:

MR-OBS-300: The Noise-Equivalent Spectral Radiance (NESR) of the FSI shall be less than:

0.4 mW/(m² sr cm⁻¹) in the spectral range [200-800 cm⁻¹]

1.0 mW/(m² sr cm⁻¹) outside of the spectral range [200-800 cm⁻¹]

This requirement is specified in the Mission Requirement Document [12] and represents the noise goal of the mission. However, an additional acceptable NESR level, referenced in this document as NESR Agreement, has been established [18], with a cooperation between ESA and the Mission Advisory Group (MAG), a panel of scientists representing the end users of the mission. In the studies reported in Chapter 3, the NESR Agreement, and not the initial requirement, is used as targeted performance.

NESR Agreement: The NESR Agreement is determined by the following corner points:

Wavenumber	Radiance	Wavenumber	Radiance
100	0.54	710	0.47
200	0.40	800	0.51
480	0.40	1030	1.00
570	0.44	1600	1.00

Table 2.2: NESR Agreement, Wavenumber in cm⁻¹, radiance in mW/(m² sr cm⁻¹). See Figure 2.7 for the graphical representation.

NESR: Contributors

There are several factors that determine the NESR performance. Since their combined effect is obtained with a Residual Sum of Squares, since the different contributors can be considered as uncorrelated. A qualitative overview is reported in Table 2.3.

The NESR performance will be the object of multiple analyses of this report. Further detail about its derivation and the impact of single components is available in Section 3.1.

Contributor	Description	Cause
Detector	The detector has an electrical noise dependent on the interferometer motion speed, acquisition time, spectral resolution, efficiency, optical throughput.	Noise-Equivalent Power (NEP) of detector
Digital conversion	The quantization introduces a noise due to the rounding of the analog measurement.	ADC converter
Dynamic shear	Undesired movements of the optical beam cause random fluctuations.	Microvibrations
Speed fluctuations	Variations in the speed of the interferometer cause signal modulations.	Microvibrations
Offset and gain scaling	The calibration strategy determines how many gain and offset measurements are used for the radiometric correction; an amplification factor is introduced on each NESR contributor according to the number of measurements used.	Radiometric calibration

Table 2.3: *NESR Contributors [1]*.

NESR: Current status

On the contrary to the ARA, whose performance is expected to remain stable across mission lifetime, the NESR will be subject to a degradation due to radiation impact on the detectors and external contaminations. Therefore, its current status has to be considered at Beginning of Life (BoL) and End of Life (EoL). Moreover, the NESR is not yet fully determined but only estimates are available. The aspects that require further characterization are the efficiency of detector absorption and instrument transmission. Until these aspects are measured on the flight model, a Best case (BC) and Worst Case (WC) are defined to collect the full envelope of possible performances both for the BoL and EoL conditions.

The total NESR at BoL for the Best Case and the NESR at EoL for the Worst Case are reported respectively in Figure 2.7 and Figure 2.8, along with their contributors. As described in Section 2.4.1, the FSI has two detectors running in parallel. The NESR performance, i.e. total NESR, is always referred to the signal resulting from the average of the two detectors output. This is the reason why, in Figure 2.7 and Figure 2.8, the total NESR is lower than the single detector contribution.

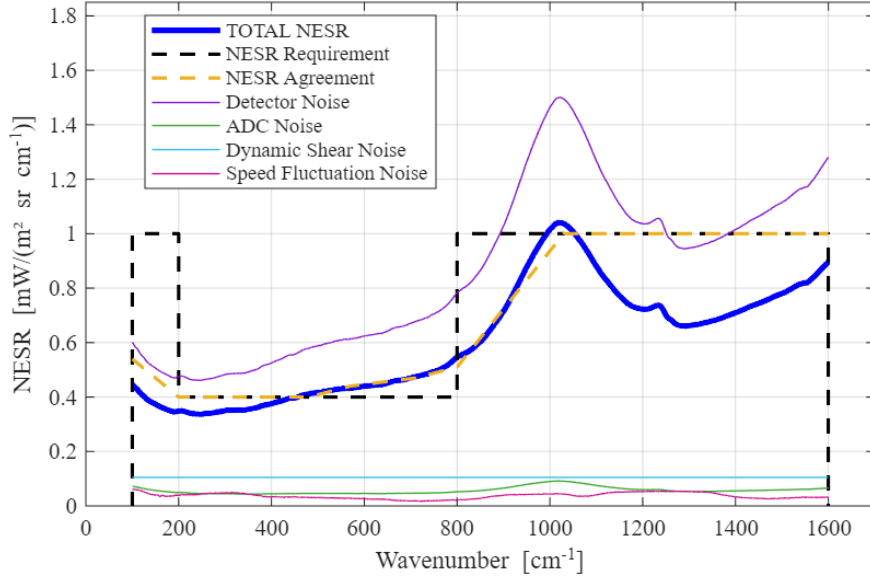


Figure 2.7: *Estimated NESR BoL Best Case [18]. The total NESR performance is represented by the thick blue line, requirement/agreement marked with "- -", single contributors marked with thin continuous lines.*

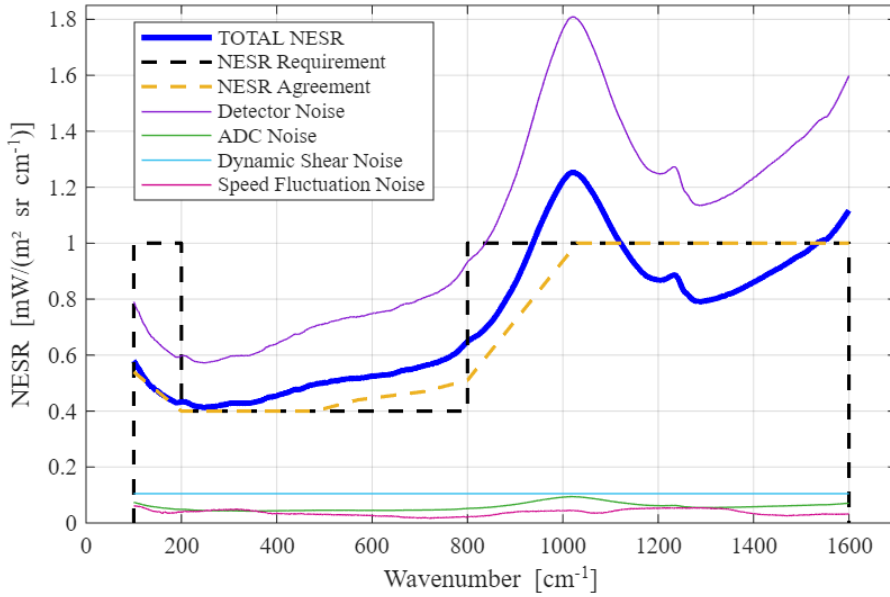


Figure 2.8: *Estimated NESR EoL Worst Case [18].*

Depending on the considered scenario (BoL or EoL, BC or WC), the NESR shows partial non-compliances both with the Requirement and the Agreement specified in Section 2.3.3. The impact of the non-compliances and improvement strategies are discussed in Section 3.1.

2.3.4. ISRF: Instrument Spectral Response Function

ISRF stands for Instrument Spectral Response Function. It represents the spectral response of the whole instrument, including filters, optical transmittance and detectors. It relates the measured, radiometrically calibrated spectral radiance with the input spectral radiance. The ISRF is an equivalent of the ILS, presented in Section 2.2.1.

ISRF: Requirements

There are three main mission requirements related to the ISRF: knowledge, asymmetry and FWHM [12].

The knowledge of the ISRF is fundamental for the retrieval of the scientific products. The core of the scientific processing consist in comparing a simulated spectra to the FSI measurements. The simulated spectra is obtained through a convolution of a high resolution spectra (numerically simulated) with an estimate of the ISRF, to simulate the spectral response of the instrument. Thanks to the difference between the simulated and measured spectra, information about the atmospheric composition can be retrieved.

Any error in the estimate of the ISRF implies an error on the reconstructed spectrum, thus degrading the quality and reliability of the data. The knowledge requirement is [12]:

MR-OBS-200: The knowledge error of the apodised ISRF shall result in a radiometric error on the reconstructed spectra with RMS smaller than:

$<0.003 \text{ mW}/(\text{m}^2 \text{ sr cm}^{-1})$ in the spectral range $[200-800 \text{ cm}^{-1}]$

$<0.007 \text{ mW}/(\text{m}^2 \text{ sr cm}^{-1})$ outside the spectral range $[200-800 \text{ cm}^{-1}]$

The asymmetry of the ISRF is defined as the absolute difference of the first two minima adjacent to the main lobe of the ISRF, divided by the ISRF maximum. If the asymmetry is low enough, a direct comparison of two measured spectra can be performed without any asymmetry correction [12].

MR-OBS-222: The asymmetry of the unapodized ISRF shall be $< 1.67\%$.

A requirement is established on the Full-Width Half-Maximum of the unapodized ISRF to guarantee that the FSI has the desired spectral resolution to resolve the fine water vapour spectral signatures. This requirement expresses the spectral resolution as [12]:

MR-OBS-180: The spectral resolution shall be better than 0.5 cm^{-1} .

ISRF: Contributors

The ISRF contributors are listed in Table 2.4.

Contributor	Description	Cause
Interferometer movement range	The Optical Path Difference of the interferometer determines the theoretical FWHM of the ISRF.	Truncated Fourier-transform
Self-apodisation	An imperfectly collimated beam covers a lower OPD in the interferometer, thus causing a widening effect on the ISRF.	Divergence in input beam
Aliasing effect	For a signal at $x \text{ cm}^{-1}$, the FT generates an ISRF at $\pm x \text{ cm}^{-1}$. The alias of the ISRF has an infinite extension (sinc-like), and the superposition of the two ISRF results in a loss of symmetry.	Numerical Fourier transform
Radiometric correction	The gain correction introduces a multiplication in the spectral domain. If the gain has a high slope, this can introduce and accentuate asymmetries.	Rapid change of radiometric response

Table 2.4: *ISRF Contributors [1].*

The theoretical Instrument Spectral Response Function results from the optical layout of the instrument and the range of movement of the interferometer (MPD). The real ISRF of the instrument can be estimated by evaluating the effects of the additional degradation factors listed in Table 2.4.

ISRF: Current status

The current estimates of the ISRF show a full compliance with its requirements. The relevant ISRF values are summarized in Table 2.5.

	Requirement	Current estimate [18]
Knowledge	$< 3 \mu\text{W}/(\text{m}^2 \text{ sr cm}^{-1})$	$2.6 \mu\text{W}/(\text{m}^2 \text{ sr cm}^{-1})$
Asymmetry	$< 1.67\%$	1.375%
FWHM	$< 0.5 \text{ cm}^{-1}$	0.476 cm^{-1}

Table 2.5: *ISRF requirements and current status.*

The self-apodisation effect is the primary cause of deviation of the FWHM from the theoretical maximum described by Eq. 2.4 [1]. This effect varies across the instrument's spectral range, as higher wavenumbers undergo faster oscillations and consequently stronger attenuation. As a result, the ISRF FWHM is not constant over the bandwidth. The value reported in Table 2.5 corresponds to the worst performance, observed at 1600 cm^{-1} ; the variation of the FWHM across the spectral range is shown in Figure 2.9.

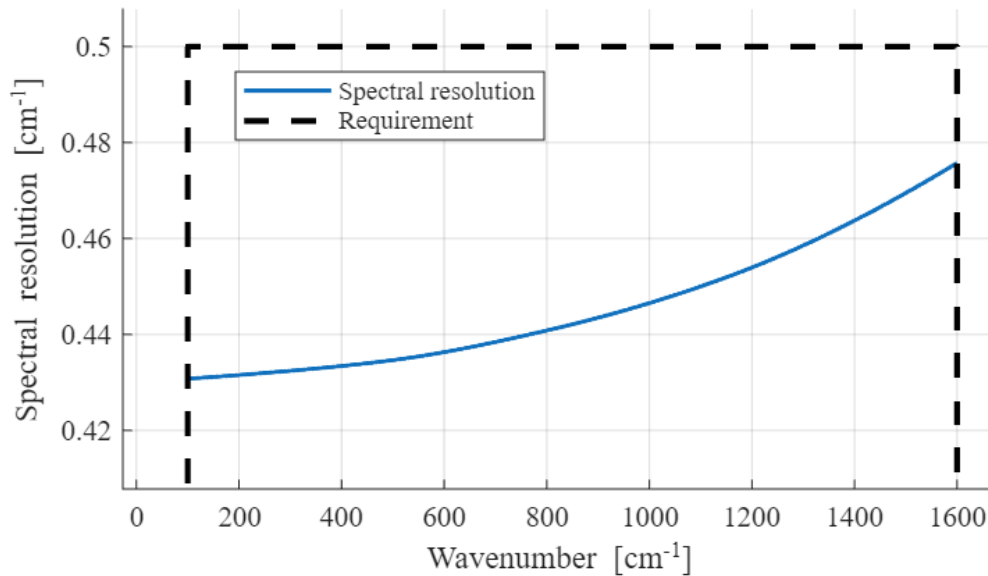


Figure 2.9: *Spectral Resolution over the bandwidth [18].*

2.3.5. Geometric requirements

There are several requirements that specify the desired observational geometry for the FORUM Mission. In this Section, the most relevant for the scope of this document are reported.

Footprint

The footprint represent the diameter of the scene observed by the instrument. Its size is selected according to the expected cloud cover and in accordance with the specification of the Metop-SG(A) mission that will fly in close formation with FORUM [12].

MR-OBS-010: The FSI footprint shall have a diameter of 15km.

The current design of the FSI guarantees compliance with this requirement.

Spatial Sampling Distance

FORUM will observe with a step and stare procedure, described in Section 2.5.1. The Spatial Sampling Distance represent the distance between two subsequent samples on ground and is determined by the acquisition time of one single measurement [12].

MR-OBS-020: The FSI spatial sampling distance shall be smaller than 100 km.

The orbit and dwell time selected for the acquisition guarantee the satisfaction of this requirement.

De-pointing angle

The FSI observes the scene at nadir, with a slight de-pointing during the dwell time. The maximum de-pointing angle is set to avoid significant atmospheric distortions on the measured spectra [12].

MR-OBS-040: The FSI Observation zenith angle shall not exceed 3.5° during a dwell time.

The nadir pointing attitude and the acquisition time selected guarantee the satisfaction of this requirement.

2.4. FORUM Payload description

The FORUM payload is composed of two instruments:

- FORUM Sounding Instrument (FSI) is an FTS spectrometer.
- FORUM Embedded Imager (FEI) is a thermal camera, co-aligned with the FSI.

Although the FSI and FEI are formally considered as separate instruments, the FEI is functionally integrated within the FSI architecture; as reported in the Functional Block Diagram (Figure 2.10), the FEI shares common optical and control elements with the FSI. For this reason, the FEI is described together with the FSI components rather than in a dedicated section.

In short, the FSI can be described as a double-pendulum interferometer (IA), equipped with a set of optics and pointing components (i.e. baffles, Pointing Unit POU, Scan Unit SCU, Front Telescope Unit FTU) to observe the Earth, deep space or an internal blackbody unit (BBU). The double-pendulum interferometer features two input and two output ports; the interferogram is collected by two dedicated detectors (Back Telescope

Detector Assembly BTDA) at the output ports, along with the metrology information. The FEI is co-aligned with the FSI and performs its measurements through the same set of optical components.

The FSI and FEI are managed by the Instrument Control Unit (ICU), whose role is to run the operation modes, the software, and handle telemetry and telecommands. It represents the main interface with the platform. Additional control units (i.e. Interferometer Control Electronics ICE and Scan Control Electronics SCE) support the detailed operations of the IA and SCU [1].

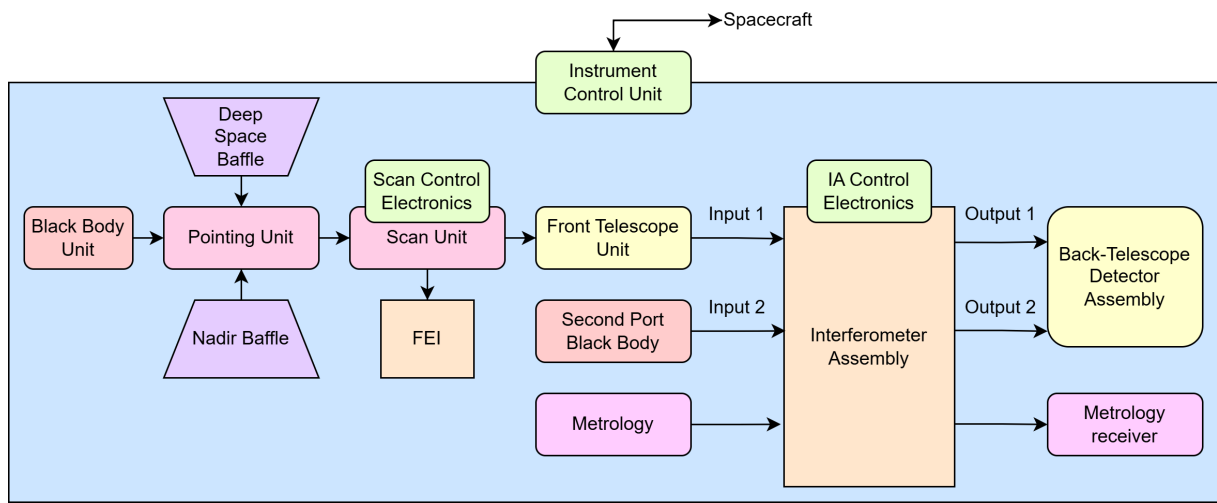


Figure 2.10: *FORUM Payload Functional Block Diagram.*

To outline the working principle of the FSI, let's consider an input beam of light and its path inside the instrument.

1. The input beam enters the instrument from one of the three input ports: Earth view, deep space view and black body unit (BBU). The Pointing Unit (POU) selects one of the three input ports. Earth and deep space view each have a dedicated baffle.
2. The beam propagating from the selected input port is reflected by the Pointing Unit to the Scan Unit (SCU), whose role is to compensate for the satellite orbital movement, for a step and stare observation.
3. The beam is fed into both the FEI input port and in the Front Telescope Unit (FTU). The FEI collects the data with a micro bolometer detector. The FTU conditions the light to adapt it to the input port of the interferometer.
4. The collimated beam is fed into the input port 1 of the interferometer (IA). A stable signal is fed into the input port 2 by the Second Port Black Body (SPBB).

5. The signal travels through the interferometer, is splitted by the beam splitter, reflected by mirrors and recombined. During this process, the interferometer moves around a pivot point, to create an OPD dependant interference, i.e. the interferogram.
6. After the second interference at recombination, the signal is still divided in two beam, due to the architecture of the double-input double-output interferometer. The two output ports are connected to two Back Telescope Detector Assembly (BTDA). These component work in parallel to condition and measure the signal with a pyroelectric detector. The recorded interferograms are then transferred to the platform for Level 0 processing.
7. In parallel, a circularly polarized laser beam is injected into the interferometer. The laser is subjected to the interference process, afterwards it's separated into its horizontal and vertical components, that are detected by two dedicated sensors. The recorded signal is used to determine the metrology of the interferometer, i.e. its movement over time.

2.4.1. FSI Components

This section outlines the main properties and operating principles of the components constituting the FSI, providing the level of detail necessary to support the component-level analyses presented in Chapter 3. Appendix B contains descriptions of additional FSI components that fall outside the scope of the analyses in Chapter 3.

The configuration of the components in the FSI is reported in Figure 2.11.

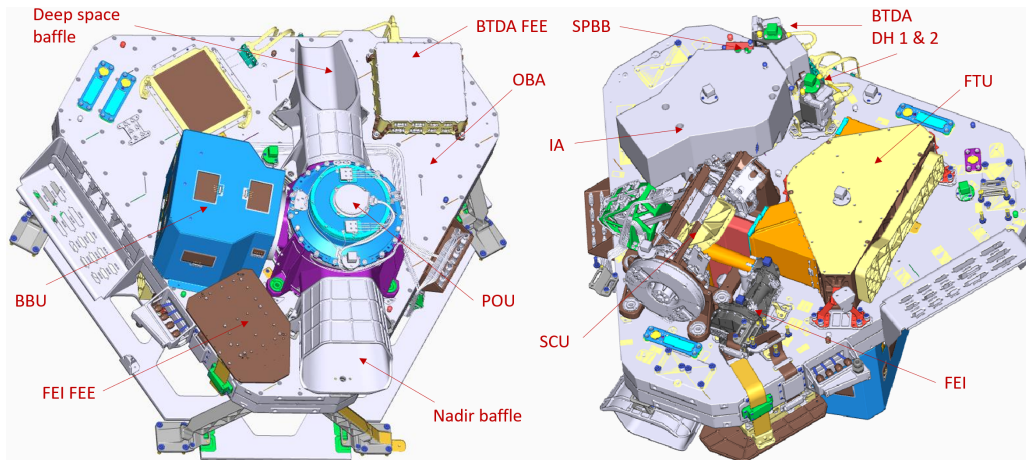


Figure 2.11: *FSI Components configuration (top view on left, bottom view on right), courtesy of OHB System AG.*

POU, SCU, SCE: Pointing and Scanning Subsystem

The Pointing and Scanning Subsystem role is to select one of the input sources (i.e. Earth, Deep Space, BBU) and compensate for orbital movement to maintain a step and stare acquisition strategy.

The Pointing Unit (POU) is composed by a mirror and an actuator; depending on the selected input port, the POU moves along its vertical axis accordingly. A rotating shield acts as a shutter for the ports that are not under observation.

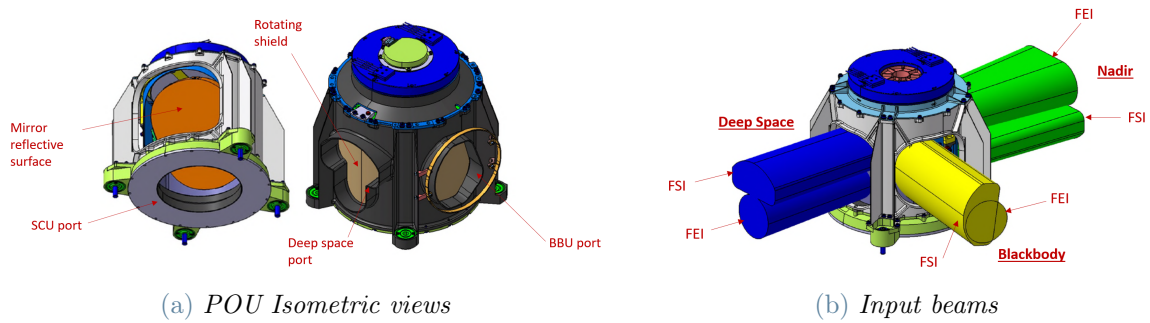


Figure 2.12: Pointing Unit (POU) isometric views (A) and input beams (B), courtesy of OHB System AG & Sener Group.

The Scan Unit is located directly below the POU (see the SCU port in Figure 2.12a) and consists of a mirror and an actuator, as illustrated in Figure 2.13, that tilts along the horizontal axis to precisely compensate for orbital motion during each Earth measurement. The SCU moves only during Earth observation, since there is no necessity of performing a step and stare acquisition when the blackbody or deep space are observed. The range of movement depends on the orbital position, but it is always performed with the same duration. Given a range of movement 2α , the SCU moves from $-\alpha$ to $+\alpha$ during the dwell time, and then return to $-\alpha$ within a fixed turnaround time.

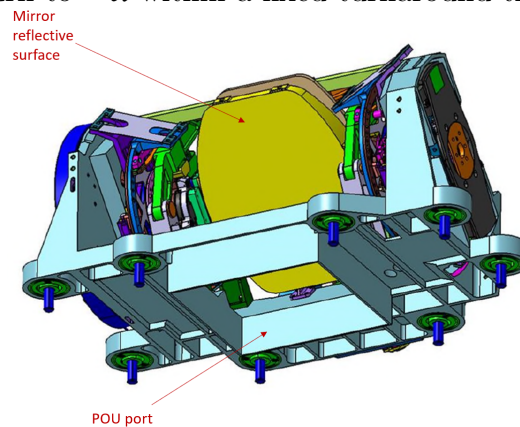


Figure 2.13: Scan Unit (SCU), courtesy of OHB System AG & Sener Group.

The Scan Control Electronics (i.e SCE) controls the movement of the POU and SCU in closed loop and handles the telemetry of the pointing and scanning subsystem.

Baffles

The purpose of the baffles is to protect the instrument from potential straylight outside of the FOV. The Earth baffle is referred to as Nadir Baffle, while the deep space one is the Cold Space Baffle.

The shape of both baffles is selected to encompass the beamwidth of the FSI with sufficient margin. The Nadir Baffle is wider than the Cold Space, taking into account the scanning range of the instrument, for step and stare acquisitions.

BBU: Black Body Unit

The Black Body Unit provides a radiometric reference signal for calibration purposes. It consists of a black-painted grooved surface with a precisely characterised emissivity. As an accurate knowledge of its temperature is essential for the calibration, multiple temperature sensors are embedded in the grooved surface to supply continuous and reliable measurements to the ICU. The surface is enclosed within a baffle, which is itself wrapped in MLI, to minimise thermal coupling with the surrounding environment.

IA: Interferometer Assembly

The Interferometer Assembly represents the core of the FSI. Thanks to the interference process on the input beam generated by this component, it is possible to encode spectral information in the interferogram (see Section 2.2.1).

The IA has several differences compared to the simple Michelson Interferometer:

- **Corner Cube reflectors:** in the IA, the reflectors are cubic and not flat mirrors. The beam reflected by a corner cube is always parallel to the input beam, regardless of tilts in the reflector, ensuring high alignment stability of the interferometer arms. In addition, corner cubes allow the recombination of the two beams to occur at a different physical location than the beam-splitting point, providing greater flexibility in the optical layout and relaxing mechanical alignment constraints. An example of this reflection behaviour is shown in Figure 2.14.
- **Double-pendulum configuration:** the mirrors are connected by a rigid structure with a central fixed pivot point, causing the reflective surfaces to move altogether with a pendulum motion; in a typical Michelson interferometer, only one of the two mirrors is free to move.

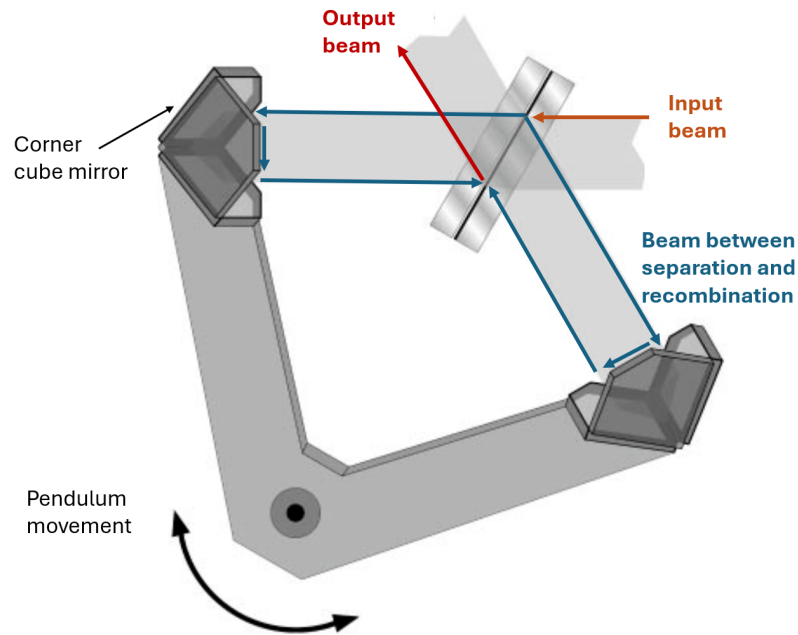


Figure 2.14: *Double Pendulum Interferometer* [19].

This configuration is selected due to its compact design. Given a displacement of a mirror of x cm, the OPD will be $4 \cdot x$ and not $2 \cdot x$ as in Michelson's (since both mirrors are moving), therefore to achieve the same OPD a lower volume to account for the movement is required.

Moreover, the double-pendulum guarantees a partial compensation of motion disturbances effects; due to the common rigid structure of the pendulum, both mirrors are equally affected by the disturbance, thus cancelling the effect.

- **Double-Input Double-Output:** a key design requirement is to provide two fully separated and accessible output beams, to use two dedicated science detectors. This offers practical advantages over the single-output configuration of a traditional Michelson interferometer, such as improved redundancy and the possibility of combining the measurements in post processing to enhance the SNR. This architecture is implemented using a Mach-Zehnder interferometer structure, which naturally provides two distinct optical paths and two input/output ports, as shown in Figure 2.15.

In the FSI, the scene radiance enters only one of the two input ports, while the second input is illuminated by a stable reference source (SPBB) whose contribution is later removed during processing. The two output beams are detected independently, and their resulting interferograms are averaged to reduce uncorrelated noise and improve the overall SNR of the instrument.

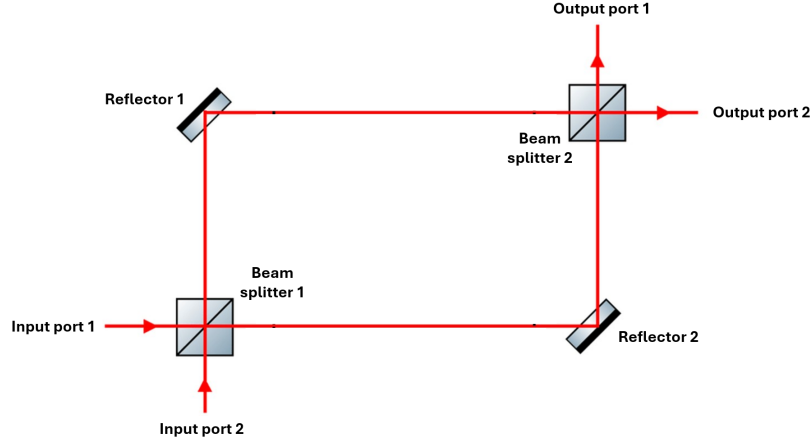


Figure 2.15: *Mach-Zehnder Interferometer scheme [20].*

The combination of the double-pendulum and the Mach-Zehnder configuration results in the layout presented in Figure 2.16.

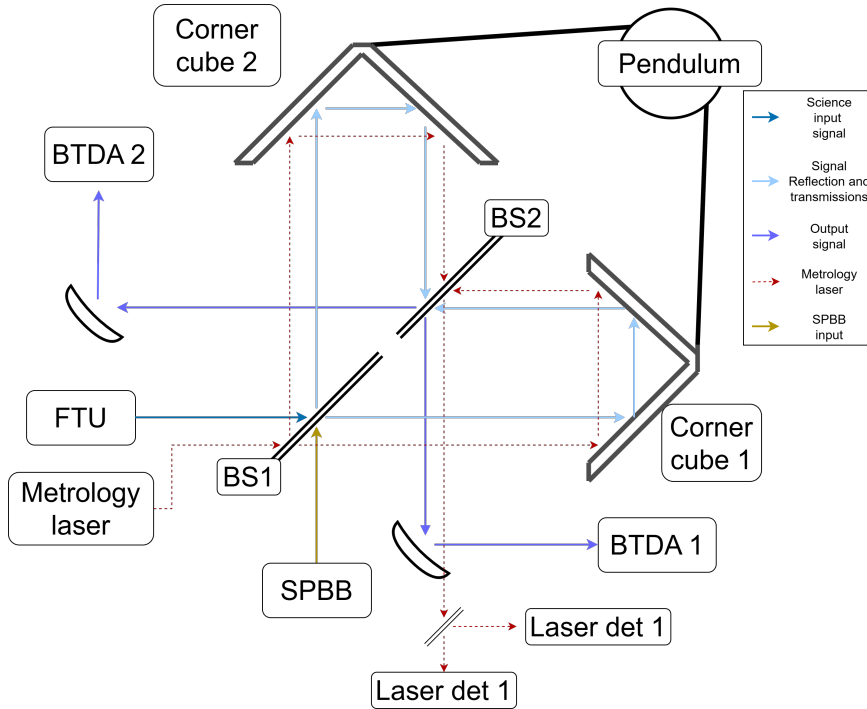


Figure 2.16: *FSI Interferometer Assembly (IA) optical layout.*

The input beam enters the IA through the Input port 1, while a constant signal emitted by the Second Port Black Body enters through port 2. The beamsplitter 1 divides the beams into a reflected and transmitted component. Both beams are self reflected by the corner cubes and recombine at beamsplitter 2. The two beams produced by the beamsplitter 2, referred to as science signals, exit the IA through the unbalanced and balanced ports.

To generate the interferogram, the pendulum moves over its pivot point with a constant speed, from $-MPD$ to $+MPD$ (and vice-versa in the successive scan), thus generating a double sided interferogram, with the centreburst at ZPD. To guarantee a step and stare observation, the Scan Unit (SCU) tilts from $+\alpha$ to $-\alpha$, creating a depointing angle with respect to nadir. This mode of operation allows to have the centreburst of the interferogram synchronized with nadir observation at $\alpha = 0$. This is a desirable condition, because the calibration is also performed at this SCU angle; as the most relevant spectral informations are recorded with the centreburst, having an accurate calibration of this portion of the interferogram is highly favourable. Double-sided interferograms are also desirable since their symmetry guarantees an easier centreburst/ZPD identification, leading to lower phase errors.

The Metrology system, integrated within the Interferometer Assembly, precisely measures the pendulum's position, velocity, and direction of motion. It consists of a laser source, a collimator, a phase retarder to generate circular polarization, a polarizing beam splitter to separate the horizontal and vertical components of the beam, and two dedicated detectors. The two polarization components are referred to as reference signal. An explanation of the metrology principle is available in Section 2.2.1. For the IA, the metrology signal path is represented in Figure 2.16 with a dotted red line.

The motion of the IA, the metrology and the housekeeping data are managed by the Interferometer Control Electronics (ICE) unit.

BTDA: Back Telescope Detector Assembly

The BTDA collects the output of the IA, measuring the optical power after the interference process. The BTDA consists of two detection heads, one per output port of the IA, linked to a common Front-End Electronics board.

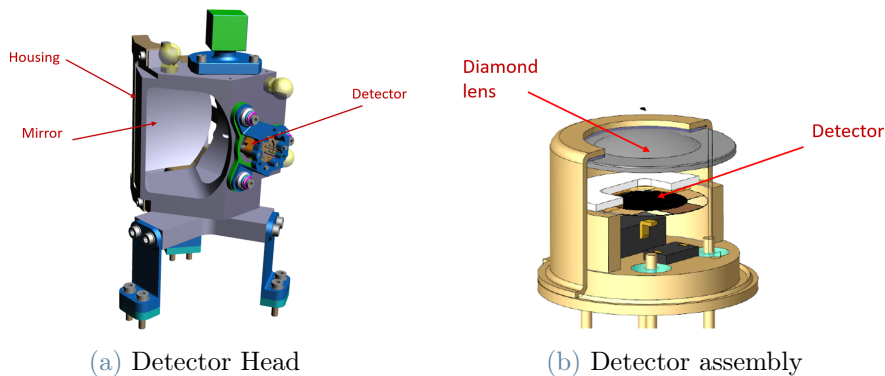


Figure 2.17: BTDA Detector head (a), and Detector assembly (b), courtesy of ADS DE & Leonardo U.K.

The signal from the IA output ports is reflected on a parabolic mirror to a diamond lens. A pyroelectric detector, suited for the detection of optical power in FORUM's bandwidth, is placed underneath the lens. This type of detector is capable of generating a voltage when subjected to a temperature change [21]. The analog voltage over time is converted into a digital signal by the Front-End Electronics and transmitted to the ICU for Level 0 processing. Figure 2.17 shows the BTDA detector head and the detector assembly.

2.5. Operational Concept

The FORUM Mission will fly on a Sun-Synchronous orbit at an average altitude of 830km, in loose formation with MetOp-SG(A). This orbit guarantees high global coverage, continuous sun illumination offers synergy opportunities with the IASI-NG instrument on board of MetOp-SG(A). The mission is currently designed for a minimum duration of 5.5 years, with 0.5 years dedicated to the commissioning phase [12].

There are several modes of operations designed for FORUM, however, for the purpose of this document, only the nominal mode is described.

2.5.1. Nominal Acquisition

The FORUM mission adopts a step and stare acquisition technique, where a sample on ground is measured for the whole dwell duration. Therefore, Earth surface is not scanned continuously but discretely, with each acquisition spaced out by the Spatial Sampling Distance (SSD), as in Figure 2.18.

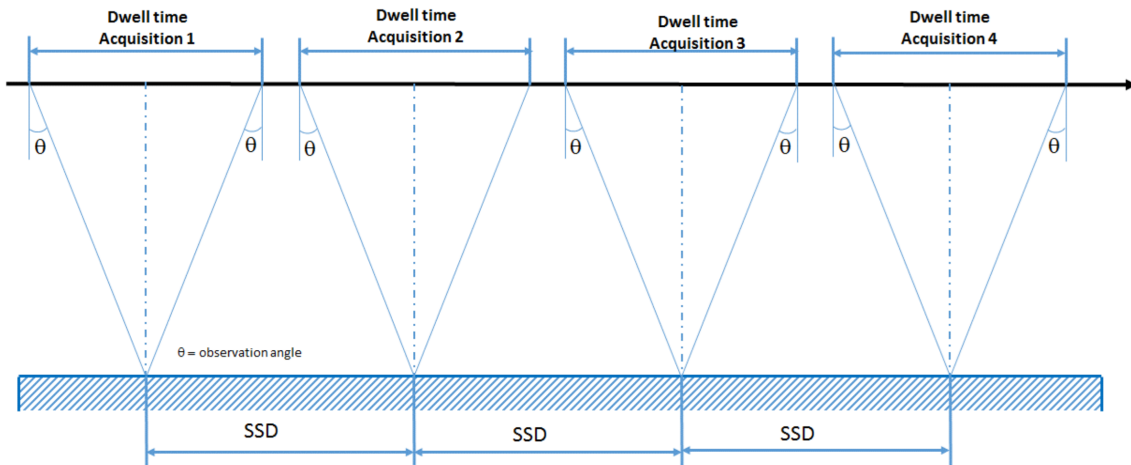


Figure 2.18: *FSI Scanning Geometry* [12].

A nadir-pointing attitude is maintained through the nominal acquisition mode; to achieve a step and stare acquisition, the SCU (described in Section 2.4.1) points at $+\theta$ at the dwell start, and gradually moves to $-\theta$. Once one full acquisition is measured, the SCU points to the next ground sample, by moving from $-\theta$ to $+\theta$; the time interval for this last SCU movement is referred to as turnaround time.

Calibration Strategy (Onboard BB, Deep Space Views)

The nominal operations of the instrument are based on a repetition of sequences of calibration and Earth observation dwells. A single Nominal Acquisition cycle is composed of 15 dwells, subdivided as follows [1, 18]:

- Earth Observation (12 dwells): twelve dwells of 14s, each with an additional turnaround time of 0.8s. The interferometer moves from -MPD to +MPD and viceversa in alternation.
- FSI and FEI deep space calibration: with a movement of the POU, both the FSI and the FEI are illuminated with the signal coming from deep space. As for the FSI BBU scan, six dwells at reduced OPD are performed by the interferometer.
- FSI Blackbody calibration (1 dwell): the POU moves to illuminate the FSI with the internal BBU. The interferometer scans six times the BBU at a shorter OPD compared to the full MPD of Earth observation. Scanning quickly allows to reduce earth observation time loss.
- FEI Blackbody calibration (1 dwell): the POU moves to illuminate the FEI with the BBU, the interferometer scans the BBU one time.

The radiometric correction of an Earth observation relies on multiple calibration events. Two calibration measurements acquired before the Earth observations and two obtained afterwards are used to derive a linear fit for both offset and gain as a function of time. Additional considerations on the radiometric correction process are provided in Section 2.6.2. Additionally, a special calibration mode has been designed, where the BBU and deep space will be observed at full OPD. This guarantees the possibility to detect fine spectral signatures in the instrument self-emissions. Further detail on the utilization of full OPD calibration events are available in Section 2.6.2.

2.6. Instrument Simulator and Level 0/1 Processing

This section introduces the simulation tools used as starting point to perform the analyses of Chapter 3 and to evaluate the FSI performance under various disturbance conditions. Two dedicated simulators have been developed by Micos Engineering GmbH for the FSI:

- **Instrument Simulation Module (ISM):** the ISM models how an input radiance propagates through the FSI, up to the detection of the interferogram at detector level. It accounts for the optical properties of the instrument and its self-emission contributions. External disturbances can also be introduced within this simulator to assess their impact on the interferograms.
- **Level 1 Processing Module (L1PM):** the L1PM processes the interferograms generated by the ISM to produce Level 1 products. It performs radiometric correction and generates Earth's emissions spectra. The resulting L1PM outputs are used to evaluate the effects of the disturbances applied in the ISM.

2.6.1. ISM: Instrument Simulator Module

The objective of the ISM is to provide a reliable representation of how an input radiance is converted into a time-domain interferogram. As discussed in Section 2.4.1, the FSI is composed of multiple interconnected components. A full physical simulation of every element would be complex and computationally demanding. Instead, the ISM focuses on a selected set of key aspects, offering a simplified yet representative model of how the input radiance propagates through the FSI. This is accomplished by dividing the ISM into five modules, each addressing a specific aspect of the FSI. A functional breakdown of the ISM modules is presented in Figure 2.19.

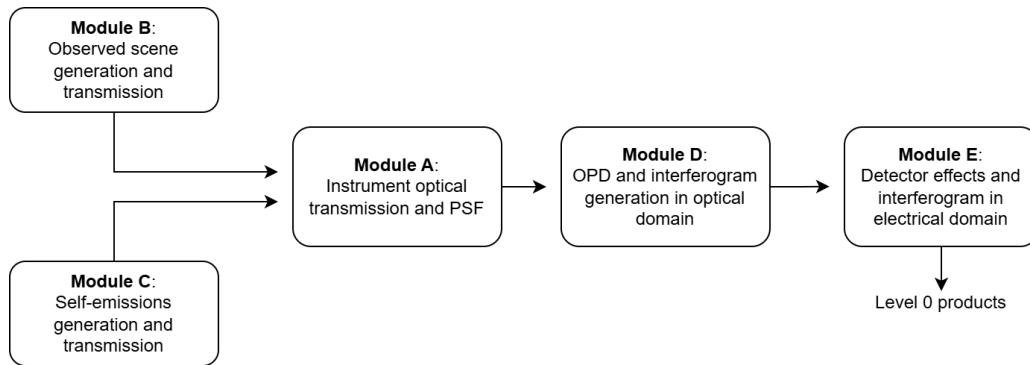


Figure 2.19: *ISM modules architecture.*

ISM/A: Instrument definition

The role of ISM/A is to simulate the optical behaviour of the FSI. Starting from the optical and transmission properties of each component up to the Interferometer Assembly (IA), it produces the overall instrument transmission response. The optical effects introduced by the Front Telescope Unit (FTU) are modelled, via computation of a transfer function between the scene, FTU, and IA.

This module process the input radiance by applying the transmission losses occurring up to the FTU, the PSF convolution and the additional losses associated to the optical path from the FTU to the detectors.

ISM/B: Scene generation and transmission

ISM/B generates the input scene of the FSI and simulates its transmission to the detectors. There are several options for the input scene:

- Earth Observation: a theoretical high resolution spectra of Earth's emissions. There are multiple options for the Earth temperature, each associated with a different spectra.
- Deep space: a simple black body spectrum generated by a black object at 6 K
- Black Body Unit: a simple black body spectrum generated by a black object at 295 K

Depending on the observational scenario, the scene generation simulates the input radiance in the ISM domains. Afterwards, the transmission function and the PSF computed by ISM/A are applied, to simulate the optical power at detector level.

ISM/C: Self-emissions

This module simulates the thermal self-emissions produced by the instrument within the observational bandwidth. It takes into accounts multiple internal sources, each characterized by specific optical properties and operating temperatures. The emitted signals are propagated through the system using the same transmission and PSF models, to obtain the corresponding optical power at detector level.

This contribution will be added to the scene radiance simulated in ISM/B, to obtain the total power reaching the detector.

ISM/D: OPD and interferogram at the detector

In ISM/D, the interferometer and its disturbances are modelled, to obtain the interferogram that will be measured by the detector. ISM/D has two submodules.

The first submodule is dedicated to the generation of the perturbed OPD informations. The disturbances considered are: speed fluctuations, dynamic shears, metrology disturbances; their effect on the OPD over time is simulated.

The second submodule role is to combine the optical power at detector level (obtained by ISM/B and ISM/C) with the OPD over time. The resulting output is an interferogram in optical power over time.

ISM/E: Interferogram at electrical level

This module applies the electrical transfer function of the Back-Telescope Detection Assembly to the interferograms resulting from ISM/D. The resulting signals are expressed in the electrical domain of the detectors. Within this module, the electrical noise of the detection is applied.

The output of ISM/E will be fed into Level 0 and Level 1 data processing modules.

2.6.2. L1PM: Level 1 Processing Module

The objective of the Level 1 Processing Module (L1PM) is to obtain Level 1 products, i.e. radiometrically calibrated Earth's emission spectra.

The level 0 data packages are the input of the L1PM. They consist of a set of Earth, deep space and black body interferograms, paired with the corresponding orbital parameters for the data processing. Figure 2.20 illustrates the set of calibration events used to process a single Earth observation cycle.

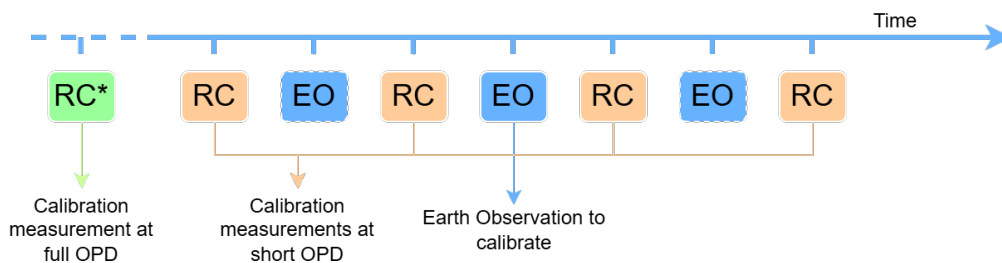


Figure 2.20: Radiometric calibration approach. The Earth observation (EO) event is radiometrically corrected with four calibrations (RC) performed at short OPD and one at full OPD (RC*).

To reduce the uncertainty of the calibration and satisfy the tight requirement on the radiometric accuracy (see Section 2.3), four calibration events at short OPD are selected, each composed of one deep space and one black body observation. By creating a polynomial fit of the gains and offsets associated to the calibration events over time, it is possible to accurately approximate the radiometric correction parameters during Earth observation. As anticipated in Section 2.5.1, the radiometric measurements are performed with a shorter OPD compared to the Earth observations. This ensures lower calibration time and better signal quality, at the cost of a degraded spectral resolution. To complement the short OPD calibrations, an additional calibration event at full OPD (MPD) is performed. This measurement is used to accurately detect fine spectral features of gain and offset parameters, that are merged with the short OPD calibrations. The combination of four calibration events close to the Earth observation at low spectral resolution with one calibration at full spectral resolution guarantees a high radiometric calibration accuracy. The L1PM is divided in five modules. They are presented hereafter in their order of execution for the data processing.

L1PM/A: Interferogram on OPD grid

L1PM/A converts the interferograms from time domain to a uniform and calibrated OPD domain.

For each dwell, there are four signals to process: two measured by the output ports of the interferometer (science signals) and two by the metrology (reference signals). These data streams are collected with different detectors, each with its own transfer function. Therefore, the L1PM/A processing sequence is:

1. Coarse OPD: a coarse OPD grid is identified from the reference signals.
2. BTDA inversion: the inverse of the detectors' transfer functions are applied to the recorded interferograms.
3. OPD oversampling: for Fast-Fourier-Transform (FFT) purposes, zero filling is applied to the coarse OPD, to have a number of samples equal to a power of two.
4. ZPD identification: accurately resampling the acquired IGM on a uniform OPD grid is essential to prevent phase errors during the radiometric correction. This requires a first estimate of the approximate ZPD position from the science signal, which is then used to precisely locate the ZPD crossing in the reference signal.
5. Interferogram interpolation: the oversampled OPD is shifted to be centred in the identified ZPD position.

This OPD resampling procedure corrects phase errors, for proper radiometric correction and comparison of the science interferograms. In Section 3.3, further considerations about this method are presented.

L1PM/E: Radiometric calibrations at Full OPD

L1PM/E generates the normalized spectra of the full OPD radiometric calibration. This is achieved by Fourier transforming the interferogram of the black body and deep space measurements, and then by applying a normalization to obtain a neutral instrument temperature condition. This method allows to obtain a spectrum with the desired spectral features, only visible at full OPD, independent from the actual instrument temperature.

L1PM/C: Offset and Gain from radiometric calibration events

L1PM/C converts short and full OPD radiometric calibrations into offset and gain. This is achieved by:

1. Signal merger: the full OPD signal is converted back to interferogram with an inverse-FFT (IFFT). The short and full OPD calibrations are merged by applying an apodisation to both signals and summing the resulting values.
2. Offset computation: the offset at the time of the calibration event is given by:

$$\text{Offset}(\sigma) = \text{FFT}(\text{IGM}_{DS}) \quad (2.6)$$

3. Gain Computation: the gain is computed exploiting the knowledge of the temperature of the reference black body (BBU) as follows:

$$\text{Gain}(\sigma) = \frac{L_{BBU}(\sigma)}{\text{FFT}(\text{IGM}_{DS} - \text{IGM}_{BBU})} \quad (2.7)$$

where L_{BBU} is the radiance emitted by the BBU at the measured temperature.

This operation is repeated for each short OPD calibration events, obtaining four sets of spectrally dependent offset and gain measures.

L1PM/D: Polynomial fit of offset and gain

L1PM/D creates a polynomial fit of the offset and gain computed in L1PM/C. For each wavenumber, a linear fit over time is created, with the two calibration events before the Earth observation to calibrate and the two after, as in Figure 2.20.

L1PM/B: Radiometric correction of Earth observation dwells

L1PM/B applies the radiometric correction to the Earth measurements, obtaining the Level 1 products. This is achieved with the following steps:

1. Earth dwell Fourier transform: the interferograms processed by L1PM/A are Fourier-transformed to obtain radiance as a function of wavelength, yielding Level 1a products (L1a). Optical and electronic disturbances introduce residual phase errors, resulting in both real and imaginary components of the Fourier transformed spectra. The imaginary part contains noise due to uncorrected phase errors and other disturbances, and is discarded in the following steps.
2. Gain and offset retrieval: the gain and offset values at the time of the Earth observation are obtained from the outputs of L1PM/D.
3. Radiometric correction: the correction for each science signal is applied as:

$$L1b(t, \sigma) = \text{Re}\{[L1a(t, \sigma) - \text{Offset}(t, \sigma)] \cdot \text{Gain}(t, \sigma)\} \quad (2.8)$$

For each output port of the IA, a Level 1b product (L1b) product is obtained.

4. Spectra averaging: the two L1b products of the detectors are arithmetically averaged to improve the SNR, resulting in one single Level 1c product (L1c) composed of the radiometrically corrected spectra measured during the dwell.

3 | Disturbances impact and improvement strategies

The FORUM Sounding Instrument (FSI), introduced in Chapter 2, is a high-accuracy Fourier Transform Spectrometer. Given the stringent observational requirements listed in Section 2.3, particular attention must be posed on modelling and assessing the effects of both external and internal disturbances on the performances. This chapter evaluates the impact of two key disturbances: detector noise and speed fluctuations. Both factors are critical for FTS instruments, due to their impact on the SNR of the measurements, and thus impose stringent limitations to the overall instrument performance [13, 14]. The following sections describe the methodology adopted to evaluate their influence, to verify the robustness of the FSI design and investigate possible improvement strategies.

3.1. Impact of sub-optimal detector NEP on NESR and improvement strategies

The detectors of the FSI, integrated in the Back-Telescope Detector Assembly (BTDA), are uncooled pyroelectric sensors [21]. Their sensibility is expressed through the Noise-Equivalent Power (NEP) metric, that represents the amount of power associated to a unitary SNR, in a bandwidth of 1 Hz. The NEP figure should be as low as possible to measure faint signals such as infrared emissions with an adequate SNR. The detector noise contributes to the total NESR performance with the NESR_{det} term, linearly related to the NEP and dependant to the acquisition parameters. Eq 3.1 reports the formulation of the NESR_{det} .

$$\text{NESR}_{det} = \frac{2 \text{MPD}}{\eta G \sqrt{t}} \cdot \text{NEP} \quad (3.1)$$

where MPD is Maximum optical Path Difference, η is the instrument efficiency (the fraction of power effectively converted into a measurable signal), G is the optical throughput and t is the acquisition time.

As introduced in Section 2.3.3, the $NESR_{det}$ is not the sole contributor to the total radiometric noise. Other factors, outlined in Table 2.3, add in quadrature due to their uncorrelated nature, as in Eq 3.2.

$$NESR_{tot, 1 Det} = NESR_{RC} \cdot \sqrt{NESR_{det}^2 + NESR_{ADC}^2 + NESR_{shear}^2 + NESR_{SF}^2} \quad (3.2)$$

where $NESR_{RC}$ represents the random components of radiometric correction, $NESR_{det}$ is the electrical noise, $NESR_{ADC}$ is the digital conversion, $NESR_{shear}$ are movements of the input beam and $NESR_{SF}$ are speed fluctuations of the interferometer.

The FSI has two distinct output ports, each with a dedicated detection channel, as outlined in Section 2.4.1. To obtain Level 1c products and improve the SNR of the measurements, the output of the two detectors is averaged. Since the noise of the two detectors is uncorrelated, this results in the $NESR_{tot}$ of Eq 3.3.

$$NESR_{tot} = \frac{\sqrt{2} NESR_{tot, 1 Det}}{2} \quad (3.3)$$

The different contributors and the NESR resulting from the averaging process are presented in Figure 3.1, at the End of Life and Worst Case Performance, considering a high radiation degradation and a loss of instrument efficiency (EoL WC).

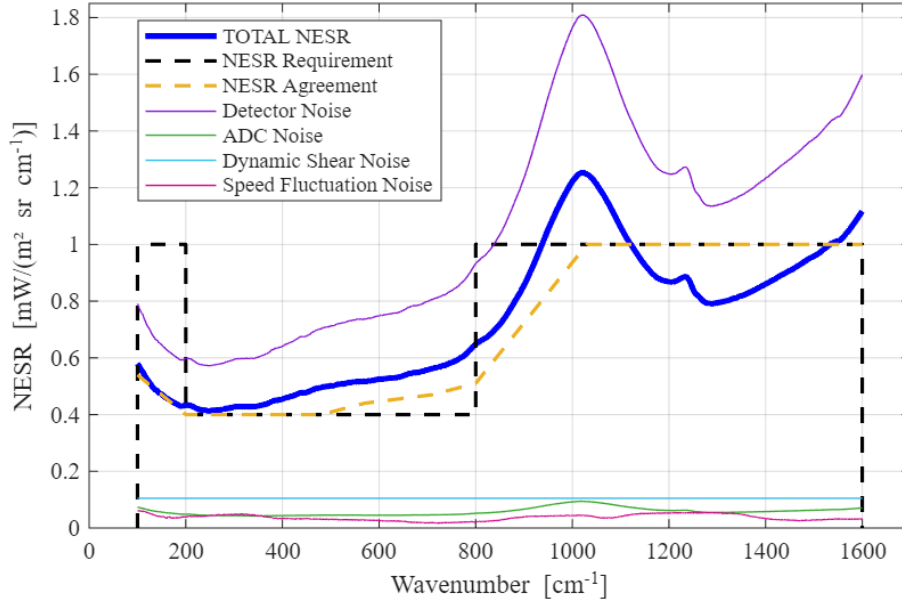


Figure 3.1: *NESR EoL Worst Case [18].*

The detector noise is the dominating factor, while other contributors are almost negligible, considering that they are summed in quadrature. The FSI can be therefore considered as detector noise limited.

From Figure 2.8, it can be observed that, in several spectral bands, the $NESR_{tot}$ is not compliant with the NESR Agreement, formalized in Section 2.3.3. The deviation from the NESR Agreement is plotted in percentage in Figure 3.2.

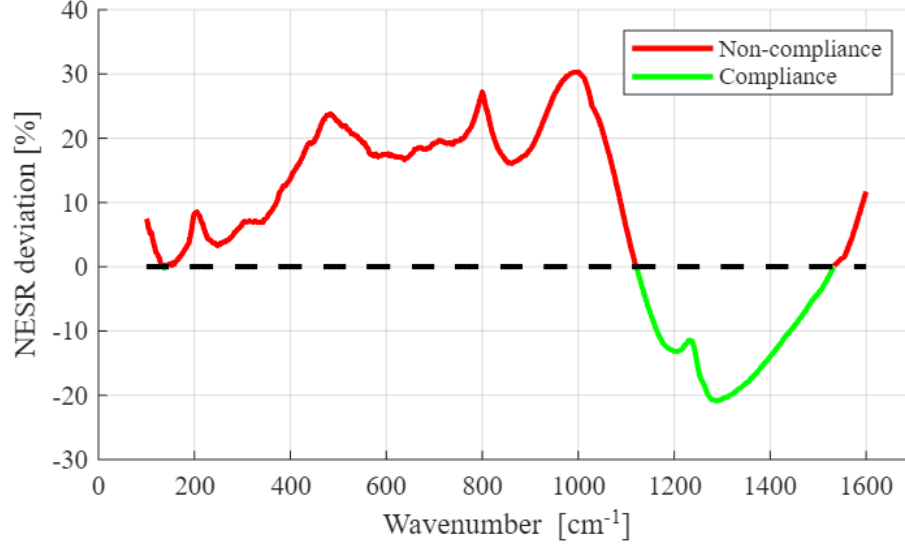


Figure 3.2: *Deviation of the NESR from the NESR Agreement.*

The NESR non-compliance originates from the sub-optimal NEP of the selected flight detectors. During Phase B and early Phase C, it was envisaged that a screening campaign of the manufactured detectors would yield flight detectors with lower NEP. However, this was not fully achieved: the two best-performing sensors were selected, yet their NEP remains insufficient to meet the requirement under EoL WC conditions.

The deviation is significant (up to 30% non-compliance), therefore further analyses are required to investigate the impact on the mission objectives and improvement strategies.

3.1.1. NESR non-compliance consequence on climate studies

Climatological studies are often characterized by spatial and temporal averages, due to the statistical nature of Earth's weather [12]. When multiple acquisitions with uncorrelated noise are averaged, the resulting measure is characterized by a radiometric noise, $NESR_{avg}$:

$$NESR_{avg} = \frac{NESR_{tot}}{\sqrt{N}} \quad (3.4)$$

where N is the number of averages and $NESR_{tot}$ the noise resulting from Eq 3.3. For the climate studies of the FORUM mission, several averages of the measurements will be performed, to lower the NESR up to the Absolute Radiometric Accuracy requirement [12].

The NESR Agreement is selected in accordance with its associated number of averages, deemed acceptable by the scientific community. To assess the impact of the NESR_{tot} non-compliance at EoL WC, the ARA has to be converted into radiance via Planck's law:

$$B(\sigma, T) = \frac{2hc^2\sigma^3}{\exp\left(\frac{hc\sigma}{k_B T}\right) - 1} \quad (3.5)$$

where h is Planck's constant, c is the speed of light, σ is the wavenumber, k_B is the Boltzmann constant, and T is the temperature. Its derivative with respect to temperature can be used to convert the ARA (expressed in kelvin) into radiance units:

$$\text{ARA}_{rad} = \frac{\partial B(\sigma, T)}{\partial T} \cdot \text{ARA} \quad (3.6)$$

It is now possible to retrieve the amount of averages to lower the NESR up to the radiance corresponding to the ARA requirement, as:

$$N = \left(\frac{\text{NESR}_{tot}}{\text{ARA}_{rad}} \right)^2 \quad (3.7)$$

The amount of averages N is dependent on the wavenumber, since the ARA and the NESR are not constant over the observational bandwidth, and the temperature of the observed scene. By computing the required averages at 190K, representative of the worst case condition for the ARA, it is possible to identify the maximum number of averaging operations required for climate studies.

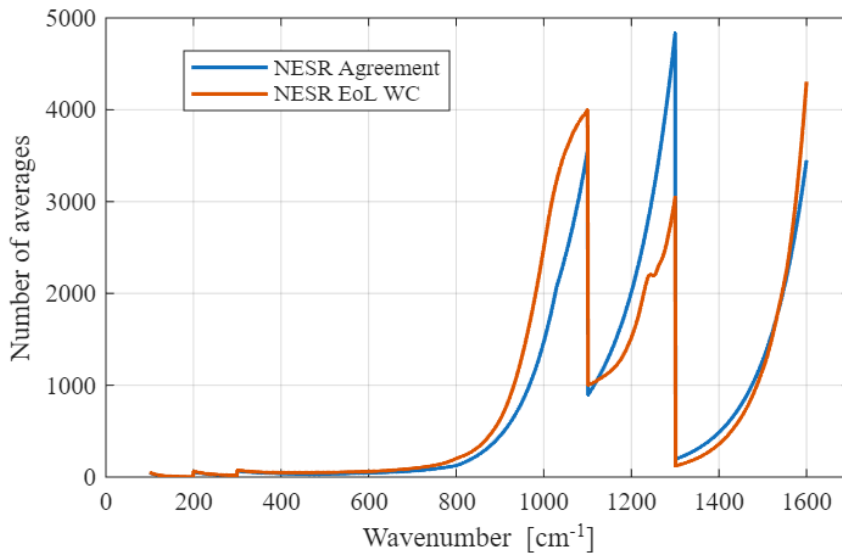


Figure 3.3: Number of averages to lower the radiometric noise up to the ARA for the NESR Agreement and the EoL WC NESR, at 190K.

Figure 3.3 shows the number of averages required to reach the ARA level for an instrument with a noise level equal to the NESR Agreement and for the current NESR estimates at EoL WC (from Figure 3.1). The largest number of averages required for FORUM climate studies, identified from this computation, is lower than 10^4 .

The NESR non-compliance results in a higher number of necessary averages compared to an instrument with a NESR performance equal to the NESR Agreement (identified by the blue line of Figure 3.3). At mission level, this reduces the number of reliable measurements achievable within the lifetime, impacting the overall scientific return.

3.1.2. NESR improvement objective and constraints

The goal of the research presented from Sections 3.1.3 to 3.1.5 is to lower the deviation of the NESR EoL WC non-compliances over the NESR Agreement, by exploiting the current instrument capabilities.

The FSI is undergoing the final stages of the Critical Design Review (CDR), marking the conclusion of Phase C of mission development. Formally, the CDR closes the instrument design, thus preventing any future modification to the selected baseline. Any suggested alteration of the current baseline from a hardware or software perspective, proposed to improve the NESR performance, will impact the CDR. Moreover, cost and schedule add additional constraints on the range of investigated alternatives for performance improvements.

To avoid unacceptable increases in cost and delay, four improvement areas are investigated:

- Trade-offs with other performance metrics.
- Exploitation of the current margins available in the hardware design.
- Software adjustments.
- Operational concept adaptation.

Other design modifications, such as hardware adjustments, are not investigated but may provide alternative solutions for an FTS instrument in an earlier development phase with similar non-compliances. Therefore, no adjustment in the optical throughput G and instrument efficiency η of Eq 3.1 are considered in this analysis.

3.1.3. Adjustment of interferometer speed and spectral resolution

The sub-optimal NEP of the selected detectors is the driving factor for the NESR non-compliance, therefore, the focus has to be placed on lowering the impact of this contributor. Unfortunately, due to the reasons listed in Section 3.1.2, it is not possible at this stage to modify the selected detectors. However, there are exploitable margins in the FSI design on two intrinsically related aspects of the $NESR_{det}$:

- Interferometer speed, related to the electrical bandwidth of the detector and the associated NEP, as discussed hereafter.
- Interferometer range, the MPD, is one of the contributors of the $NESR_{det}$ and is related to the spectral resolution.

In this document, interferometer speed refers to the OPD over time, and not to the physical speed of the interferometer mirrors, that is 1/4 of the interferometer speed (due to the relation between physical distance and OPD, addressed in Section 2.2.1). The same is valid for interferometer scan range, that refers to the OPD covered and not to the physical distance.

The relationship between NEP and interferometer requires the introduction of the modulation frequency concept, defined by Eq 3.8.

$$f = v_i \sigma \quad (3.8)$$

where f is the modulation frequency, σ the wavenumber of the observed signal, and v_i the interferometer speed. The modulation frequency represents a link between the optical frequency of the signal and the temporal variations sensed by the detector in an FTS instrument. The nominal speed of the FSI mirrors is 0.204 cm/s [18] and the wavenumber range is 100-1600 cm^{-1} [12], hence each detector senses a band of signals between:

$$f_{min} = v_i \sigma_{min} = 20.4 \text{ Hz} \quad f_{max} = v_i \sigma_{max} = 326.4 \text{ Hz}$$

This frequency range identifies the NEP band term of Eq 3.1, to determine the $NESR_{det}$. The noise curve presents a lower NEP, i.e. a higher performance, at lower modulation frequencies (Figure 3.4). As a consequence, a reduction of interferometer speed translates the detector bandwidth to a more beneficial NEP region, resulting in an improved NESR performance.

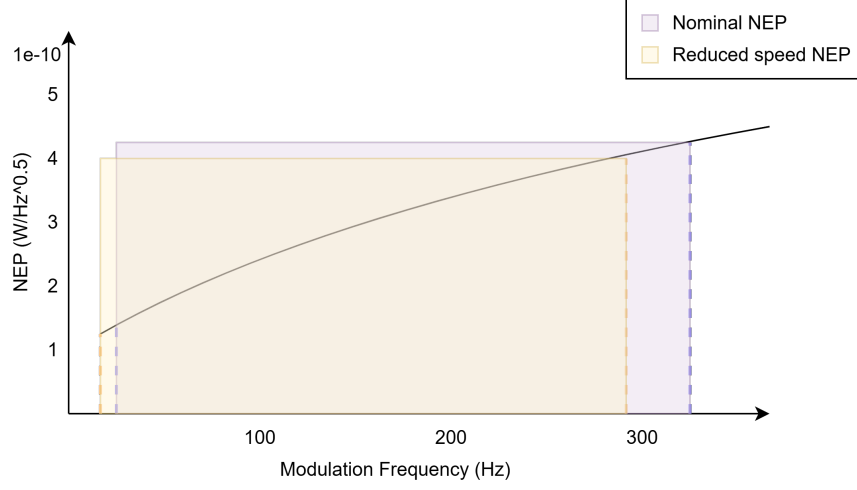


Figure 3.4: NEP of the detectors selected for the FSI: purple box represents the nominal NEP band, the orange box represents the NEP with a reduction of the speed by 10%. NEP curve from [22].

It is therefore worth investigating the benefits of a slower interferometer movement, due to its direct impact on the NEP.

The IA scan speed is intrinsically related to the movement range. Given a fixed acquisition time (intrinsically related to the Spatial Sampling Distance) and a constant interferometer speed, the range of movement is determined. As discussed in Section 2.2.1, the MPD is the main factor in the determination of the spectral resolution. Therefore, a physical relationship exists between acquisition time, interferometer speed and range, spectral resolution $\Delta\sigma$ and Spatial Sampling Distance, as represented in Figure 3.5.

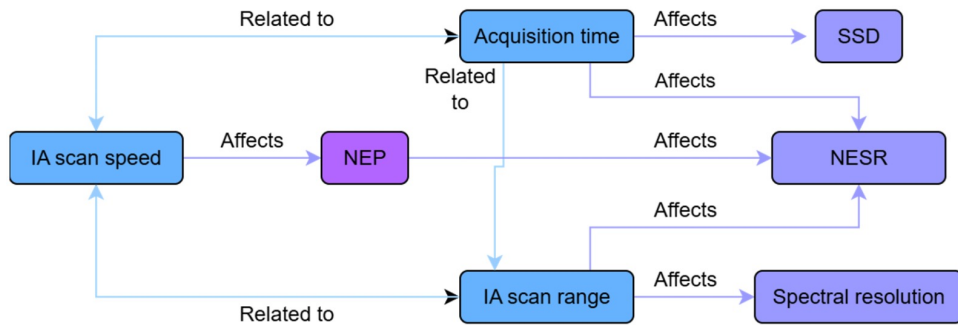


Figure 3.5: Relations among the $NESR_{det}$ parameters.

Given a fixed scan duration, any reduction of the scan speed comes at a cost of a reduction of the MPD, thus causing a degradation of spectral resolution (from Eq 2.4). The current spectral resolution, reported in Figure 2.9, shows that there is a margin with respect to the requirement, that could be exploited before encountering a partial non-compliance.

Moreover, the $\Delta\sigma$ is not constant over the bandwidth, but it manifests the worst performance at higher wavenumbers. It is worth to investigate the benefits in terms of NESR that result from the introduction of a minor $\Delta\sigma$ non-compliance only at higher wavenumbers, while the rest of the bandwidth is kept compliant, especially in the FIR region. For the purpose of this research, a maximum deviation of 5% from the spectral resolution requirement is considered an acceptable compromise, pending validation by the scientific community. In the high wavenumbers region, the scientific demand for high spectral resolution is comparatively lower [1]. This tolerance allows for an investigation into whether minor relaxations in resolution could yield significant benefits in NESR.

To perform this research, the OPD associated to a spectral resolution with a non-compliance of 5% is identified. By fixing the acquisition time to the baseline value, it is possible to obtain the interferometer speed, and therefore the NEP band of the detectors. The NESR_{tot} with this alternative approach is simulated and the results are reported in Section 3.1.7, along with the necessary modifications and the resulting spectral resolution. An optimum research problem to refine this performance trade-off is implemented and presented in Section 3.1.5. Table 3.1 summarizes the necessary adjustments for this improvement strategy.

	Current values [18]	Modification
Interferometer speed	0.204 cm/s	Decrease
Interferometer range	1.4 cm	Decrease
Scan duration	14 s	Unmodified
Spectral resolution	0.476 cm^{-1}	Degraded to 5% non-compliance at higher wavenumbers

Table 3.1: *Interferometer speed and spectral resolution adjustment.*

3.1.4. Adjustment of interferometer speed and acquisition time

The NESR_{det} term is inversely proportional to the square root of the acquisition time, as in Eq 3.1. Since some margins on this metric in the current design exist, it is worth to investigate the benefits for the NESR of such modification.

Before diving into the necessary adjustments for an acquisition time increase, the Spatial Sampling Distance (SSD) and its requirement should be detailed. The SSD represents the separation among two samples on ground relative to two acquisitions taken in sequence.

The SSD can be computed, at first approximation, as:

$$\alpha = \sin^{-1}\left(\frac{1}{2} v_{orb} \cdot (t_{dwell}) / (R_{Earth} + h_{orbit})\right) \quad \text{SSD} = 2 R_{Earth} \sin(\alpha) \quad (3.9)$$

where v_{orb} is the orbital speed, t_{dwell} is the acquisition time, h_{orbit} the orbital altitude, R_{Earth} the Earth radius. The SSD geometry is qualitatively represented in Figure 3.6 .

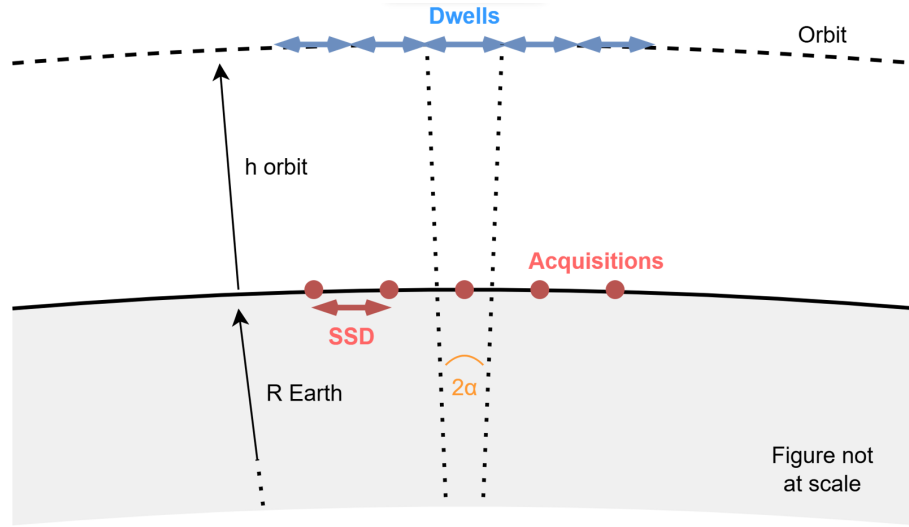


Figure 3.6: *SSD Geometry (not at scale). The SSD is the distance between two acquisition (red dots), computed with trigonometrical relations. Due to the short time span (14s) and the large distances involved, the geometry is approximated to be almost flat.*

The modification of t_{dwell} is strongly constrained by the current hardware capabilities. The Scan Unit (SCU) tilts during the acquisition to compensate for orbital movement, so the design limits of the SCU impose a limitation on the maximum acquisition time. Moreover, with a longer dwell, the Nadir Baffle could enter in the field of view of the IA, posing an additional constraint to the maximum SCU scan angle.

In Section 2.3.5, the requirement relative to the SSD is reported. The maximum allowed SSD value is set at 100 km. The current t_{dwell} is associated to an SSD that guarantees a 2-3% margin with the requirement. It is therefore possible to investigate the NESR advantages resulting from the exploitation of this margin. As for the spectral resolution degradation presented in Section 3.1.3, it is also worth to investigate the benefits of the introduction of a non-compliance on the SSD, since a sparser measurement might be an acceptable compromise if traded for improved radiometric noise.

Recalling Figure 3.5, any modification of the acquisition time is intrinsically related to the interferometer movement, due to the existing synchronization among the two quantities.

If the speed of the interferometer is not modified, a longer dwell would yield a larger OPD and thus a finer spectral resolution. According to Eq 3.1, an increase of the OPD would degrade the NESR performance, thus lowering the benefits of the time increase. To counterbalance the MPD increase is to reduce the speed of the interferometer, to obtain the same MPD of the baseline design. The significant additional benefit of this speed adjustment is the reduction of the NEP, due to the modification of the modulation frequency band, as discussed in Section 3.1.3. Table 3.2 summarizes the adjustments necessary for this improvement strategy.

	Current values [18]	Modification
Acquisition time	14 s	Increase
SSD	97.76 km	Degraded to 10% non-compliance
SCU range	3.16°	Increase up to 3.6°
Interferometer speed	0.204 cm/s	Decrease
Interferometer range	1.4 cm	Unmodified
Spectral Resolution	0.476 cm ⁻¹	Unmodified

Table 3.2: Interferometer speed and acquisition time adjustment.

The results in terms of specific modifications and NESR improvements are presented in Section 3.1.7.

3.1.5. NESR Improvement strategy optimization

An optimum research has been implemented to identify the most effective way to reach a compliance on the NESR performance, avoiding large degradations of SSD and $\Delta\sigma$. The objective function identified for this optimum research problem is reported in Eq 3.10.

$$J = w_1 \frac{\text{NESR} - \text{NESR}_{\text{Agreement}}}{\text{NESR}_{\text{Agreement}}} + w_2 \frac{\Delta\sigma - \Delta\sigma_{\text{req}}}{\Delta\sigma_{\text{req}}} + w_3 \frac{\text{SSD} - \text{SSD}_{\text{req}}}{\text{SSD}_{\text{req}}} \quad (3.10)$$

where $\text{NESR}_{\text{Agreement}}$, $\Delta\sigma_{\text{req}}$ and SSD_{req} are the targeted observational performances, while w_1 , w_2 and w_3 are weight factors selected to prioritize the reduction of a specific quantity. Due to the intrinsic links between NESR, spectral resolution $\Delta\sigma$ and SSD, an improvement of one of the quantities will lead to a degradation of the others. By minimizing this objective function, it is possible to find the optimal trade-off among the three performances considered. Imposing $w_1 > w_2, w_3$, the priority is given to the NESR improvement, while at the same time excessive degradation of the $\Delta\sigma$ and SSD is avoided.

The NESR performance will benefit from:

- Decrease of the detector NEP due to the interferometer speed reduction.
- Increase of the acquisition time.
- Decrease of the interferometer range (MPD).

The optimization variables are the acquisition time t and the MPD. The former will determine the SSD and the interferometer scan duration, the latter will identify the interferometer range and the $\Delta\sigma$. The optimization problem is formulated as follows:

$$\min_{t, MPD} \mathbf{J}(t, MPD) \quad \text{s.t.} \quad \begin{cases} NESR < NESR_{Agreement}, \\ SSD < 110 \text{ km}, \\ \Delta\sigma < 0.55 \text{ cm}^{-1}, \end{cases} \quad (3.11)$$

As for the previous sections, a partial degradation of SSD and spectral resolution is allowed, to assess the benefit of a trade-off among these quantities. The optimization variables t and MPD are further constrained according to the hardware limitations, in particular due to the maximum range of the Scan Unit.

Table 3.3 summarizes the adjustments implemented for the optimum research problem. The results of this performance adjustments are reported in Section 3.1.7.

	Current values [18]	Modification
Acquisition time	14 s	Increase
SSD	97.76 km	Degraded up to max 10% non-compliance
SCU range	3.16°	Increase up to 3.6°
Interferometer speed	0.204 cm/s	Decrease
Interferometer range	1.4 cm	Decrease
Spectral Resolution	0.476 cm ⁻¹	Degradation up to max 10% non-compliance

Table 3.3: NESR Optimum research problem adjustments.

Additional Constraints on SSD and $\Delta\sigma$

To complement the optimum research, it is also possible to investigate the maximum NESR improvement that can be obtained from the exploitation of the margins on the SSD and $\Delta\sigma$, without resulting in non-compliances.

This alternative optimum research problem is formalized as follows:

$$\min_{t, MPD} \mathbf{J}(t, MPD) \quad \text{s.t.} \quad \begin{cases} SSD < 100 \text{ km} \\ \Delta\sigma < 0.5 \text{ cm}^{-1} \end{cases} \quad (3.12)$$

This solution will not guarantee the compliance of the NESR, but it will cause a partial improvement while maintaining the full compliance of SSD and $\Delta\sigma$, providing an alternative solution to be selected if the partial non-compliances on other performances are not desirable. The results of this analysis are reported in Section 3.1.7.

3.1.6. NESR improvement with single sided IGM acquisition

An additional alternative has been explored to more extensively reduce the impact of the detector NEP on the NESR performance. The adjustments proposed in this section constitute a larger deviation from the FSI baseline compared to what has been discussed so far, therefore they should be treated as a secondary alternative, to be selected if the optimum research solution results to be not applicable. Moreover, the adjustments proposed in this section can be considered as a valid design alternative for an FTS instrument in an earlier development phase compared to the FSI.

The FSI records double-sided interferograms, moving the double-pendulum interferometer from -MPD to +MPD and vice versa depending on the scan direction. The rationale for this mode of operation is discussed in Section 2.4.1. However, the same spectral information can also be encoded into a single sided interferogram, i.e. obtained with a scan between ZPD and $\pm$ MPD. The two alternative interferograms are presented in Figure 3.7.

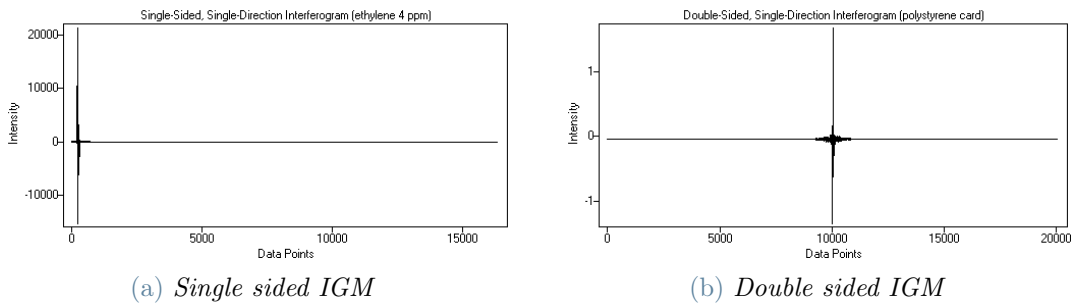


Figure 3.7: *Different types of interferograms (IGM) [16].*

The immediate advantage of this alternative is that, if the acquisition time is kept the same (to maintain the SSD compliance), the interferometer has to move at half the speed. Recalling Eq 3.8, the electrical bandwidth of the detector modifies with a decrease of the interferometer scan speed. A reduction of 50% would yield substantial changes, since the

new bandwidth of operation would be 10-163 Hz, while the nominal was 20-326 Hz [18]. As can be seen from Figure 3.8, the NEP substantially reduces at lower frequencies.

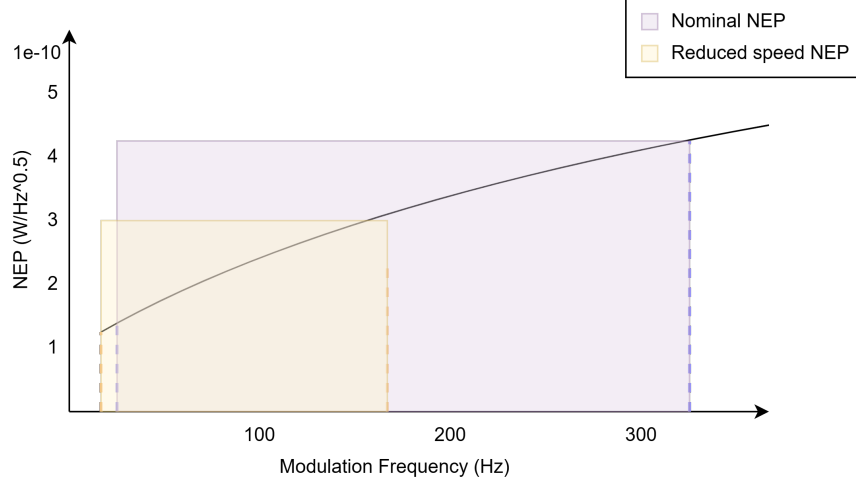


Figure 3.8: *NEP of the detectors selected for the FSI: purple box represents the nominal NEP band, the orange box represents the NEP with a reduction of the speed by 50%.*

The optical distance scanned from ZPD to the maximum Path difference (the MPD), would be unaffected, therefore the spectral resolution would not be modified as well, according to Eq 2.4. This type of acquisition would therefore yield great improvements in terms of NESR, without any degradation of spectral resolution and SSD. The resulting NESR with a single sided IGM acquisition is reported in Section 3.1.7.

However, this acquisition strategy is inherently more susceptible to phase errors, due to its lack of symmetry compared to the double-sided configuration [13]. Consequently, more advanced and robust ZPD identification and phase correction techniques are required. Although this approach increases the complexity of data processing, its implementation is well established, with several examples of similar methodologies available in the literature [14, 17]. Different options have been considered for the adaptation of the single sided IGM acquisition to the FSI architecture.

Option 1: SCU scan from +100 km to 0 km

The interferograms centreburst, recorded at Zero optical Path Difference, should be acquired with the same SCU tilt angle used during the calibration events. This comes from the SCU mirror's polarization properties, that are dependant on its tilt angle. During calibration, the SCU remains fixed, and the instrument's offset and gain are characterized for that specific orientation. Ensuring that the centreburst is acquired with the same tilt angle as the calibration maximizes the accuracy of the radiometric correction, as the centreburst contains the most critical spectral information.

Figure 3.9 shows the SCU orientation during Earth observation and calibration, the position of the observed scene relative to the S/C and the IA pendulum movement.

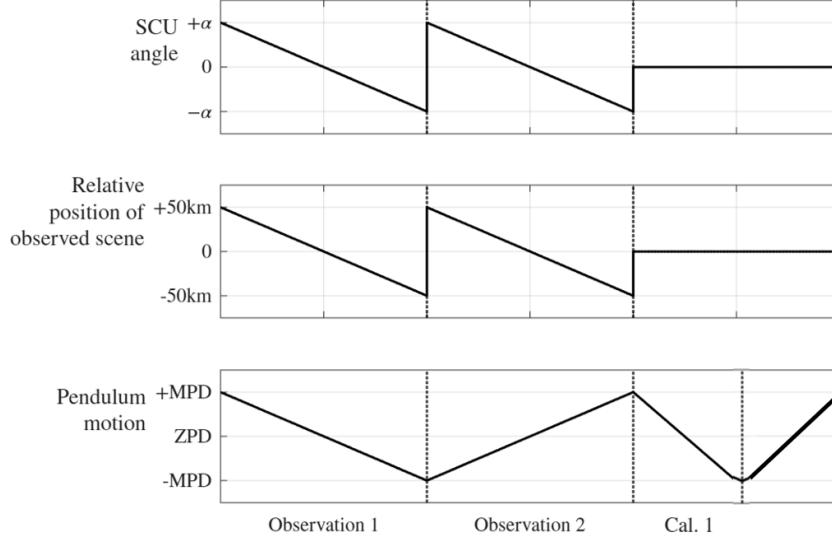


Figure 3.9: SCU position, scene position and pendulum (interferometer) motion over time during Earth observation and calibration.

Let's consider a Spatial Sampling Distance of 100 km and the baseline acquisition. To acquire the scene, the SCU must point at $+50\text{ km}$ ($+\alpha$) at the start of the acquisition and then gradually tilt up to -50 km ($-\alpha$) during the dwell, as represented in Figure 3.9. Here the ZPD corresponding to the nadir measurement. If we want to acquire a single sided interferogram with the ZPD synchronized with nadir (to maintain the same SCU angle of the calibrations), while maintaining the SSD at 100 km, this means that the SCU should initially point at $+100\text{ km}$ ($+2\alpha$) and gradually tilt up to 0 km (0α), as in Figure 3.10.

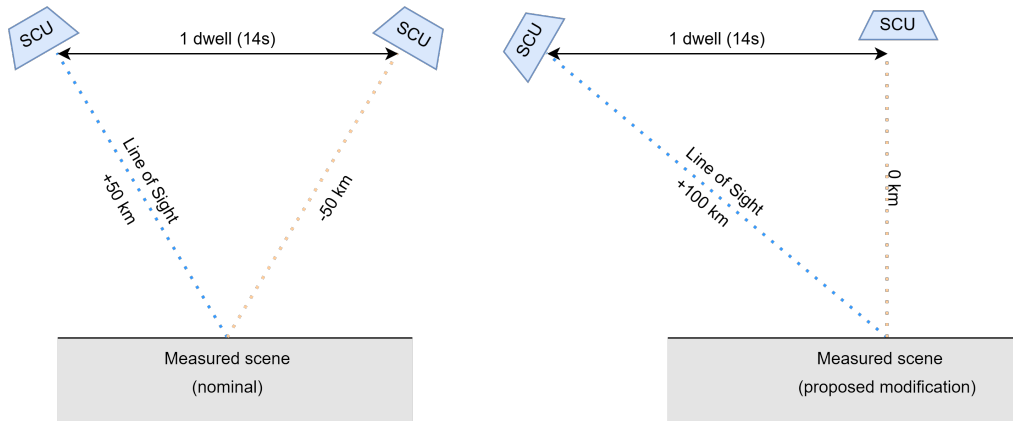


Figure 3.10: Acquisition strategy: nominal observation (left), and modified (right).

This alternative would ideally guarantee a high NESR performance due to the single sided interferogram acquisition, same spectral resolution and SSD of the baseline, no degradation of the radiometric correction accuracy. The applicability of this alternative to the FSI and the necessary adjustments are reported in Section 3.1.7.

An alternative spacecraft configuration that allows observation from +100 km to 0 km without modifying the SCU scan profile has been considered. By tilting the entire spacecraft, the scene at +50 km can be observed when the SCU is in its neutral position, corresponding to 0 km in the previous configuration. In this setup, shown in Figure 3.11, the SCU can approximately follow its nominal scan profile, with only minor adjustments, covering the range from +100 km ($+\alpha$) to 0 km ($-\alpha$).

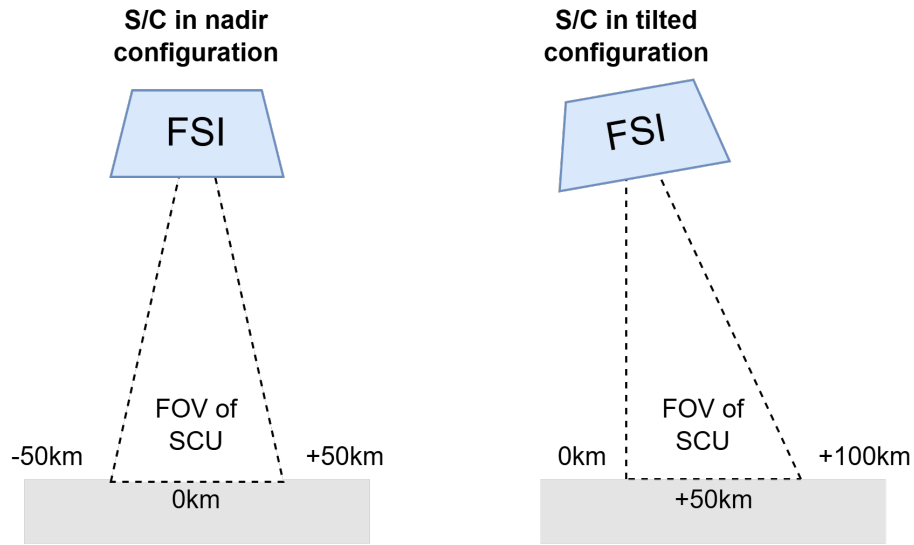


Figure 3.11: Tilted spacecraft configuration (right) and nominal configuration (left) with SCU observation range.

The drawback of this configuration is that the centreburst of the interferogram acquired at ZPD is associated to a SCU configuration in $-\alpha$, while the calibration is performed with the SCU at 0° . The degradation of radiometric accuracy with this configuration has been estimated and reported in Section 3.1.7.

This configuration might not be fully desirable as there would be a likely non-compliance with the maximum depointing angle specified by MRD-OBS-040 in Section 2.3.5, due to the extended scan at +100 km. The results and the overall compatibility of the FSI with this option is reported in Section 3.1.7.

Option 2: SCU scan from +50 km to -50 km

An alternative configuration that does not require changes in pointing procedures and SCU range is also investigated. It is possible to consider again a nadir-pointing S/C orientation and a nominal SCU scan, from $+\alpha$ to $-\alpha$. Recording a single sided interferogram means that the centreburst/ZPD would be aligned with the SCU configuration in $+\alpha$ and $-\alpha$ in alternation, as shown in Figure 3.12.

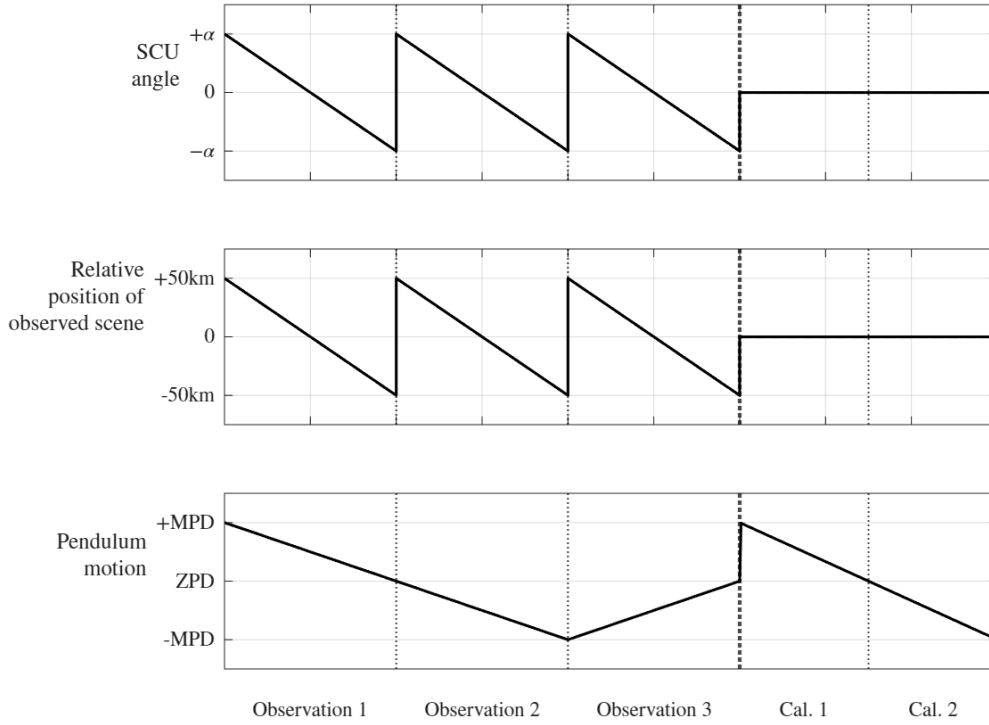


Figure 3.12: SCU position, scene position and pendulum motion over time during Earth observation and calibration with single sided IGM acquisition.

This alternative configuration would guarantee compliance with the depointing angle, would stay within the operating boundaries of the SCU and would improve the NESR without degradation of SSD and spectral resolution. However, the radiometric accuracy will be subject to a degradation, since the centreburst would be acquired with the SCU at a different tilt angle with respect to the one selected for the calibrations. The estimation of the radiometric errors and compatibility of the FSI hardware with this option are reported in Section 3.1.7.

3.1.7. Results: Sub-optimal NEP impact on NESR

The suboptimal NEP of the FSI detectors causes partial non-compliances on the NESR performance at the End of Life and Worst Case condition. Different improvement alternatives have been investigated to lower the NEP impact. The effectiveness of each improvement strategy is reported in Section 3.1.7.

Adjustment of IA speed and range

To reduce the NEP impact on the NESR through the adjustment of interferometer speed and range, the modifications of Table 3.4 are proposed.

Parameter	Current values [18]	Modified values
Interferometer speed	0.204 cm/s	0.181 cm/s
Interferometer range	1.40 cm	1.24 cm
Spectral Resolution	0.476 cm ⁻¹	0.525 cm ⁻¹
Acquisition time	14.0 s	-
SCU motion range	3.16°	-
SSD	97.76 km	-
Detector bandwidth	20-326 Hz	18-289 Hz

Table 3.4: *FSI adjustments for NESR improvement with reduced interferometer speed and range. Unmodified values marked with "-".*

The spectral resolution reported in Table 3.4 is relative to the worst case performance over the spectral range, at 1600 cm⁻¹. While this value corresponds to a 5% non-compliance, the performance improves significantly at lower wavenumbers, as illustrated in Figure 3.13. The non-compliance is confined to the region above 1000 cm⁻¹.

Compared to the FSI baseline, the lower detector bandwidth is associated to a more beneficial NEP performance that, combined with the reduction of interferometer range, results in an improved NESR. The performance deviation from the NESR Agreement, i.e. the target noise level, is shown in percentage in Figure 3.14.

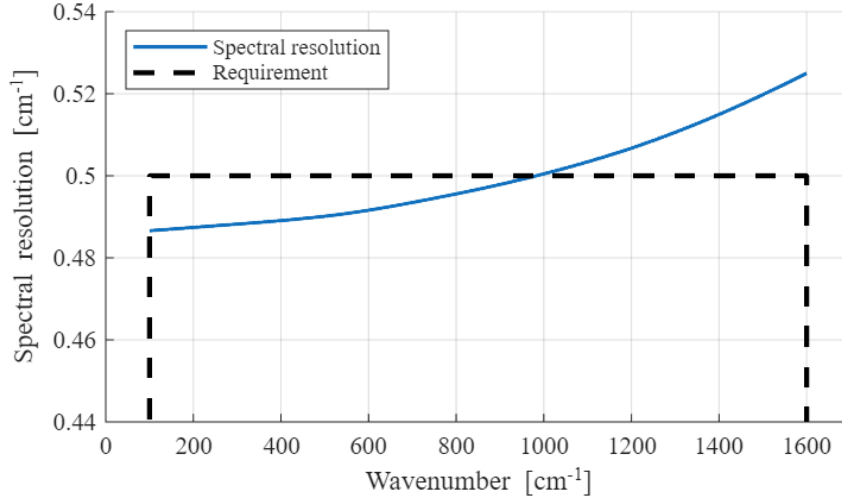


Figure 3.13: Spectral resolution over the FSI bandwidth after the adjustment of interferometer speed and range.

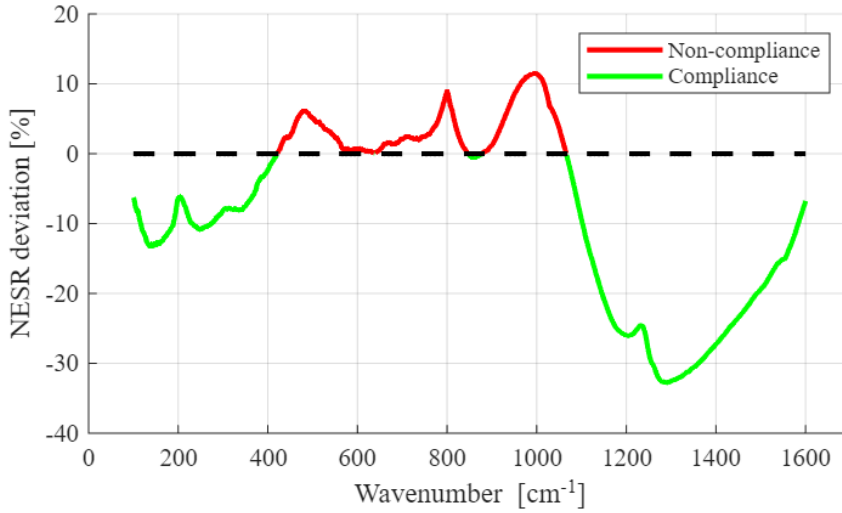


Figure 3.14: Total NESR deviation from NESR Agreement resulting from the modifications of Table 3.4.

With the proposed adjustment, the non-compliance bands are less extended compared to the baseline performance, and their amplitude is limited to $<12\%$. This represents a large improvement, since the original non-compliances were as high as 30% (see Figure 3.2).

Adjustment of IA speed and acquisition time

The results relative to Section 3.1.4 are presented hereafter. Here the high NEP impact is reduced by decreasing the interferometer speed and increasing the acquisition time, according to the modifications of Table 3.5.

Parameter	Current values [18]	Modified values
Interferometer speed	0.204 cm/s	0.180 cm/s
Interferometer range	1.40 cm	-
Spectral Resolution	0.476 cm^{-1}	-
Acquisition time	14.0 s	15.85 s
SCU motion range	3.16°	3.58°
SSD	97.76 km	110 km
Detector bandwidth	20-326 Hz	18-288 Hz

Table 3.5: FSI adjustments for NESR improvement with reduced interferometer speed and increased acquisition time.

On the contrary to the modifications proposed in Table 3.4, here the interferometer range is not adjusted, therefore the spectral resolution is the same as the baseline instrument (see Figure 2.9). The detector bandwidth is similar to the one reported in Table 3.4, however, when paired with the increase of acquisition time and not the adjustment of interferometer range, the effectiveness of the improvement is lower. The resulting NESR performance is expressed in deviation from the NESR Agreement, in Figure 3.15.

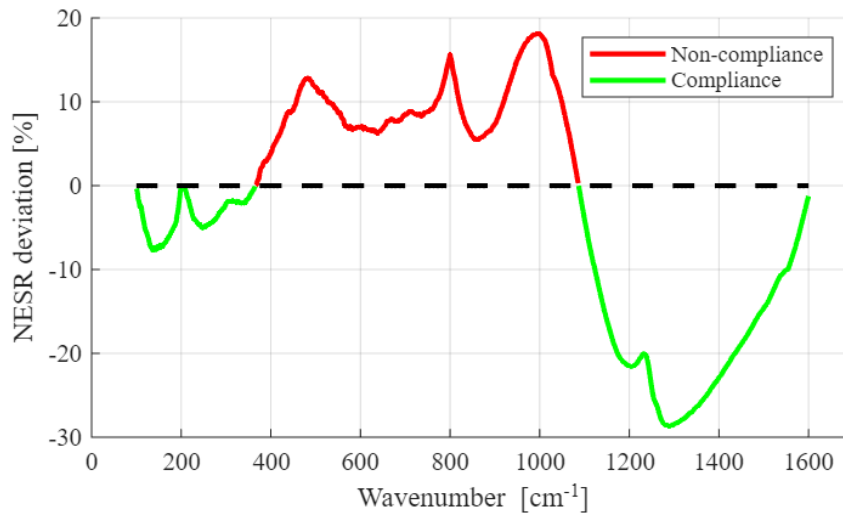


Figure 3.15: Total NESR deviation from NESR Agreement resulting from the modifications of Table 3.5.

The improvement with respect to the baseline performance is observed, with maximum non-compliance $<19\%$, compared to the original maximum value of 30% . However, compared to Figure 3.14 the benefit of the modification is lower.

Improvement strategy optimization

The optimum adjustment of the FSI parameters, discussed in Section 3.1.5, to lower the NEP impact and improve the NESR are reported in Table 3.6.

Parameter	Current values [18]	Modified values
Interferometer speed	0.204 cm/s	0.159 cm/s
Interferometer range	1.40 cm	1.24 cm
Spectral Resolution	0.476 cm ⁻¹	0.526 cm ⁻¹
Acquisition time	14.0 s	15.80 s
SCU motion range	3.16°	3.57°
SSD	97.76 km	109.66 km
Detector bandwidth	20-326 Hz	16-254

Table 3.6: FSI optimum adjustments for NESR improvement, with degradations on spectral resolution and SSD allowed.

Similarly to the configuration proposed in Table 3.4, the spectral resolution is degraded up to a $\sim 5\%$ non-compliance at 1600 cm⁻¹. Figure 3.16 shows that the non-compliance band is limited to wavenumbers higher than 900 cm⁻¹.

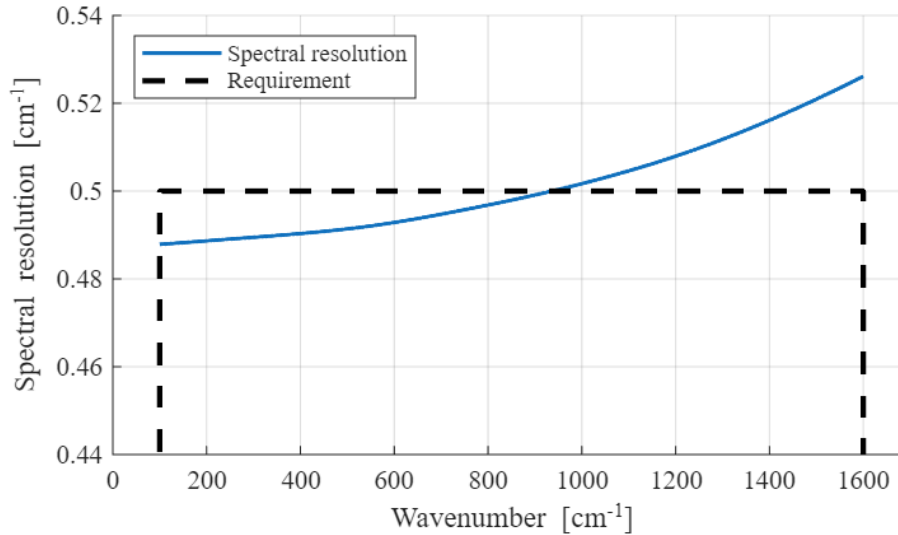


Figure 3.16: Spectral resolution with NESR improvement strategy optimization.

The spectral resolution non-compliant band is slightly larger compared to Figure 3.13. This is balanced by a large improvement in NESR performance. Considering the reduced detector bandwidth and interferometer range of Table 3.6, and the increased acquisition time, the resulting NESR is close to a full compliance, as shown in Figure 3.17.

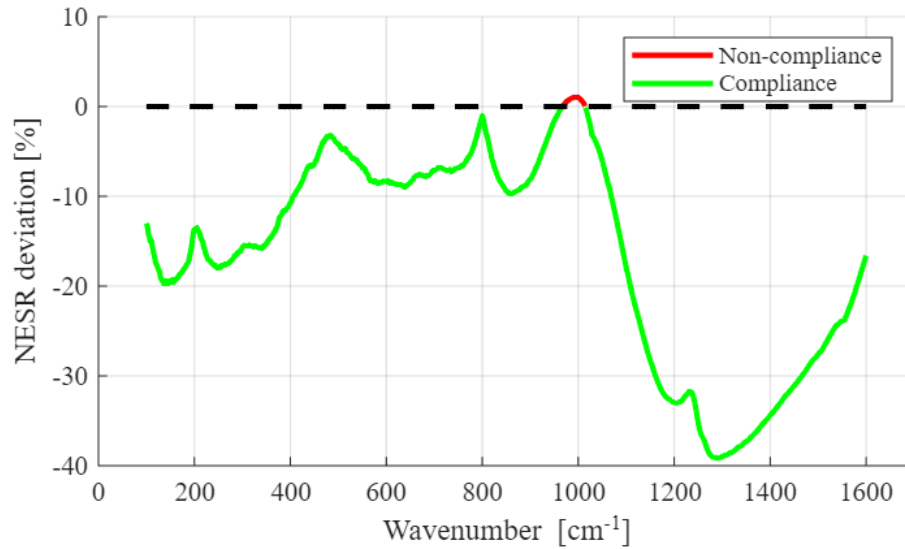


Figure 3.17: Total NESR deviation from NESR Agreement, from Table 3.6 adjustments.

A non-compliance limited to less than 2%, occurs exclusively at 1000 cm^{-1} (Figure 3.17). This minimal deviation was accepted by the optimization setup established in Section 3.1.5 as a strategic trade-off. A non-compliance below 2% is considered acceptable, as guaranteeing absolute compliance would require disproportionately large modifications, which are not desirable to correct a minor deviation confined to a limited spectral band.

Optimization without SSD and spectral resolution non-compliances

The results relative to the NESR improvement optimization process, repeated while constraining the maximum value of SSD and spectral resolution according to their requirements, are presented hereafter. The optimum adjustment of the FSI parameters that guarantees compliance of SSD and spectral resolution is reported in Table 3.7.

Parameter	Current values [18]	Modified values
Interferometer speed	0.204 cm/s	0.187 cm/s
Interferometer range	1.40 cm	1.32 cm
Spectral Resolution	0.476 cm^{-1}	0.500 cm^{-1}
Acquisition time	14.0 s	14.3 s
SCU motion range	3.16°	3.23°
SSD	97.76 km	100.00 km
Detector bandwidth	20-326 Hz	19-299 Hz

Table 3.7: FSI optimum adjustments for NESR improvement, with constrained degradation on SSD and spectral resolution.

The spectral resolution is fully compliant over the whole FSI spectral range, as it reaches the value of 0.5 cm^{-1} at 1600 cm^{-1} . The NESR benefits from the lower detector bandwidth, degraded spectral resolution and larger acquisition time; however, due to the lower amplitude of the adjustments, the improvement is not as effective as the one relative to Table 3.6. The resulting NESR performance, expressed in deviation from the NESR Agreement, is presented in Figure 3.18.

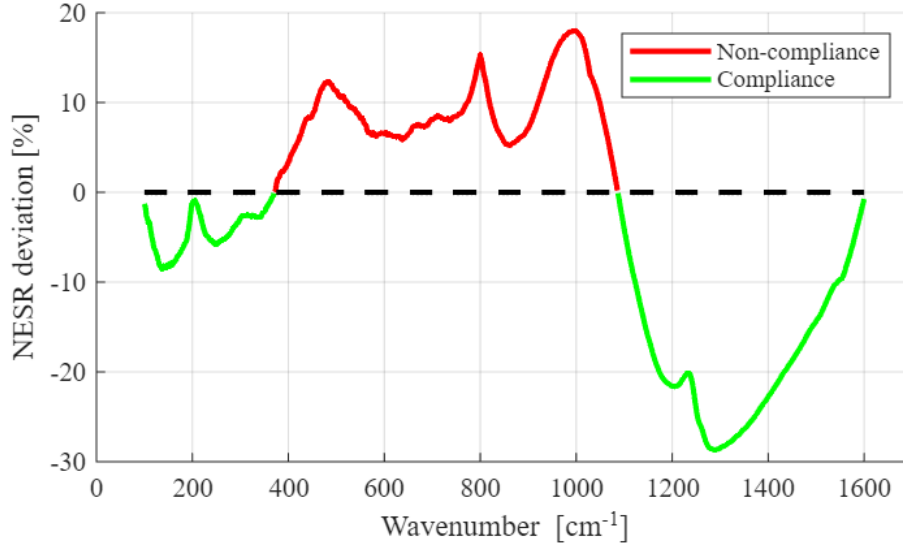


Figure 3.18: Total NESR deviation from NESR Agreement resulting from the modifications of Table 3.7.

This improvement demonstrates the optimal enhancement achievable using the current instrument capabilities, without introducing additional non-compliance across other mission-level performance parameters. While the resulting performance gain is not as substantial as that realized through an unconstrained optimization, this solution is considered relevant and worthwhile because it prevents the degradation of other critical mission performances.

Single sided IGM option

The single sided interferogram (IGM) acquisition, presented in Section 3.1.6, lowers the interferometer speed by a factor of two, thus strongly reducing the impact of the NEP on the NESR. The resulting radiometric noise performance, common for each of the alternatives considered for this acquisition strategy and expressed in deviation from the NESR Agreement, is shown in Figure 3.19.

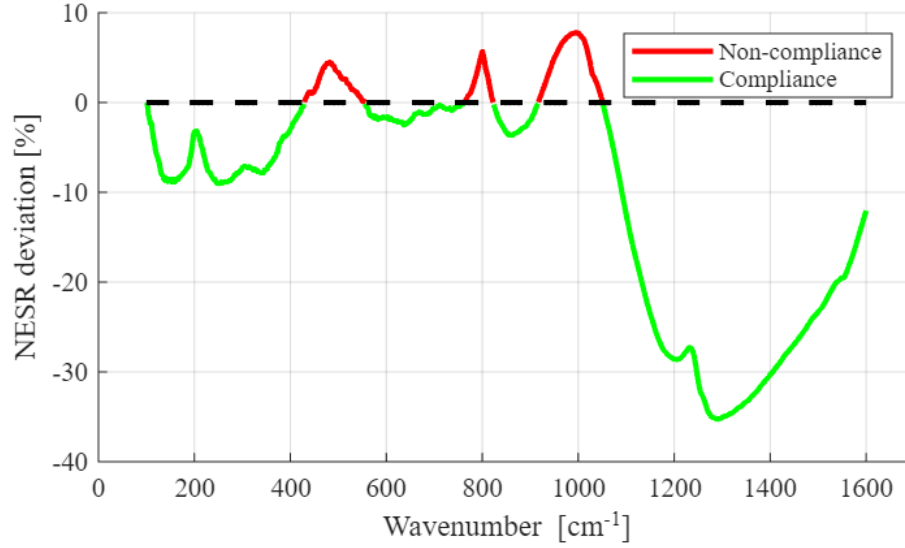


Figure 3.19: NESR deviation from NESR Agreement with a single sided IGM acquisition.

The non-compliance bands are limited to three spectral regions and their magnitude is lower than 8%, a substantial improvement compared to the instrument baseline, where values up to 30% are present (Figure 3.2). The main advantage of this modification strategy is that the performance improvement does not come at the cost of degraded SSD or spectral resolution, as reported in Table 3.8.

Parameter	Current values [18]	Modified values
Interferometer speed	0.204 cm/s	0.102 cm/s
Interferometer range	1.40 cm	-
Spectral Resolution	0.476 cm ⁻¹	-
Acquisition time	14.0 s	-
SSD	97.76 km	-
Detector bandwidth	20-326 Hz	10-163 Hz

Table 3.8: FSI adjustments for single sided IGM acquisition.

These results are common across multiple system configuration alternatives, presented shortly after. Before addressing the full compatibility of each option with the FSI, the errors relative to a mismatch between SCU angle during calibration and the SCU angle during the centreburst acquisition of an Earth dwell are presented in Figure 3.20.

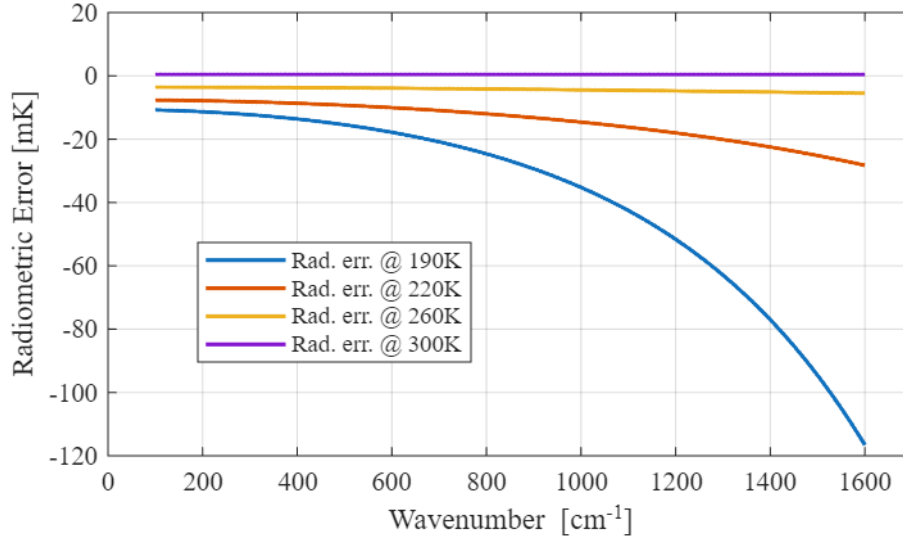


Figure 3.20: Radiometric errors given by different SCU angles during the acquisition of Earth dwell centreburst and calibration measurements [23].

The radiometric errors given by the SCU angle mismatch are dependent on the temperature of the observed scene. These errors are non-negligible, since they reach order of magnitudes similar to the ARA requirement. Therefore, for each of the alternatives considered for the single sided interferogram acquisition that are affected by this SCU angle mismatch, careful considerations on the ARA budget shall be performed.

Table 3.9 reports the compatibility of the FSI configuration with the "Option 1" presented in Section 3.1.6, with a scan from +100 km (the SSD in this section is approximated from 97.76 km to 100 km) to 0 km relative to the normal projection of the spacecraft position on Earth's surface.

This option can be effectively discarded due to the range of the SCU scan, that would reach values of 6.32° , well above its design range of 3.6° [18]. Moreover, the partial observation of baffles and the non-compliance on the depointing angle requirement are likely to represent additional reasons to discard this option, although they require further and more detailed assessments outside of the capabilities of the simulator used in this research.

Parameter	Baseline configuration	Alternative configuration
Scan range relative position	+50 km to -50 km	+100 km to 0 km
SCU angle range	$+\alpha$ to $-\alpha$	$+2\alpha$ to 0 α
Nadir baffle in FOV	X	✓
Radiometric errors (Fig 3.20)	X	X
Depointing angle (Sec. 2.3.5)	Compliant	Non-compliant
S/C pointing	Nadir	Nadir

Table 3.9: *FSI adjustments for single sided IGM acquisition from +100 km to 0 km - non tilted configuration. α refers to half of the nominal SCU angle of 3.16° .*

An alternative is investigated to observe from +100 km to 0 km, without exceeding the design limits of the SCU, by tilting the S/C as in Figure 3.11; the modifications associated are reported in Table 3.10

Parameter	Baseline configuration	Alternative configuration
Scan range relative position	+50 km to -50 km	+100 km to 0 km
SCU angle range	$+\alpha$ to $-\alpha$	$+\alpha$ to $-\alpha$
Nadir baffle in FOV	X	X
Radiometric errors (Fig 3.20)	X	✓
Depointing angle (Sec. 2.3.5)	Compliant	Non-compliant
S/C pointing	Nadir	Tilted to +50 km relative to nadir

Table 3.10: *FSI adjustments for single sided IGM acquisition from +100 km to 0 km - tilted configuration.*

Although the SCU and baffle configuration aligns with the baseline, effectively removing them as grounds for rejection, the option remains likely undesirable due to the radiometric errors that are now present. By maintaining the baseline scan angle profile, the centreburst is acquired at an SCU angle of α rather than 0° . This offset introduces radiometric errors of sufficient magnitude to degrade the Absolute Radiometric Accuracy (ARA). Furthermore, this configuration fails to comply with the maximum depointing angle requirement, providing a additional rationale to discard this solution.

An additional alternative has been considered for the single sided interferogram acquisition, referred in Section 3.1.6 as "Option 2". Here, the position on ground relative to the spacecraft ranges from +50 km to -50 km, as for the baseline acquisition. Table 3.11 summarizes the alternative configuration to achieve such acquisition.

Parameter	Baseline configuration	Alternative configuration
Scan range relative position	+50 km to -50 km	+50 km to -50 km
SCU angle range	$+\alpha$ to $-\alpha$	$+\alpha$ to $-\alpha$
Nadir baffle in FOV	X	X
Radiometric errors (Fig 3.20)	X	✓
Depointing angle (Sec. 2.3.5)	Compliant	Compliant
S/C pointing	Nadir	Nadir

Table 3.11: *FSI adjustments for single sided IGM acquisition from +50 km to -50 km.*

With respect to the configurations relative to an acquisition from +100 km to 0 km, with this alternative there is no non-compliance on the depointing angle, the SCU and baffles are within their design margins and no major modification except for the interferometer speed is required. However, due to the mismatch of the SCU angle between calibration measurements and centreburst acquisition, the radiometric errors are still present. These error will affect the ARA budget in a non-negligible manner. If this option is investigated more in detail or selected, a trade-off between the gain in NESR performance and the loss of ARA is advised, and should be carried out through a cooperation between ESA and the Mission Advisory Group (MAG, Section 2.3.3).

3.2. Impact of differing detectors NEPs and signal recombination strategies

The FORUM Sounding Instrument has two independent detectors located at the output ports of the Interferometer Assembly. As discussed in Section 3.1, these sensors are characterized by their Noise Equivalent Power (NEP), a performance figure representative of their sensibility.

During the last stages of Phase C, a batch of candidate flight detectors was manufactured and their NEP performance was measured. To identify the highest performing detectors, every unit NEP's has to be measured, since minor differences and imperfections in the manufacturing and assembly process cause a different final performance. Among the manufactured batch, a relatively wide range of NEP has been observed; the two highest performing units, i.e. with the lowest NEP, were selected as flight detectors. Their NEP over the modulation frequency is reported in Figure 3.21.

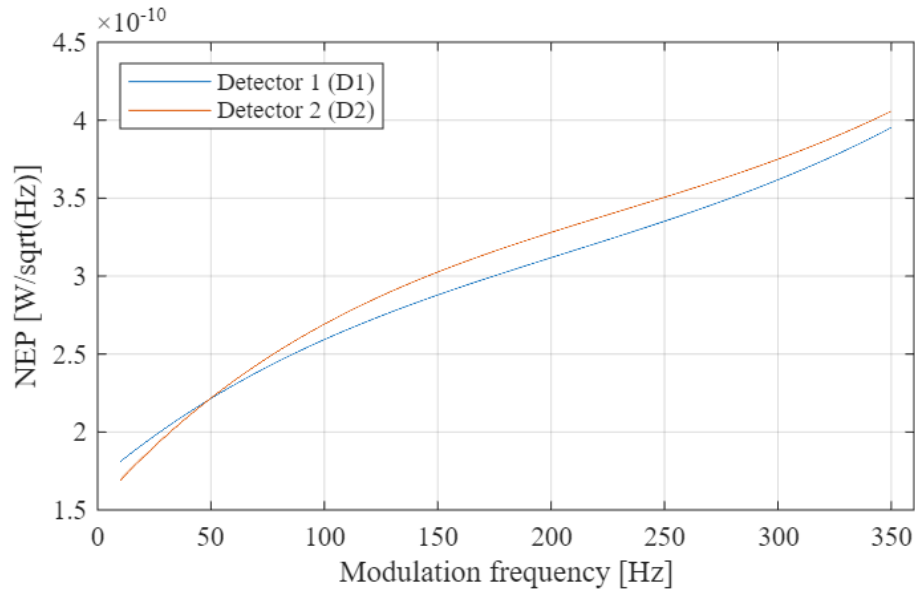


Figure 3.21: *Noise Equivalent Power of selected flight detectors [18].*

Their performance is relatively similar, however, at $f > 50$ Hz, Detector 1 (D1) has a more desirable NEP with respect to Detector 2 (D2). Recalling Eq 3.1, this translates in a superior NESR performance for D1, as shown in Figure 3.22.

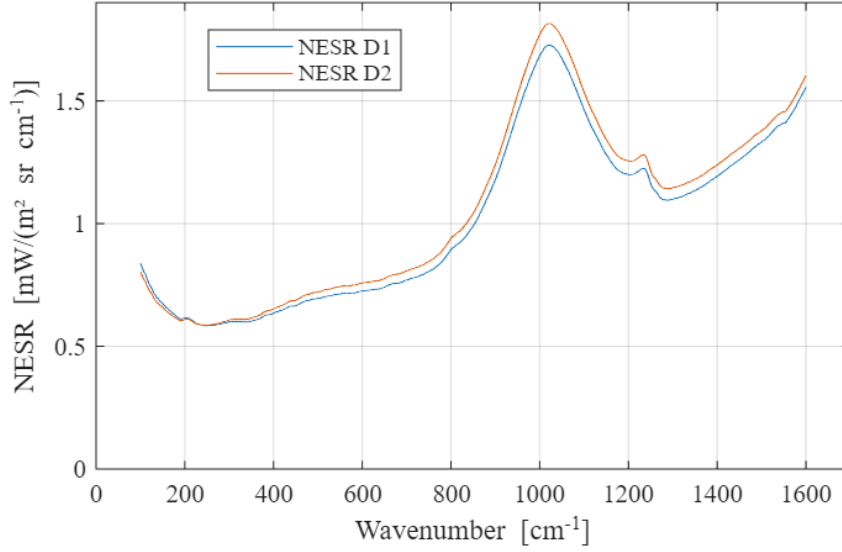


Figure 3.22: NESR of the selected flight detectors (@ EoL and WC condition [18]).

Let's consider two signals, f_1 and f_2 , as the two data streams of the detectors, and their variances $\sigma_{f_1}^2$ and $\sigma_{f_2}^2$. The following properties are true for two uncorrelated signals:

$$\sigma_{f_1+f_2}^2 = \sigma_{f_1}^2 + \sigma_{f_2}^2 \quad \text{and} \quad \sigma_{f_1 \cdot a}^2 = \sigma_{f_1}^2 \cdot a^2 \quad (3.13)$$

where a is a scalar. Hence, if the signals are averaged:

$$f_3 = \frac{f_1 + f_2}{2} \quad \sigma_{f_3}^2 = \frac{1}{4}(\sigma_{f_1}^2 + \sigma_{f_2}^2) \quad (3.14)$$

Therefore, the variance of the average will be lower than the variance of the single measurements. As discussed in Section 2.6.2, to obtain Level 1c products, the spectra acquired by the two detection chains are averaged. Since the NESR represents the standard deviation of the measurements, and due to the uncorrelated nature of the radiometric noise of the two detectors, then according to Eq 3.14, the NESR of the L1c spectra will be:

$$\text{NESR}_{\text{tot}} = \frac{\sqrt{\text{NESR}_{D1}^2 + \text{NESR}_{D2}^2}}{2} \quad (3.15)$$

This averaging process improves the NESR according to Eq 3.4, thus by a factor of $\sqrt{2}$. This is the current baseline for the Level 1c products computation.

This method does not take into account that the quality of the L1b products of D1 is theoretically higher than D2, due to the lower NEP figure. Hence, it is possible to investigate alternatives to the signal averaging of Eq 3.14, to factor in the different NEP performance and potentially identify a technique to improve NESR_{tot} .

This will be explored from Section 3.2.1 to 3.2.3 with three different strategies:

1. The optimal combination of the detectors' signals according to the theoretical NESR performances.
2. The optimal combination of the detectors' signals according to the Level 1b radio-metrically calibrated spectra accuracy.
3. The optimal combination of the detectors' signals at interferogram level, earlier in the Level 1 processing sequence, with respect to the Level 1b average.

Due to the relatively limited difference in the NEP of D1 and D2, it is possible that the simple arithmetic average of Eq 3.15 represents the most effective solution and that other techniques might bring only negligible advantages. It is the scope of this research to verify this statement.

3.2.1. Signal recombination for optimum NESR

Given the different NEPs of D1 and D2, it is possible to investigate a signal recombination technique based on the introduction of a weighted average, to prioritize the signal with a more desirable NESR performance.

Simple weighted average

From Figure 3.21, the NESR of D1 is theoretically lower than that of D2. The most effective way to account for this during averaging is to assign a higher weight to the D1 signal ($L1b_{D_1}$) than to the D2 signal ($L1b_{D_2}$), as follows:

$$L1c = \frac{w_1 \cdot L1b_{D_1} + w_2 \cdot L1b_{D_2}}{w_1 + w_2} \quad (3.16)$$

$$NESR_{L1c} = \frac{\sqrt{w_1^2 \cdot NESR_{D_1}^2 + w_2^2 \cdot NESR_{D_2}^2}}{w_1 + w_2} \quad (3.17)$$

where w_1 and w_2 are scalar weights. To identify the optimal signal recombination, the value of w_2 is fixed at $w_2 = 1$, while a simple research for w_1 is performed. For each combination of the weights, the $NESR_{L1c}$ is retrieved according to Eq 3.17. The selected value for w_1 is the one yielding the lower value of the $NESR_{L1c}$ mean.

The benefits of this averaging method in terms of NESR, and the associated weights are reported in Section 3.2.4.

Weighted average wavelength dependent

Among the selected flight detectors, D1 shows the best overall performance in terms of NEP, as shown in Figure 3.21, but the advantage on D2 is not constant over the observational bandwidth. At lower modulation frequencies (i.e. <50 Hz or 245 cm^{-1}), D2 is slightly over performing D1. This can be taken into account in the signal recombination with the introduction of a wavelength dependant weighted average, that will prioritize the signal collected by D2 at lower frequencies, while D1 will be associated to higher weights in the rest of the spectral band.

The optimum combination factor for each wavelength σ can be analytically retrieved from Eq 3.18, by fixing $w_2 = 1$ and computing w_1 through the first derivative of the NESR:

$$\text{NESR}_{\text{L1c}}(\sigma_i) = \frac{\sqrt{w_1^2(\sigma_i) \cdot \text{NESR}_{D_1}^2(\sigma_i) + \text{NESR}_{D_2}^2(\sigma_i)}}{w_1(\sigma_i) + 1} \quad (3.18)$$

$$\frac{\partial \text{NESR}_{\text{L1c}}(\sigma_i)}{\partial w_1(\sigma_i)} = 0 \quad \rightarrow \quad w_1(\sigma_i) = \frac{\text{NESR}_{D_2}^2(\sigma_i)}{\text{NESR}_{D_1}^2(\sigma_i)} \quad (3.19)$$

The weight factors over the bandwidth and the NESR performance associated with this signal recombination strategy are reported in Section 3.2.4.

3.2.2. Signal recombination for optimum Spectra accuracy

The signal techniques presented in Section 3.2.1 take into account the different detectors' NEP to identify the combination yielding the best NESR performance, i.e. the lowest radiometric noise. Alternatively, it is possible to investigate additional recombination techniques to achieve the best accuracy of the L1c spectra compared to the original observed scene.

The Instrument Simulator Module (ISM), described in Section 2.6.1, processes a high resolution input spectra through the transfer function of the FSI, taking into account disturbance factors and the resolution limitations of the instrument. The corresponding interferograms, simulated by the ISM, are post processed with the Level 1 Processing Module (L1PM), where they are converted into radiometrically calibrated spectra.

The spectra of each detector (i.e. L1b products) can be compared with the high resolution input scene of the ISM, downsampled at the same spectral resolution of the FSI, as shown in Figure 3.23. By computing the Root Mean Square of the spectra difference, a preliminary estimation of the instrument accuracy is retrieved.

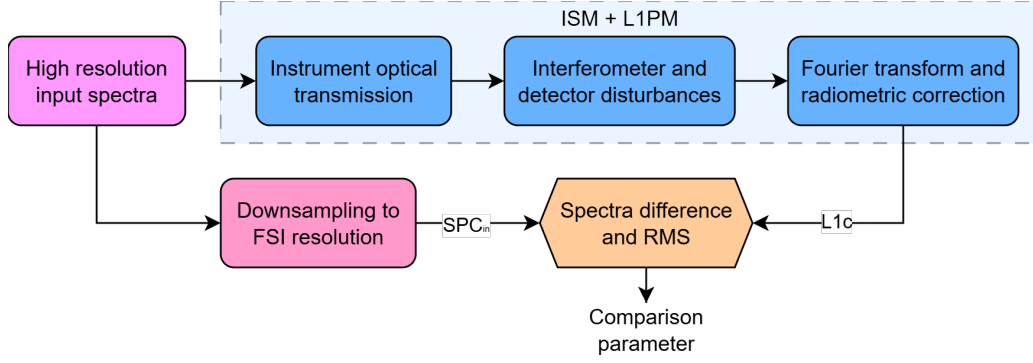


Figure 3.23: Comparison of input scene with instrument simulator output.

This procedure is applied to various signal averaging techniques, to identify the method yielding the highest L1c spectra accuracy.

Simple weighted average

The L1PM, representing the current processing baseline, obtains the Level 1c products with an arithmetic mean of the spectra recorded by the two detectors of the FSI. Since one of the two L1b product has been recorded by a detector with a lower NEP figure, it is worth to investigate the benefits of increasing the weight of this measurement in the average. The weighted average is implemented as:

$$\text{L1c} = \frac{w_1 \cdot \text{L1b}_{D1} + w_2 \cdot \text{L1b}_{D2}}{w_1 + w_2} \quad (3.20)$$

The resulting L1c spectra is compared with the input spectra SPC_{in} , by computing Δ_{rms} , the RMS of their difference for each spectral sample σ_i over the total of N samples:

$$\Delta_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^N (\text{L1c}(\sigma_i) - \text{SPC}_{in}(\sigma_i))^2} \quad (3.21)$$

A simple search algorithm to identify the optimum weights has been implemented. The combination of w_1 and w_2 yielding the best result in terms of smaller Δ_{rms} is saved. The results of this averaging technique are presented in Section 3.2.4.

Weighted average wavenumber dependent

As for Section 3.2.1, a wavenumber dependant search is implemented for the determination of the optimum weight factors. Eq 3.20 thus becomes:

$$\text{L1c}(\sigma_i) = \frac{w_1(\sigma_i) \cdot \text{L1c}_{D1}(\sigma_i) + w_2(\sigma_i) \cdot \text{L1c}_{D2}(\sigma_i)}{w_1(\sigma_i) + w_2(\sigma_i)} \quad (3.22)$$

With a simple search algorithm it is possible to identify the best values for w_1 and w_2 for each spectral sample. The results of this averaging technique in terms of Δ_{rms} and improvement from the arithmetical averaging are presented in Section 3.2.4.

Comparison among different input scenes

The proposed L1b averaging strategies determine optimal spectral weights $w_1(\sigma)$ and $w_2(\sigma)$ that best reproduce the simulator's input spectrum. The improvement in Δ_{rms} depends on using those optimal, frequency-dependent weights. Because the weights are derived from a simulated input scene whose true spectra is known, it is necessary to verify whether the same weights remain valid for arbitrary, real observations. In operational conditions, the true scene spectrum is unknown, so the approximation accuracy cannot be directly verified. If the identified weights are scene-independent, they can be safely applied operationally; otherwise, their use may lead to biased or suboptimal results.

As discussed in Section 2.6.1, the instrument simulator enables the selection of multiple input scenes, representative of a broad range of Earth observation conditions. To evaluate the effectiveness of the optimum weight factors, the optimization process described in Section 3.2.2 is repeated for six additional input scenes. This allows to assess if a consistent trend can be identified among the resulting weight combinations. The outcomes of this complementary analysis are presented in Section 3.2.4.

3.2.3. Signal recombination through interferogram averaging

The current Level 1 processing baseline performs the averaging of the detector signals after the Fourier transform and radiometric correction. This approach is considered a reliable and robust solution, as it handles the two signals independently, allowing for detector-specific corrections prior to recombination. However, from an error propagation standpoint, this approach is sub-optimal, since signal processing approximations and non-linearities can introduce additional errors, thereby amplifying the inaccuracies already present in the measurements. If the signals are averaged at an earlier stage, the noise level is reduced from the outset, and the subsequent amplification of inaccuracies introduced by

signal processing becomes less significant. From a theoretical perspective, this alternative processing technique would yield higher measurement quality compared to the baseline approach.

To investigate if this technique provides non-negligible benefits to the Level 1 products, the ISM has been modified to perform the signal averaging at an earlier stage. The detectors D1 and D2, although inherently similar, are not characterized by the same transfer function. In the baseline Level 1 processing, shown in Figure 3.24, this detector-dependant difference is corrected through the application of the inverse of the BTDA transfer function at interferogram level, as described in Section 2.6.2. This constrains the signal merger stage: performing the averaging before applying the BTDA inverse would prevent proper compensation of detector-dependent responses, potentially introducing significant inaccuracies. Therefore, the selected signal combination approach is the one presented in Figure 3.25.

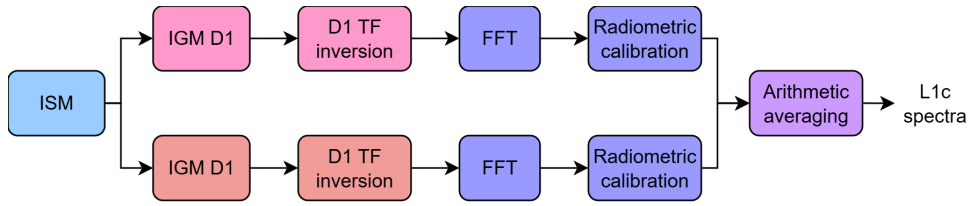


Figure 3.24: Level 1 processing sequence (*Spectra averaging*).

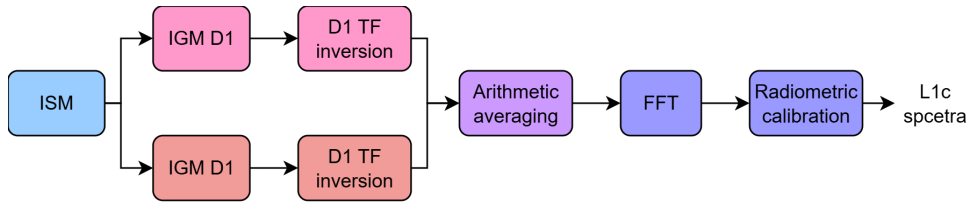


Figure 3.25: Level 1 processing sequence (*Interferogram averaging*).

This approach applies detector-dependent corrections and then to perform a signal average at an earlier stage, for noise reduction. This procedure is applied to the interferograms acquired during Earth observation as well as to the calibration measurements. After the application of the Fourier transform routine and the radiometric calibration, the resulting spectra is compared to the input scene of the simulator with Eq 3.21. The results of this signal averaging strategy are presented in Section 3.2.4.

3.2.4. Results: Differing detector NEP and signal recombination strategies

The differing NEP performance of the FSI detectors has been exploited to investigate an improvement of the FSI performances. This section collects the results relative to this study.

Optimum NESR averaging

The differing detectors' NEP can be taken into account to improve the NESR of L1c products with a weighted average:

- Simple weighted average: the optimum weights are $w_1 = 1.0796$ and $w_2 = 1$. As expected, the Detector 1 (D1) has a higher weight in the average, reflecting the more beneficial NEP performance of Figure 3.21.
- Wavenumber-dependent weighted average: the optimum weight factor for each spectral sample results in the w_1 over the FSI bandwidth of Figure 3.26. w_2 fixed at 1 for the whole bandwidth. As expected, $w_1 > 1$ above 200 cm^{-1} , where the NEP of D1 is lower than the NEP of D2.

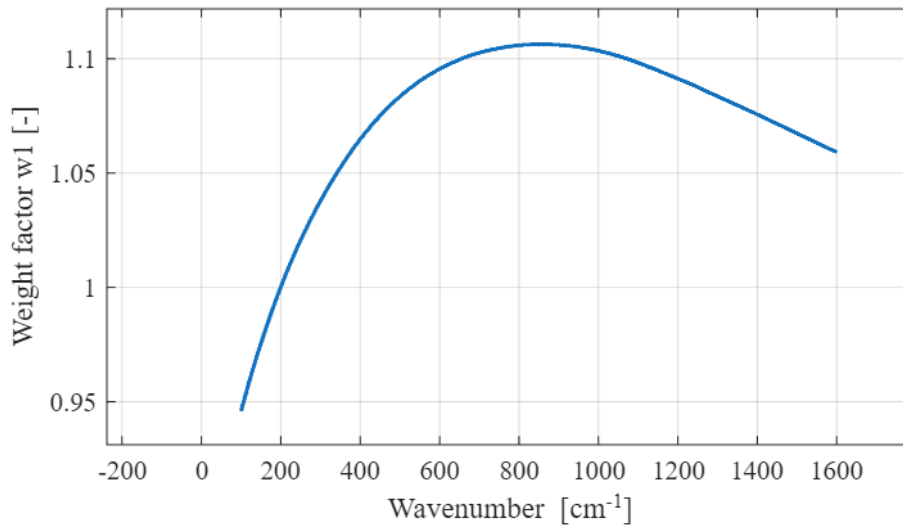


Figure 3.26: w_1 over the FSI bandwidth for optimum NESR combination.

The signal recombination through weighted average results in the NESR performance of Figure 3.27.

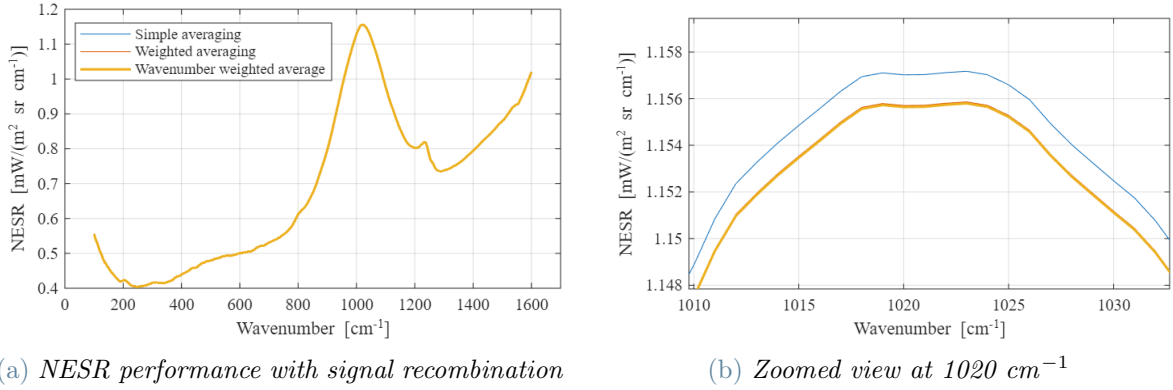


Figure 3.27: NESR performance with different signal recombination techniques: (a) shows the performance over the whole bandwidth, (the three NESR are superimposed due to the limited improvement), (b) reports a zoomed view at 1020 cm^{-1} , showcasing the minor difference.

The difference among the three methods is minor and the improvements are limited to an order of magnitude of 0.1%, as demonstrated in Figure 3.28.

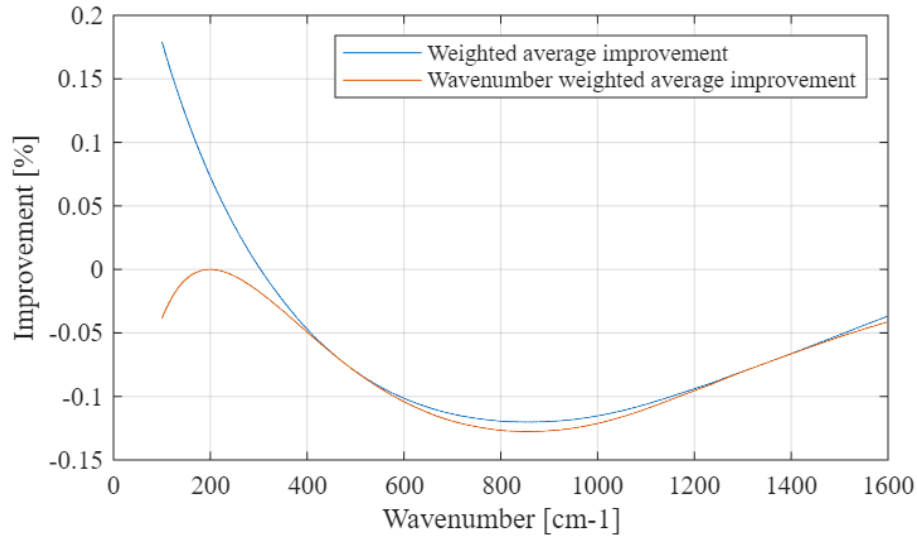


Figure 3.28: Deviation in percentage from the NESR performance obtained through arithmetical averaging. A more beneficial (i.e. lower) NESR yields a negative deviation.

The NESR computed using the simple weighted average exhibits a degraded performance (i.e. positive variation in percentage) compared to the arithmetic average below 200 cm^{-1} , since Detector 2 (D2) is associated to a more beneficial NEP compared to Detector 1 (D1) in this specific spectral band. The wavenumber-dependent combination strategy optimizes the weighting for each wavenumber, effectively accounting for the spectral variations in the detector performance. This method yields an improvement across the entire bandwidth, although the gain is marginal, limited to approximately 0.1%.

Optimum spectra accuracy averaging

The difference in the NEPs has been exploited to investigate an improvement of the quality of the L1c products, in terms of accuracy with respect of the input spectra of the simulation:

- Simple weighted average: if the two L1b products are merged in a detector dependant manner, the optimum weights identified are $w_1 = 0.999$ and $w_2 = 1$. Unexpectedly, the optimum combination is found associating almost the same weight to both detectors, thus potentially indicating that the differential NEP brings negligible differences in the spectra accuracies.
- Wavenumber-dependent weighted average: when the two L1b products are merged by computing an optimum weight factor for each individual spectral sample, the resulting w_1 distribution over the FSI spectral range is shown in Figure 3.29 (with w_2 fixed at 1). The average of w_1 is 1.02, aligning with theoretical expectations, as a slightly higher weight is assigned to the measurements acquired by the detector with the superior NEP (D1). This suggests that the wavelength-independent approach may lack the sensitivity required to fully distinguish the higher quality of the spectra acquired with D1 compared to D2, that are on the contrary observable with the Wavenumber-dependent weighted average.

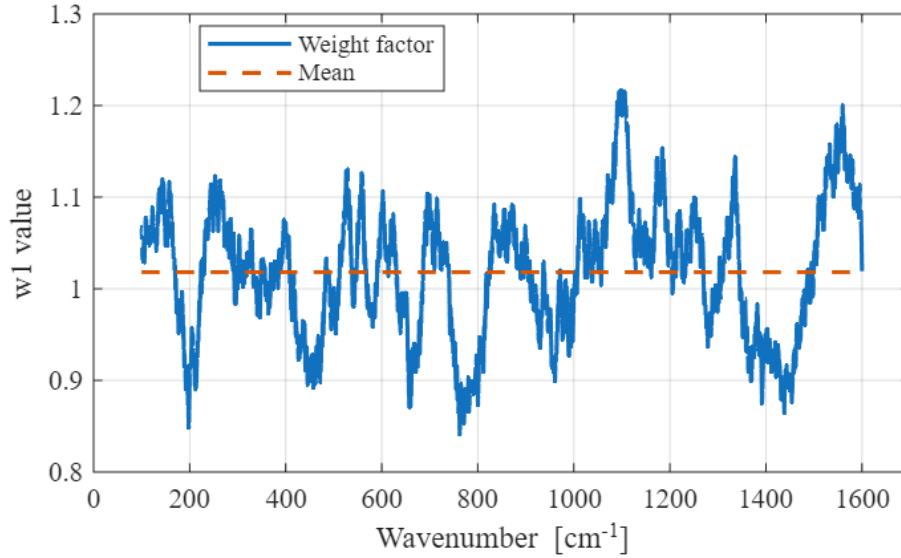


Figure 3.29: w_1 over the FSI bandwidth for optimum spectra combination.

The effectiveness in terms of accuracy of each method is retrieved by computing the RMS of the difference between the spectra resulting from the weighted combination and the input spectra of the ISM. The results are plotted in Figure 3.30.

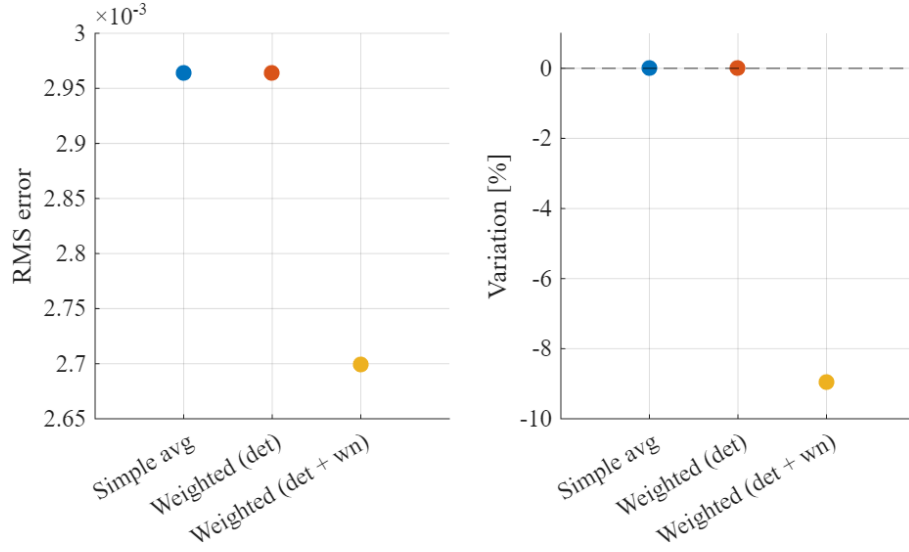


Figure 3.30: Accuracy of averaging methods and improvement in percentage. A higher accuracy translates into a negative variation. Weighted (det + wn) stands for wavenumber-dependent weighted average.

The weighted average presents similar performances compared to the arithmetical average, with differences non visible at the scale of the plot (refer to Figure 3.32 for a smaller scale, where the improvement can be observed). The wavenumber-dependent weighted average is characterized by a substantial improvement in accuracy of 9%.

This results from the w_1 identified in Figure 3.29; to verify the effectiveness of this method, w_1 is computed for several input scenes, to assess if the combination factor is constant and the improvements are consistent. The resulting w_1 , and their mean trend, are reported in Figure 3.31.

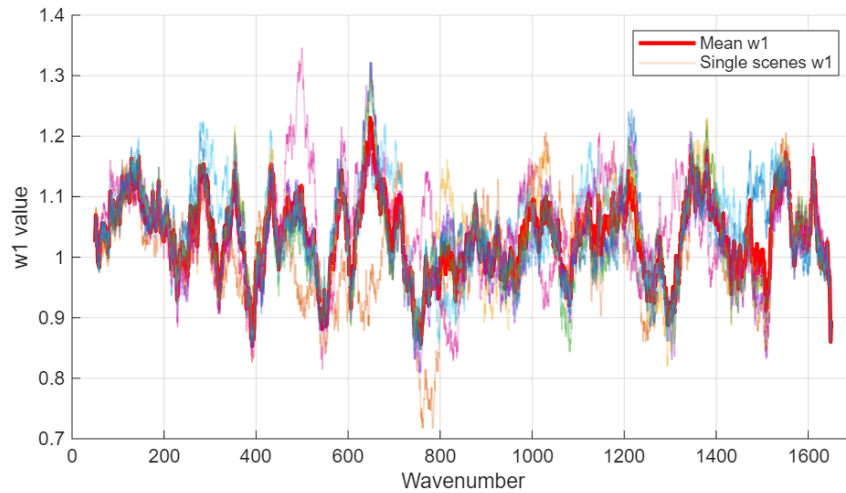


Figure 3.31: w_1 over the FSI bandwidth computed over multiple input scenes (semi-transparent lines). Mean w_1 over all the input scene represented by red line

The w_1 trends show a relatively large variability. If the mean w_1 is used to retrieve a wavenumber-dependent weighted average of the L1b spectra, then the improvement of 9% is lost, and a lower accuracy compared to the arithmetical average is observed (Figure 3.32). This suggests that the advantage of the wavenumber-dependent weighted average of Figure 3.30 is specific to the input spectra and cannot be applied to each dwell during Earth observation.

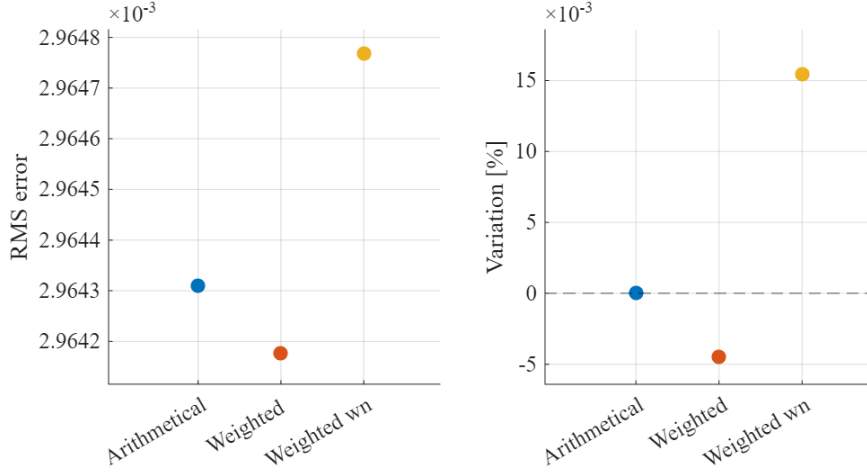


Figure 3.32: Accuracy of averaging methods and improvements. Weighted wn now computed with mean w_1 of Figure 3.31. A higher accuracy translates into a negative variation.

Interferogram averaging

The interferogram (IGM) averaging technique merges the detector outputs at an earlier stage of the signal processing. The resulting effectiveness is presented in Figure 3.33.

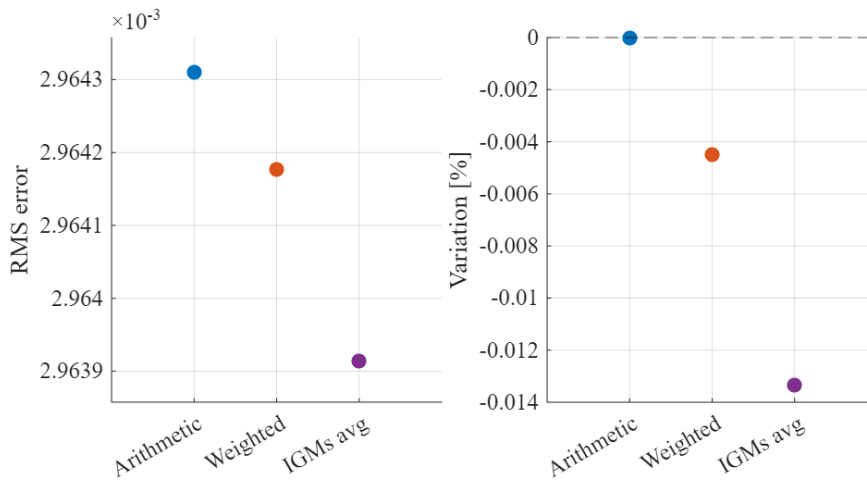


Figure 3.33: Comparison of the accuracies of averaging methods over the spectra with respect to averages of the interferograms, and relative improvement in percentage. A higher accuracy translates into a negative variation.

The IGM averaging has a marginal improvement both compared to the arithmetical average and the simple weighted average (wavenumber independent), up to 0.014%. The slight advantage of this method however can be reached only with a less robust signal processing technique, where detector dependent corrections are more complex to apply due to the early averaging stage. Therefore, due to the higher risk associated to this method compared to the baseline signal processing of the FSI, and the very marginal advantage in terms of accuracy, the IGM merger is likely to represent a sub-optimal solution.

3.3. Impact of speed fluctuations - BTDA transfer function knowledge

It is well established in the literature that interferometer speed fluctuations are among the main disturbance sources affecting Fourier Transform Spectrometers [14, 24]. Their main effect is the introduction of potentially large radiometric noise, thus contributing to the total NESR. Given the stringent accuracy and NESR requirements of the FORUM Sounding Instrument, it is crucial to assess their impact on data quality and verify whether the current design and processing strategies are adequate for their mitigation and correction. As discussed in Section 2.4.1, the Interferometer Assembly moves the mirrors on the pendulum from +MPD to -MPD and vice versa, depending on the scan direction, with a constant speed of 0.204 cm/s [18]. The movement is controlled by a feedback loop, that maintains the scan speed as close as possible to the nominal value. However, it is not possible to achieve exactly the desired scan profile, since multiple disturbances induce micro vibrations, whose effect cannot be immediately and perfectly counterbalanced by the control loop. For a spaceborn FTS instrument, the main sources of speed fluctuations will be mechanical, from vibrations of other moving components (e.g. SCU) or the platform attitude control, as well as imperfections in the drive mechanism. A representation of the simulated IA speed under the effect of 1 % speed fluctuations is reported in Figure 3.34.

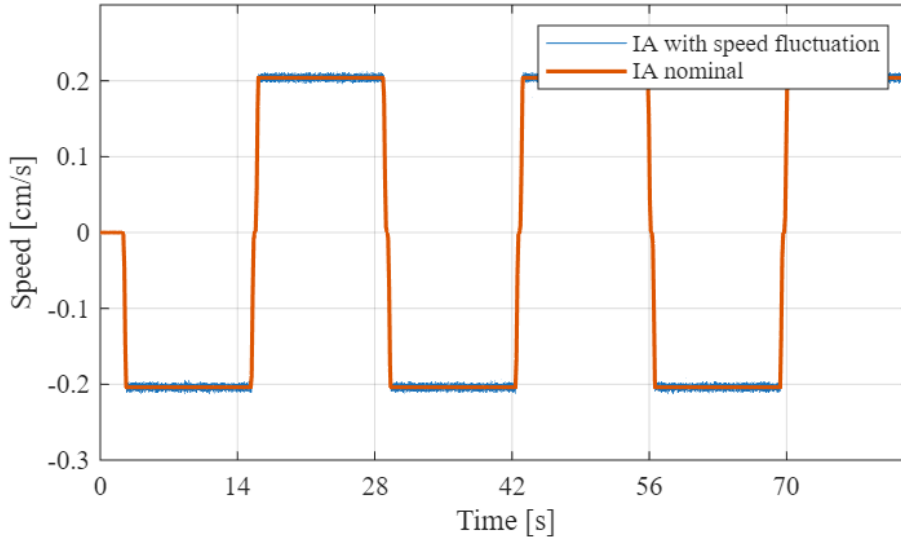


Figure 3.34: *IA scan speed over time under the effect of 1% speed fluctuations.*

To assess how speed fluctuations impact the measurement, it is necessary to introduce the concept of ghosts generations from phase modulations.

3.3.1. Ghosts generation

This section outlines the phenomenon of ghost image generation due to speed fluctuations in the interferometer mirrors movement. A theoretical derivation is provided, along with a simulation applied to the FSI.

Let's consider a purely monochromatic cosine signal at a modulation frequency $f_0 = \sigma_0 \cdot v$. If the scan speed v is constant, the OPD varies linearly, causing a linear variation of the phase of the signal, due to the different optical path covered in the interferogram. This results in a measurement $I(t)$ equal to:

$$I(t) = \cos(2\pi f_0 t) \quad (3.23)$$

the introduction of a periodic speed fluctuation at frequency f_m , for example from an oscillating platform component, causes the mirror speed to oscillate around its mean value. As a result, the OPD increases in time with a modulation at the same frequency, and the phase of the signal will follow the same behaviour, as illustrated in Figure 3.35b.

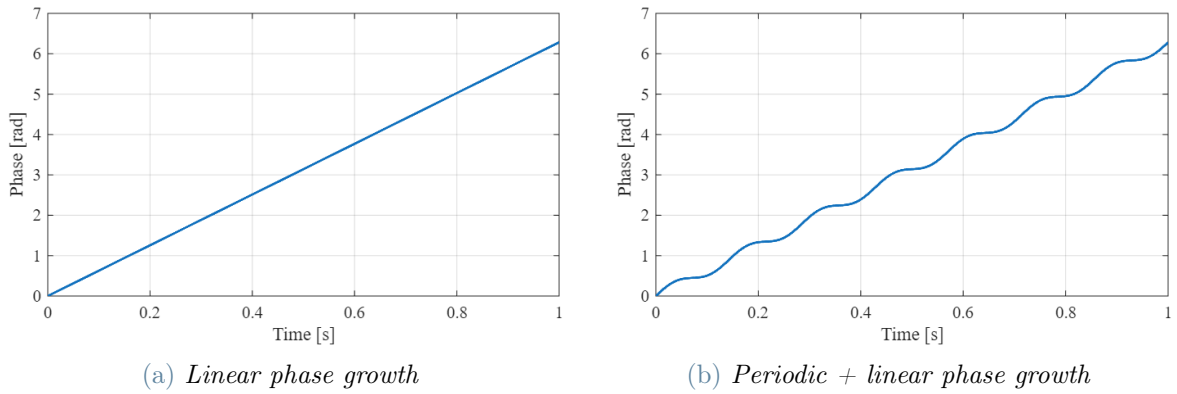


Figure 3.35: Phase growth over time: (a) represents an undisturbed 1 Hz signal, (b) is the same signal with 10 Hz speed fluctuations.

The recorded interferogram can now be expressed as:

$$I(t) = \cos(2\pi f_0 t + \sin(2\pi f_m t)) \quad (3.24)$$

For convenience, this can be represented with Euler's notation:

$$I(t) = \text{Re} \{ e^{j2\pi f_0 t} e^{j\sin(2\pi f_m t)} \} \quad (3.25)$$

According to the Jacobi-Anger identity, the exponential of a sinusoid, such as $e^{j\sin(2\pi f_m t)}$, can be expressed as a weighted sum of its harmonics, therefore:

$$e^{j\sin(2\pi f_m t)} = \sum_{n=-\infty}^{n=+\infty} J_n e^{nj2\pi f_m t} \quad (3.26)$$

where J_n are Bessel functions of the first kind, acting as weights and $e^{nj2\pi f_m t}$ are harmonics of the original function. Then:

$$I(t) = \text{Re}\left\{ \sum_{n=-\infty}^{n=+\infty} J_n e^{j2\pi(f_0 + nf_m)t} \right\} \quad (3.27)$$

$$I(t) = \sum_{n=-\infty}^{n=+\infty} J_n \cos(2\pi(f_0 + nf_m)t) \quad (3.28)$$

The original signal, a pure cosine, under the influence of a periodic speed fluctuation has become a sum of cosine waves, at frequency $f_n = f_0 + nf_m$. Each cosine at frequency f_n with $n \neq 0$ is a sideband of the signal, referred in the literature and in this document as a ghost.

In an FTS instrument without speed fluctuation, a monochromatic wave at f_0 will yield the ILS as output, approximately a sinc wave centred at f_0 . If speed fluctuations are affecting the retrieval, multiple ghosts of the original signal will be visible periodically in the spectrum every $\pm nf_m$, as represented in Figure 3.36.

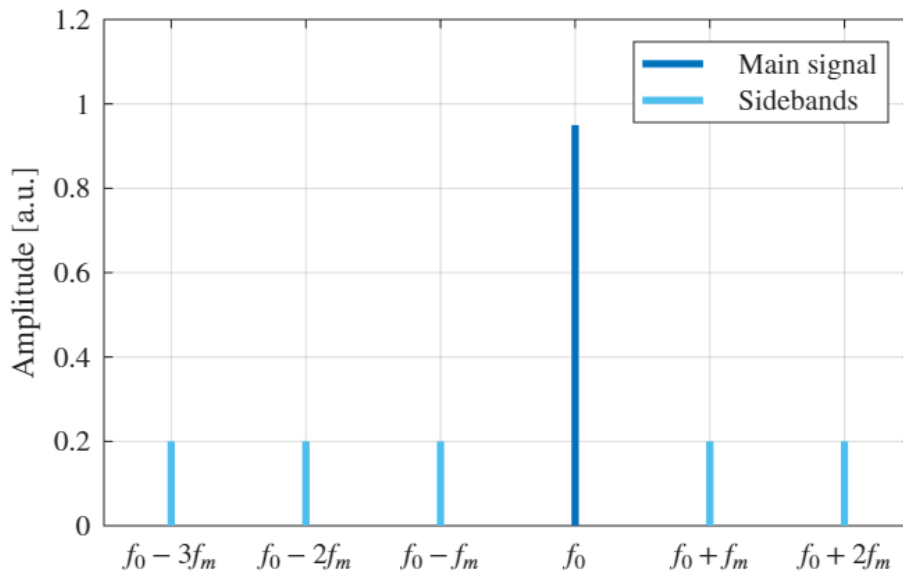


Figure 3.36: Schematic representation of the periodic nature of ghosts of a signal at f_0 . Under the effect of speed fluctuations, sidebands of the signal are generated at $\pm nf_m$.

Assessment of ghosts presence on FSI's ISRF

The generation of ghosts is a theoretical consequence of speed fluctuations in an ideal FTS instrument. However, their presence and significance in a real system such as the FSI must be verified, as other concurrent disturbances can produce similar effects, distorting the signal and potentially masking the ghost signatures.

To simplify the analysis, the following setup of the ISM has been implemented:

- Input scene: single emission line with amplitude of $100 \text{ mW}/(\text{m}^2 \text{ sr cm}^{-1})$ at 600 cm^{-1} , with a width of 0.5 cm^{-1} . The signal cannot be purely monochromatic since the FSI has a limited spectral resolution. Setting the width of the input signal at 0.5 cm^{-1} ensures its detection. The output of an almost monochromatic signal will be a close representation of the ISRF of the FSI, defined in Section 2.3.4.
- Speed fluctuations: periodic speed fluctuations with a frequency of 4 Hz and a maximum amplitude of 2% of the nominal speed. The selected amplitude is in accordance with the maximum estimated fluctuations that are expected to be observed in the FSI, according to experimental data.
- Detectors electrical noise: inactive, to limit the noise in the output data and increase the likelihood of detecting ghosts images.

The speed fluctuations are selected with a frequency of $f_m = 4 \text{ Hz}$ simply for ease of detection in the output data. As discussed in Section 3.3.1, speed fluctuations have a periodic effect on the output spectrum, generating ghost images every $f_n = f_0 + nf_m$. Since the output spectrum of the L1PM is expressed in wavenumber, and not in modulation frequency, this means that the ghosts are expected every 19 cm^{-1} , according to Eq 3.8.

Ideally, one could detect ghosts by comparing the measurements from two simulations performed with and without speed fluctuations, and computing the output spectra difference. However, this approach is not feasible for the FSI, as several unavoidable disturbances intrinsic to its architecture (e.g. beamsplitter imperfections, radiometric correction inaccuracies, numerical processing approximations) introduce additional noise dependant on the specific simulation, that therefore would mask the ghosts signatures. Nevertheless, this approach was attempted and the results are reported in Section 3.3.4.

The most effective method to filter additional disturbances and detect ghosts is:

1. The ISM is executed with the specified speed fluctuations. Interferograms at detector level are saved.
2. The L1PM processes the ISM output with the accurate BTDA transfer function (BTDA TF) inverse, FFT and radiometric correction. L1b products are saved.

3. The L1PM reprocesses the same ISM output using a slightly inaccurate BTDA TF inverse, followed by Fourier transform and radiometric correction. Because the impact of speed fluctuations depends on the BTDA TF application (as detailed in Section 3.3.2), the resulting L1b product will differ from the correctly processed spectra through the presence of ghosts.
4. The difference between the L1b products processed with the two different BTDA TF is computed for ghosts detection.

The results of this analysis are reported in Section 3.3.4.

3.3.2. Speed fluctuations and transfer function knowledge

To comprehensively assess the impact of speed fluctuations on the Level 1 data quality, two aspects have been characterized due to their relevance for measurement accuracy:

1. Knowledge accuracy of the BTDA TF [22].
2. Amplitude of random and periodic fluctuations recorded in the IDEM test campaign [25].

This section outlines the sensitivity study to assess the impact of the BTDA TF knowledge on the Level 1 products. The analysis concerning the amplitude of both random and periodic speed fluctuations is presented in Section 3.4.

As briefly anticipated during the evaluation of ghost artifacts in the instrument ILS, the BTDA TF is closely linked to the aliasing effects introduced by speed fluctuations.

To perform this analysis, it is necessary to introduce the concept of group delay.

The effect of group delay

Since the FSI detectors have a non-zero response time, the signal is not measured instantaneously. This is because the physical mechanisms underlying the detection, such as charge generation, thermal diffusion, or polarization changes in the detector material, require a finite amount of time to react to variations in the incoming optical power [13].

As a result, the detector output is delayed with respect to the true signal.

This phenomenon is represented by group delay, defined as the negative rate of change of transmission phase angle δ with respect to frequency f :

$$Group\ Delay = -\frac{\partial\delta(f)}{\partial f} \quad (3.29)$$

Formulated alternatively, a detector applies a phase delay to the recorded signal, that in turns causes a delay in time of its detection, expressed by the group delay. Since the phase delay $\delta(f)$ depends on the frequency f , then the group delay will not be constant over the bandwidth.

Since the phase response is specific of each detector, this means that also the group delay will be, as shown in Figure 3.37.

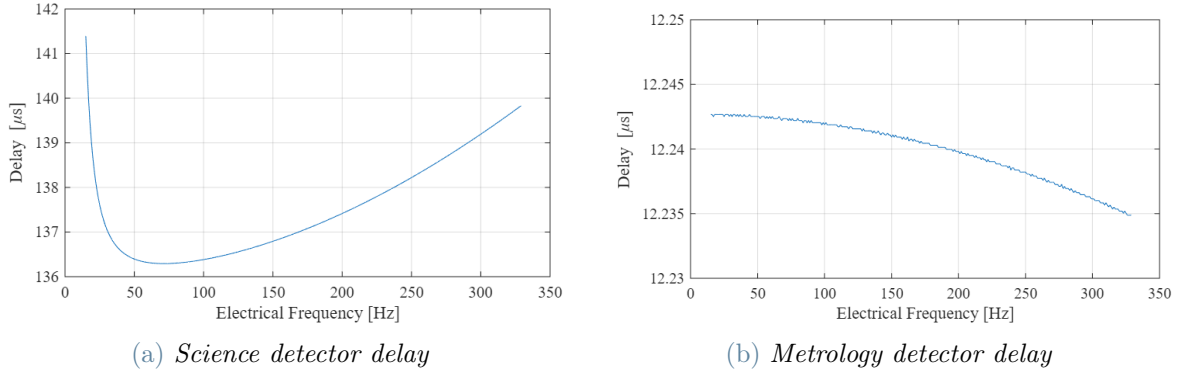


Figure 3.37: FSI detectors delays [18]: (a) represents the group delay of the science detector, (b) the group delay of metrology detector.

As described in Section 2.6.2, the signals acquired by the science and reference detectors need to be resynchronized and aligned for accurate OPD reconstruction. Since the detectors exhibit different group delays, precise knowledge of their relative difference is essential. Any mismatch directly propagates into the OPD reconstruction, introducing significant phase errors.

For the FSI, the post-processing delay compensation is done through the application of the BTDA TF inverse. Here the effect of speed fluctuations comes at play. As anticipated in Section 3.3.1, a signal at wavenumber σ_1 is modulated to a signal at frequency f_1 through the interferometer nominal speed v_1 : $f_1 = \sigma_1 \cdot v_1$. If the speed is subject to fluctuations, the signal will be modulated to a different modulation frequency $f_2 = \sigma_1 \cdot v_2$. Since the group delay is dependant on the frequency f , this means that the same signal will be recorded with two different delays.

For example, let's consider a signal at 1300 cm^{-1} . The nominal speed of the IA is 0.204 cm/s , therefore the modulation frequency will be 265 Hz . If a 10% speed fluctuation is introduced, then $f_2 = 1.1 \cdot \sigma_1 \cdot v_1 = 290 \text{ Hz}$. The group delay associated to these two modulation frequencies is not the same, as shown in Figure 3.38.

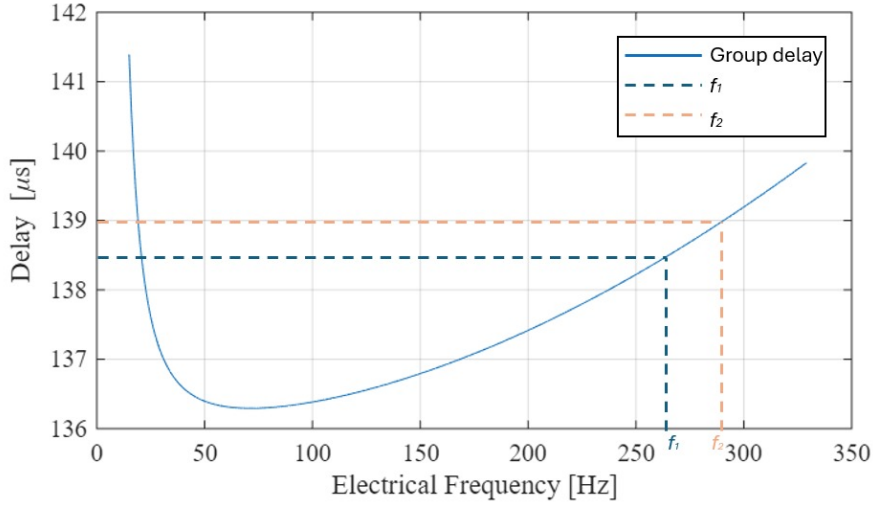


Figure 3.38: Modulation frequency shift of a signal at 1300 cm^{-1} (corresponding to f_1) under the effect of 10% speed fluctuation.

This variability over the bandwidth poses a problem for Level 1 processing, as the energy of a signal originally at a specific modulation frequency is partially shifted to another frequency band with a different delay. Consequently, when the BTDA TF inverse is applied, the compensation becomes imperfect, preventing accurate reconstruction of the original signal.

Ideally, to overcome this issue, the BTDA TF should be designed to produce a group delay as flat as possible. If this is the case, then speed fluctuations do not couple with uneven delays to create additional errors, but their effect remains limited to the ghosts generation described in Section 3.3.1. Efforts were made to design a BTDA TF to be as flat as possible, and a relatively small delay difference was achieved, as shown in Figure 3.37. However, since a non negligible delay spread is still present, the effect of speed fluctuation in relation with the group delay has to be verified.

Sources of BTDA TF knowledge inaccuracies and effects

During Level 1 processing, the inverse of the BTDA TF is applied for delay compensation. To guarantee the best correction possible, the inverse of the exact TF used in the ISM should be applied. However, in a real operational scenario, it is not possible to apply the exact inverse of the TF. There are several factors that limit the knowledge accuracy:

- The TF characterization is done on ground with a dedicated set of sensors to measure the amplitude and phase responsivity to a known input signal. The knowledge accuracy will depend by the accuracy of the sensors for the characterization [22].

- The TF is not constant over time, but it will be subject to a deviation from BoL to EoL, dependant impact of radiations on the detector. The BTDA TF and electronics are designed to guarantee a limited deviation over mission lifetime, but this will nevertheless be a source of additional uncertainty.

Any knowledge inaccuracy will inevitably result in an imperfect delay correction, thus amplifying the errors due to the speed fluctuations, and potentially introducing inaccuracies from the imperfect delay compensation between the reference and science signals. Figure 3.39 graphically represents the expected effect on the ISRF of a high inaccuracy in the BTDA TF knowledge; the ghosts generated by the speed fluctuations will be amplified, and the main peak representing the original signal will be attenuated, since energy will be moved to other regions of the spectrum.

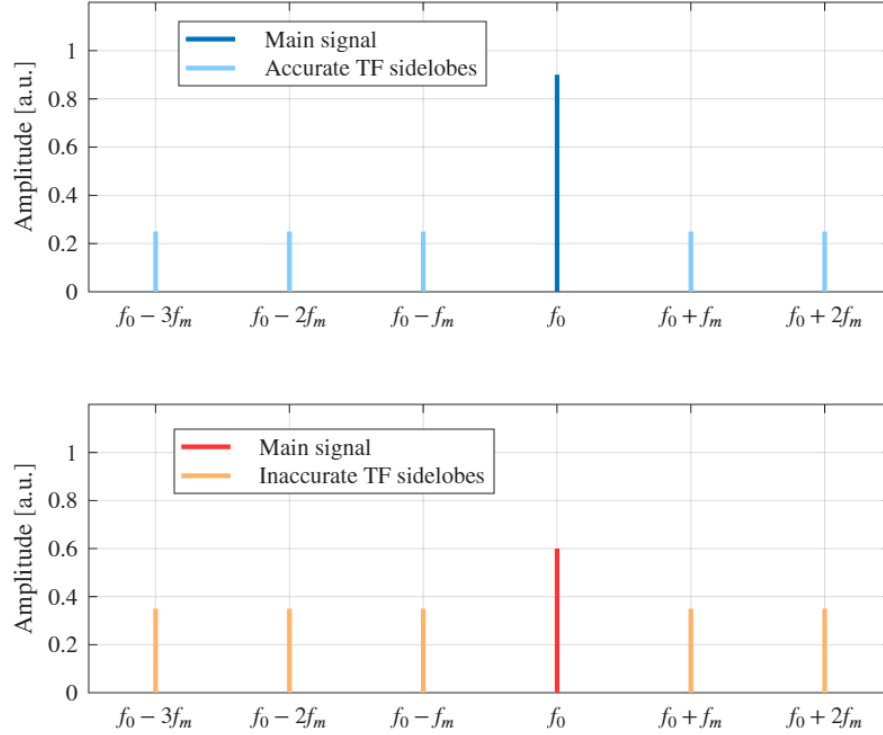


Figure 3.39: Ghosts on the ISRF with accurate (top) and inaccurate (bottom) TF knowledge, qualitative representation.

As the error on the TF knowledge is introduced during the data post-processing, and not during the actual acquisition, the periodicity of the ghosts should remain constant, while their amplitude should vary depending on the inaccuracy of the transfer function.

The test setup described in Section 3.3.1 for assessing the presence of ghosts in the ISRF is employed, repeating the analysis with a highly inaccurate BTDA TF. The resulting ghost levels are reported in Section 3.3.4.

3.3.3. Assessment of TF knowledge inaccuracies impact

In the previous sections, it was described how speed fluctuations generate ghosts in the ISRF, and how the TF errors amplify their magnitude; so far, an almost ideal instrument behaviour has been considered, with no external disturbances except speed fluctuations and with a spectrally thin input. To assess the impact of errors on the knowledge of the BTDA TF for the specific case of the FSI, a more representative simulation is implemented. The ISM has been modified to include the following aspects:

- Input scene: a high resolution atmospheric emission spectra, with thin spectral signatures, representative of the expected Earth emissions at ~ 300 K
- Interferometer and OPD acquisition: all the disturbance sources are active. These include: speed fluctuations (1% randomic), dynamic shears of the optical beam, metrology beam line width fluctuations.
- Detectors: both the electrical noise of the science and reference detectors are active.
- Transfer function: the best estimate of the BTDA TF, according to the current knowledge, is applied to generate the interferograms of each detector.

The ISM is run only once, and its outputs are stored for later use. The sensitivity analysis is carried out by processing the ISM data in the L1PM multiple times, with different configuration settings. The amplitude and stochastic characteristics of the speed fluctuations used in this study are kept constant across all simulations; a dedicated investigation on amplitude and properties of the speed instabilities based on experimental data is provided in Section 3.4. The fluctuation profile adopted is considered representative of real operations, as it originates from tests performed on an FSI interferometer mock-up, the Instrument Demonstrator (IDEM), described in Section 3.4.

The L1PM takes into account detector-dependant properties by applying the inverse of the BTDA TF to the ISM outputs. To assess the tolerance of the FSI to errors in the knowledge of the BTDA TF, the ISM data is processed with a series of increasingly incorrect transfer functions, each with an increased group delay with respect to the real TF. The inaccurate results are compared to the correct L1PM output obtained by applying to the input data the inverse of the same BTDA TF used in the ISM.

The inaccuracies in the TF are introduced with a linear variation of the phase response of the detectors. According to Eq 3.29, this introduces an offset modification of the group delay, as shown in Figure 3.40.

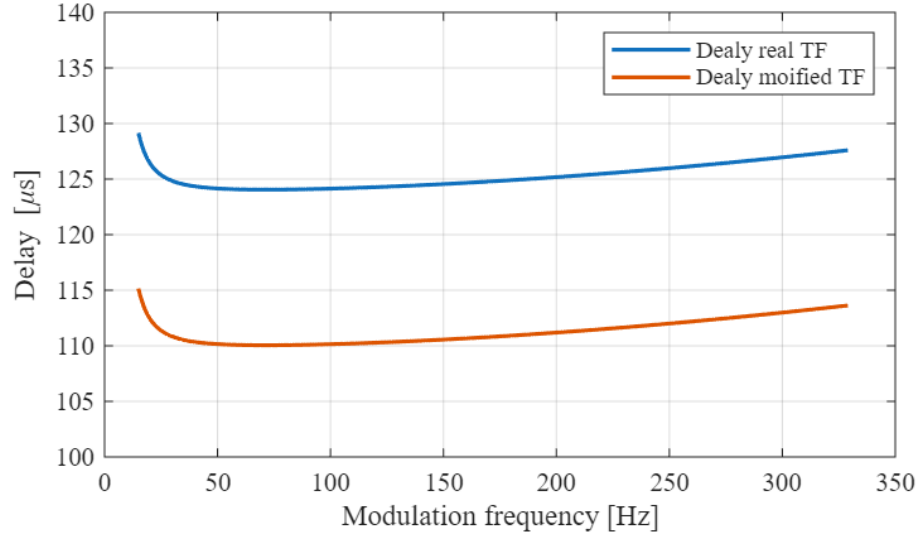


Figure 3.40: BTDA TF group delay: blue line is the correct TF, orange line is the TF with a 25 μs delay inaccuracy.

Although the delay has a constant offset compared to the correct value, the impact over the bandwidth is not expected to be equally constant. The root cause is that a speed fluctuation does not cause the same variation of modulation frequency at low or high wavenumbers. For example, a signal at 200 cm^{-1} subject to a 10% speed fluctuation around the mean value of 0.204 cm/s will be modulated between 36.7 Hz - 44.9 Hz ; a signal at higher wavenumbers, such as at 1400 cm^{-1} , will be modulated between 257.4 Hz - 314.2 Hz . The larger range of modulation frequencies is associated to a higher deviation of the corresponding group delays, therefore the inaccuracies are expected to be more significant at high wavenumbers. The L1PM processing and comparison strategy for the sensibility study is reported in Figure 3.41.

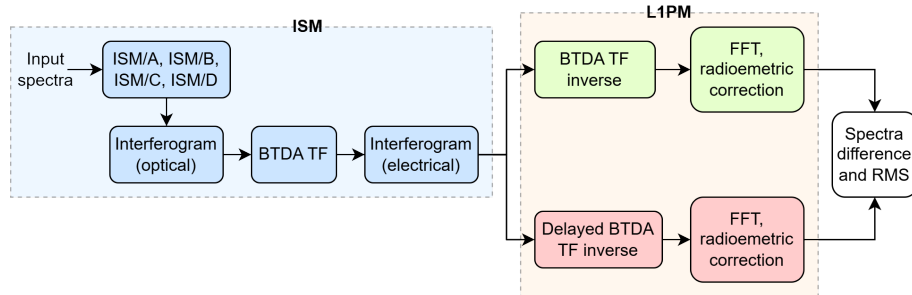


Figure 3.41: BTDA TF sensitivity study processing strategy.

The results of the sensitivity study on the transfer function knowledge inaccuracies are reported in Section 3.3.4.

3.3.4. Results: BTDA TF inaccuracies and speed fluctuations

This section outlines the result relative to the detection of ghosts in the ISRF, due to the effect of speed fluctuations, and their correlation with the BTDA TF knowledge accuracy.

Ghost generation in ISRF

The ghost presence and impact on the ISRF of the FSI has been investigated with the method discussed in Section 3.3.1. The original signal subjected to speed fluctuations was a delta function at 600 cm^{-1} , therefore its aliases are expected to be similar delta functions with a lower amplitude, periodically spaced over the spectrum. The outcome of this analysis is presented in Figure 3.42.

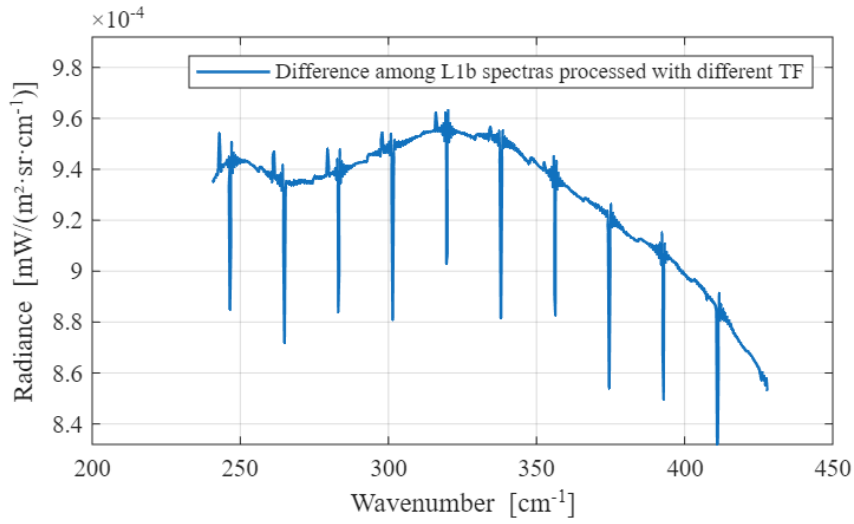


Figure 3.42: *Difference among L1b products processed with correct and partially inaccurate TF inverse ($2\mu\text{s}$ additional delay). Ghosts of the original signal are represented by the spikes, with the expected 19 cm^{-1} periodicity. Zoomed view at $240\text{--}430 \text{ cm}^{-1}$.*

As expected, the speed fluctuations cause a periodic phase modulation, resulting in the presence of repeating aliases of the original signal.

In an ideal simulation where only ghosts are affecting the L1b products, the difference among L1b products would be a flat line at zero radiance, interrupted only by sharp features (i.e. ghosts) occurring at a consistent spectral interval. However, the non-zero baseline observed in the difference spectrum deviates from this ideal flat profile. This non-flat feature is likely caused by second-order effects from additional disturbances within the FSI, which cannot be effectively suppressed through signal processing.

Despite these secondary effects, the resulting spectra difference closely matches the expectations, as the artifacts can be accurately observed at the anticipated frequency interval, validating the signal processing strategy.

The capability to detect ghosts by comparing two different ISM outputs, one relative to a simulation without instabilities and one with instabilities, has been investigated. This signal processing alternative has proven to be unsuited to detect ghosts, since additional noise sources dependent on the ISM simulation are not removed in post processing and therefore mask the faint signals of the ghosts. In Figure 3.43, the difference among the two L1b products is displayed, showcasing that it is not possible to detect the presence of ghosts with this method.

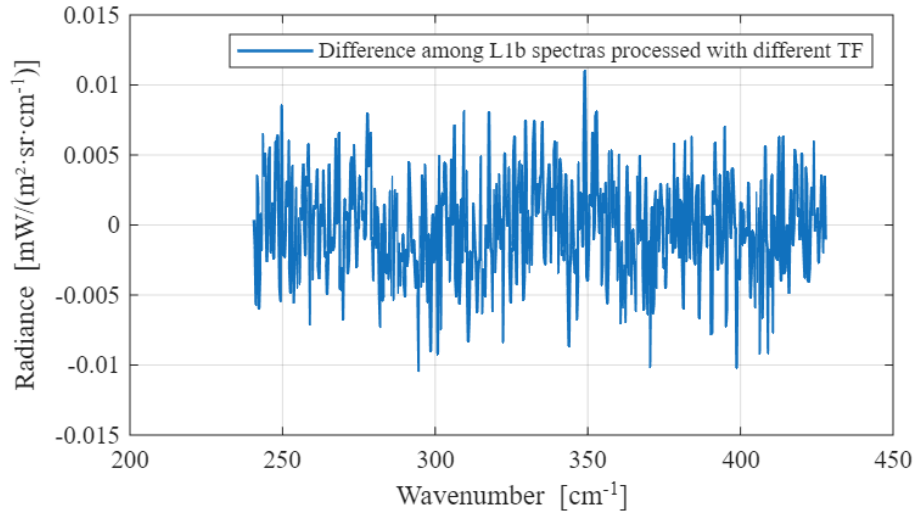


Figure 3.43: Difference among L1b products resulting from two ISM simulations, with and without speed fluctuations. The resulting noisy signal causes the ghosts to be non distinguishable. Zoomed view at 240-430 cm^{-1} .

Correlation between TF knowledge and ghosts errors

The correlation between the imperfect knowledge of the BTDA TF and the ghosts amplitude has been investigated, by repeating the study conducted on the ISRF of the FSI with a low accuracy BTDA TF. The resulting ghosts are reported in Figure 3.44.

Compared to the results of Figure 3.42, retrieved with a high accuracy TF, here the amplitude of the ghosts appears to be increased by a factor of 30/40. This is representative of the additional errors introduced by an inaccurate BTDA TF, demonstrating the impact of an imperfect TF knowledge on the data quality.

The second order effects causing a deviation of the trend from the zero baseline are still observed and they appear to be amplified for this simulation.

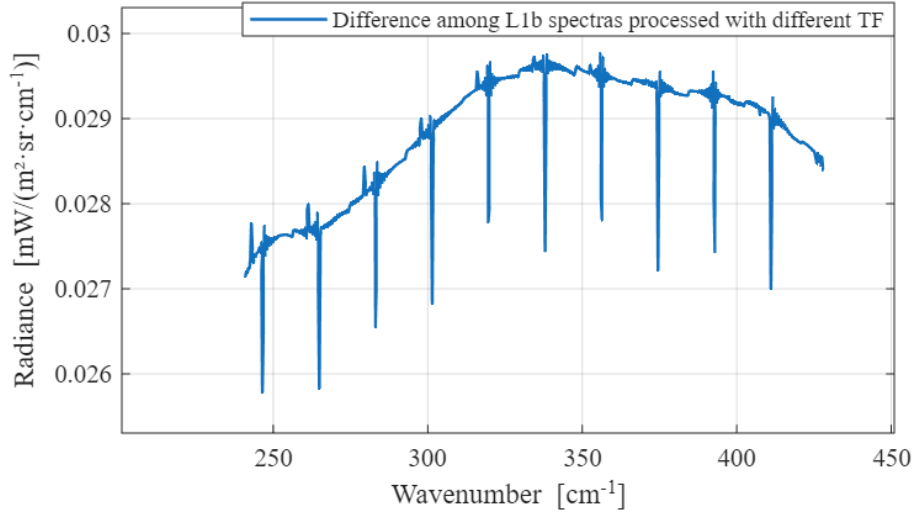


Figure 3.44: Difference among L1b products processed with correct and highly inaccurate TF inverse ($75\mu\text{s}$ additional delay). Ghosts of the original signal are represented by the spikes, with the expected 19 cm^{-1} periodicity. Zoomed view at $240\text{--}430\text{ cm}^{-1}$.

Results on TF knowledge inaccuracies impact

A representative simulation of the ghost effects during a nominal acquisition of the FSI has been performed, by processing the same ISM output with increasingly inaccurate transfer functions. The inaccuracy is implemented by adding an offset delay of $15\mu\text{s}$ to the group delay of the correct TF. Several distinct TF have been implemented and used for the signal processing, with delays ranging from $15\mu\text{s}$ to $120\mu\text{s}$.

Firstly it is possible to visualize the error caused by speed fluctuations coupled with inaccurate transfer functions over the FSI bandwidth. Figure 3.45 displays the RMS of the L1b product difference (between the L1b processed with the correct and incorrect TF) over the bandwidth, obtained by processing the ISM outputs with a TF delayed by $15\mu\text{s}$, compared to the correct TF. As expected, speed fluctuations cause in a more significant error at higher wavenumbers.

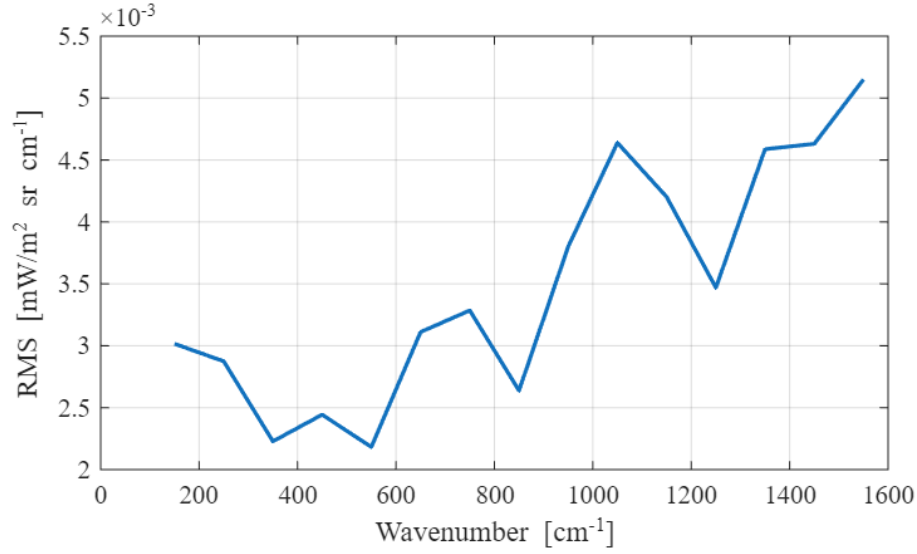
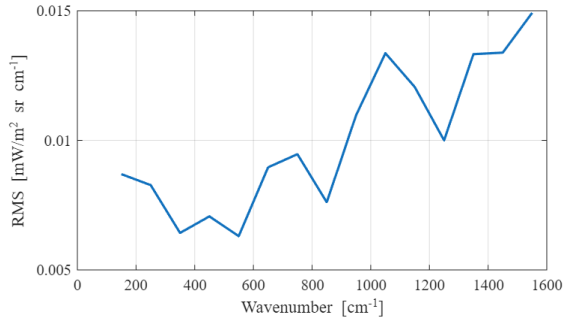
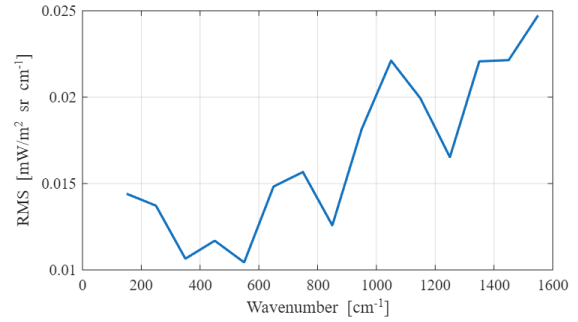


Figure 3.45: *RMS of L1b product difference (incorrect TF delayed by 15 μ s).*

It is possible to compare the trend relative to the TF delayed by 15 μ s to other TF with a higher inaccuracy (i.e. higher delay). Figure 3.46 showcases that the trend over the bandwidth is the same, with stronger errors at higher wavenumbers, but their amplitude is different, as demonstrated by the scale of the y-axis.



(a) *RMS with 45 μ s delay.*



(b) *RMS with 75 μ s delay.*

Figure 3.46: *RMS of the difference of L1b products preprocessed with correct BTDA TF and (a) delayed TF by 45 μ s, (b) delayed TF by 75 μ s. The trend is the same but the amplitude differs, as indicated by the y-axis scale.*

The error over the whole observational bandwidth is computed. The results for each delayed TF considered are plotted in Figure 3.47.

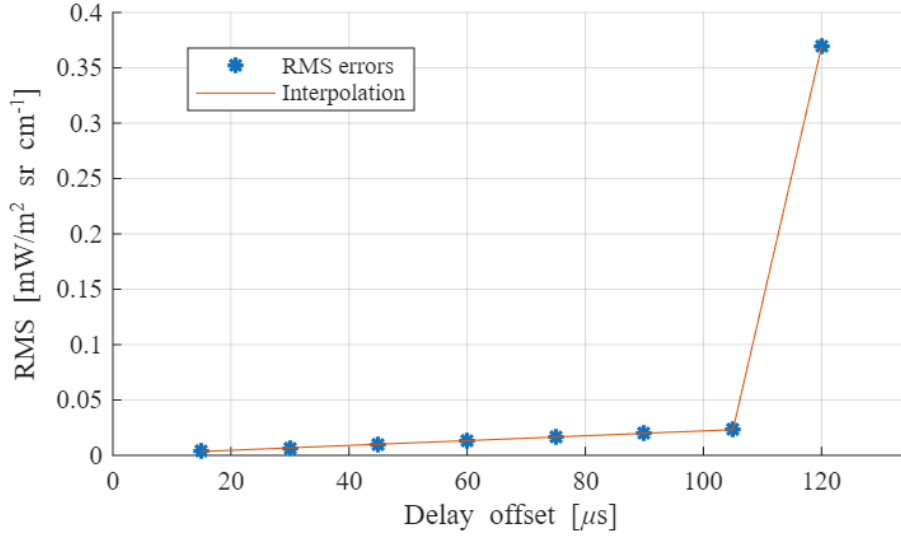


Figure 3.47: *RMS of L1b product difference over the whole bandwidth vs delay of TF considered.*

The ghost effect appears to grow proportionally with the inaccuracies of the BTDA TF up to the simulation at $105 \mu\text{s}$. The simulation at $120 \mu\text{s}$ is, on the contrary, characterized by a larger error increase. This phenomenon is not directly related to the speed fluctuation effect but was traced to an error in the ZPD identification for OPD resampling (see Section 2.6.2 for details on this procedure). With a very large delay, the L1PM fails on identifying the precise position of the ZPD crossing in the metrology data. As described in Section 2.2.1, this yields large phase errors that are the cause of the error increase of Figure 3.47. The L1b spectra under the influence of phase errors and failed ZPD identification is shown in Figure 3.48.

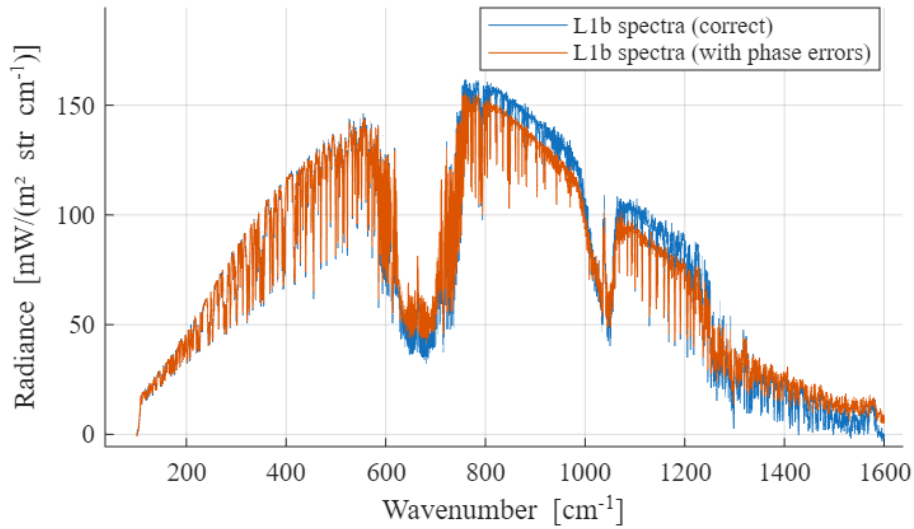


Figure 3.48: *L1b spectra under the influence of phase errors and failed ZPD identification, compared to accurate L1b spectra.*

The large errors associated to a failed ZPD identification are observed only with delays larger than $105\mu\text{s}$; the currently envisaged TF characterization accuracy is well below this number, therefore only the simulation outputs unaffected by this signal processing bug (i.e. with an inaccuracy range from 15 to $105\mu\text{s}$) are considered for the rest of this study. The specific case associated to inaccuracies larger than $105\mu\text{s}$ shall be taken into consideration only if the current estimates on the TF characterization accuracies will be subject to large modifications during the upcoming test campaigns. The linear trend of the error compared to the TF inaccuracy can be observed in Figure 3.49.

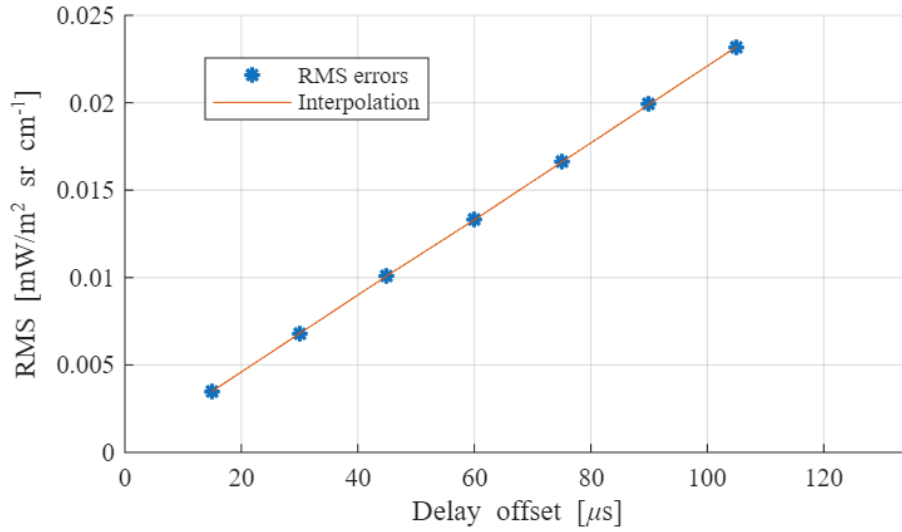


Figure 3.49: RMS of L1b product difference over the whole bandwidth vs delay of TF considered. Simulation at $120\mu\text{s}$ ignored due to ZPD identification bug influence.

Since the BTDA TF knowledge error is systematic and non-random, it cannot be suppressed through averaging. To quantitatively assess the impact of this systematic inaccuracy on data quality, it is possible to compute the number of averaged observations before the TF knowledge error becomes the dominant uncertainty (see Section 3.4 for an explanation of this procedure). This results in the trend shown in Figure 3.50.

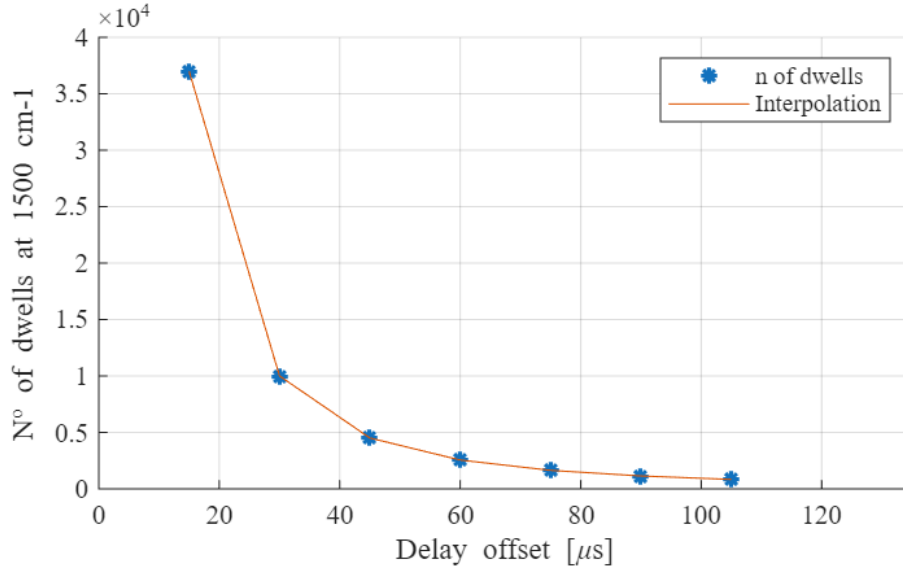


Figure 3.50: Number of averaging dwells for BTDA TF error relevance on the data quality, relative to the error at 1600 cm^{-1} .

The number of dwells N , associated with the error from the TF inaccuracies, appears to be $>10^4$ for a delay between $0\text{-}30\mu\text{s}$, which is above the maximum number of averages envisaged for FSI climate studies.

If the TF is characterized accurately enough to be within this delay range, the errors resulting from TF inaccuracies and ghosts effects can be considered negligible. Current estimates and predictions show that the TF characterization inaccuracies will likely fall within this acceptance range. If, however, the final characterization of the BTDA TF is found to be affected by higher inaccuracies, then special attention must be placed to the data quality degradation from TF errors.

3.4. Impact of speed fluctuations - IDEM data study

Variations in the interferometer scan speed pose a significant challenge to data quality. Having outlined the phenomenon of ghost generation and its relationship to TF accuracy in Section 3.3, a practical assessment based on experimental data is now performed. This chapter utilizes realistic speed fluctuations to quantify the degradation of FSI performance, to assess the robustness of the baseline design against such disturbances.

Predicting the exact profile of speed fluctuations without empirical data is practically infeasible, as mechanical models often fail to accurately resolve micro-vibrations and the associated instabilities. Moreover, attempting to assess these errors through simulation alone would require a global sensitivity analysis, resulting in a computationally prohibitive processing. To address this, experimental data collected from the Instrument DEMonstrator (IDEM) is utilized as a baseline for realistic fluctuation profiles. The IDEM consist of a version of the FSI with a subsets of its components, that has been developed to check the core functionalities and performances of the Interferometer Assembly; it does not include components such as the SCU or POU, which are potential sources of micro-vibrations. Therefore, margins are applied to the observed IDEM speed profiles to account for potential performance degradations that might be observed in the fully integrated FSI.

3.4.1. Categories of speed fluctuations

Speed fluctuations can be effectively divided into two categories:

- Random fluctuations: unpredictable in their trend and different in each dwell. Their mean amplitude and frequency content can be measured for characterization.
- Periodic fluctuations: predictable behaviour over time, often given by the platform or other internal components with a periodic movement (e.g. SCU, reaction wheels). They are characterized by their amplitude and period.

In the FSI, both categories are expected to be present. Although their effect on the data quality is the same (ghosts generation outlined in Section 3.3.1), their impact should be assessed independently, due to their different behaviour under averaging. This can be explained as follows. To generate representative climate models, FSI measurements are averaged to reduce the random noise component until the total uncertainty is dominated by the Absolute Radiometric Accuracy. The radiometric noise induced by speed fluctuations is uncorrelated, therefore it decreases according to Eq. 3.4, scaling with the square root of the number of averages. Consequently, if the random fluctuations noise is low, their impact becomes negligible in the final averaged product.

In contrast, periodic speed instabilities do not average out. Because these fluctuations induce an identical Optical Path Difference disturbance and radiometric error in every scan, they cause as a systematic bias that persists regardless of the number of averages. Since random noise will be lowered by averaging but periodic noise won't, it is possible to identify the crossover point where periodic fluctuations become the dominant contributor.

$$N = \left(\frac{\text{NESR}_{\text{Agreement}}}{\text{Noise}_{SF,P}} \right)^2 \quad (3.30)$$

where N is the number for averages and $\text{Noise}_{SF,P}$ the radiometric noise of a periodic fluctuation. If N is sufficiently large (e.g. 10^4 , well above the expected averaging to be performed for FORUM climate studies, from Figure 3.3), then the periodic fluctuations effect can be considered negligible.

3.4.2. IDEM random speed fluctuations

During the IDEM test campaign, several radiometric measurement of a stable scene were acquired. Over one single dwell, the random speed fluctuations over the mean value of 0.204 cm/s [18] are reported in Figure 3.51.

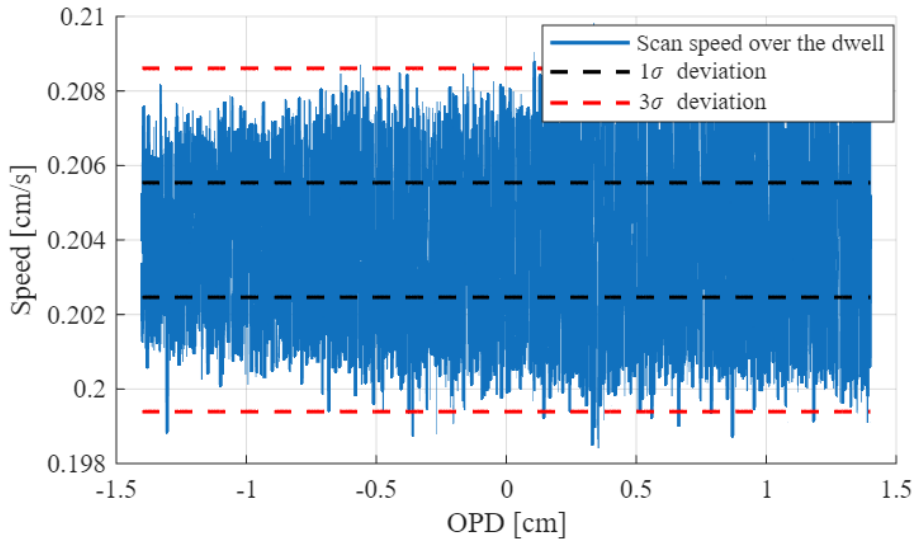


Figure 3.51: Speed fluctuations observed during IDEM test campaign [25].

At 1σ confidence level, the fluctuations have a mean value of 0.0015 cm/s, corresponding to 0.74% of the nominal speed. The scope of the study presenter hereafter is to determine if these fluctuations create a radiometric noise below critical disturbance thresholds, as well as assessing the FSI tolerance to higher instability amplitudes.

Assessment of random speed fluctuations impacts

The speed fluctuations observed in the IDEM test campaigns give an indication of the order of magnitude that can be expected in the real instrument. To assess the impact of the disturbances and their potential increase, a larger range of amplitudes has been investigated. This study is conducted with the following ISM and L1PM configurations, for a representative simulation:

- Input scene: a high resolution atmospheric emission spectra, representative of the Earth at $\sim 300\text{K}$.
- Interferometer and OPD acquisition: all the disturbance sources are implemented.
- Detectors: the electrical noise of the science and reference detectors is active.
- Transfer function: the best estimate, according to the current knowledge, of the BTDA TF is applied to generate the interferograms of each detector and to correct detector-dependant effect in the L1PM.

An amplitude range of speed fluctuations from 0.5% to 2% is considered. To quantify the impact of random instabilities, a reference threshold is set at a fraction of the total noise budget, 10% of the NESR requirement. This threshold is justified by the statistical nature of uncorrelated noise sources, which combine in quadrature (Root-Sum-Square). Due to the properties of RSS summation (Eq. 3.2), a noise component that is one-tenth the magnitude of the dominant noise source adds less than 0.5% to the total system noise. Therefore, if the radiometric error induced by random speed fluctuations remains below this threshold across the spectral range, its contribution to the NESR is negligible. Furthermore, because these fluctuations are random, their residual impact will be effectively suppressed during the averaging process.

The random instabilities effect is quantified by:

1. Generation of L1b outputs corresponding of a simulation with 0% fluctuations, with every other disturbance active.
2. Generation of L1b outputs with the same disturbances (and same randomic seed for repeatability) with the additional effect of random speed fluctuation, at an amplitude of $x\%$.
3. L1b spectra difference and RMS over the bandwidth.
4. Comparison of RMS with 1/10 of NESR requirement.
5. Repeat from point 2 with different fluctuations amplitude $x\%$.

The RMS is computed over the bandwidth since, as discussed in Section 3.3.3, speed fluctuations result in more significant degradation at higher wavenumbers.

The results of the study on random speed fluctuation amplitudes are reported in Section 3.4.4.

3.4.3. IDEM periodic speed fluctuations

For the periodic speed fluctuation assessment, consistently with the methodology applied to random instabilities, the analysis exploits the experimental data acquired from the IDEM, to establish a realistic baseline profile. The disturbance can be observed clearly by computing the OPD over the IDEM dwells and then subtracting it with its ideal linear trend. If the instrument has an ideal behaviour, this operation would yield a null vector, suggesting that the OPD over the dwells follows the linear profile. In the case of the IDEM measurements, this operation results in the trend of Figure 3.52. A periodic behaviour is observed.

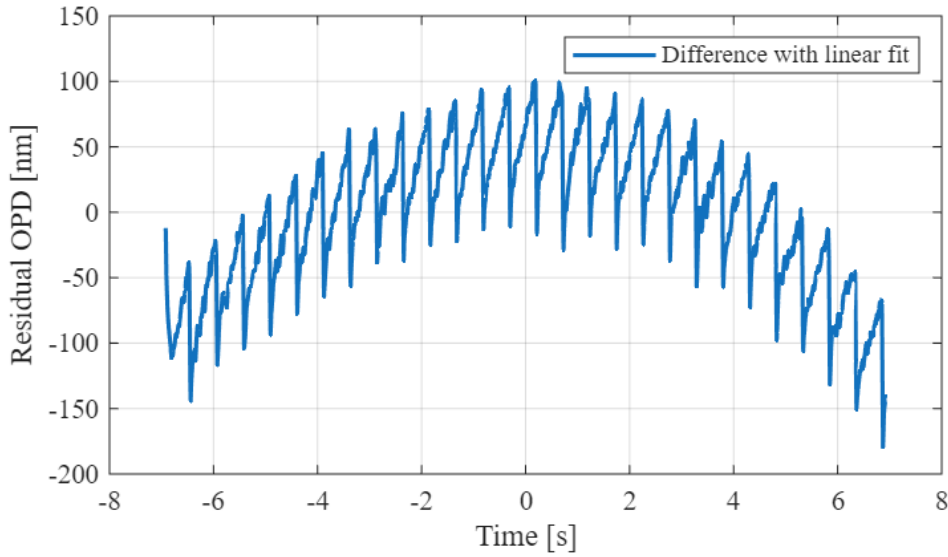


Figure 3.52: IDEM OPD difference with linear fit.

There is a regular jump in the OPD movement, with an approximate frequency of 2 Hz, i.e. every 0.5s. This is the consequence of the presence of a periodic speed fluctuation with the same frequency. The source of this instability is not fully identified at the moment of redaction of this document, but due to its period it could be related to the synchronization pulse of the platform. This is only an hypothesis and further investigations are needed to verify this statement. Nevertheless, although the origin is not identified at the moment, it is still possible to investigate its effects on the data quality.

With simple derivatives, it is possible to compute the speed amplitude and duration associated to the OPD instabilities observed in Figure 3.52. By averaging the resulting speed profile across the IDEM measurements, a mean periodic instability of 1.95Hz is identified, as shown in Figure 3.53.

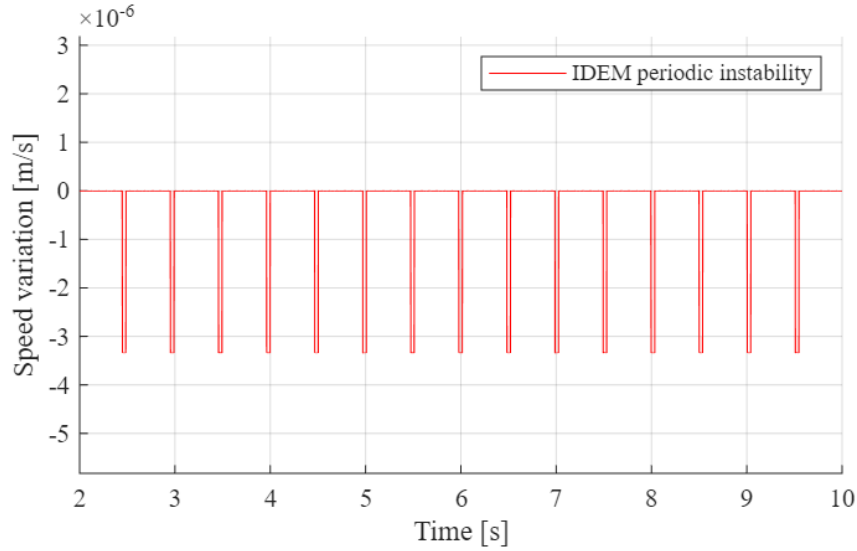


Figure 3.53: *IDEM periodic speed instability.*

Assessment of periodic speed fluctuations impacts

The periodic speed instability extracted from the IDEM data is used as reference point. To conduct a representative simulation, the ISM and L1PM have been configured as for the amplitude study (see Section 3.4.2). The periodic profile is added to the the IDEM random variations, as shown in Figure 3.54.

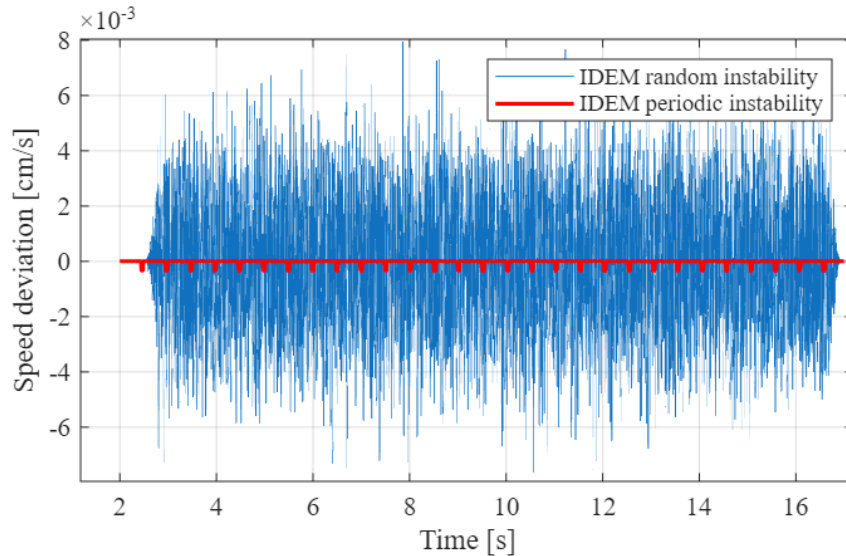


Figure 3.54: *Random and periodic speed fluctuations over the mean value.*

In comparison to the random instabilities, the amplitude of the periodic profile is limited, suggesting that its effect might be negligible. However, as discussed, the averaging process will not remove the periodic fluctuation contribution, therefore it is necessary to precisely assess their relevance. The effect of the periodic fluctuations is quantified as follows:

1. ISM + L1PM are executed with only random speed fluctuations. L1b spectra are saved.
2. ISM + L1PM are executed with random and periodic fluctuations, with amplitude $x\%$. L1b spectra are saved.
3. The RMS of the difference between L1c spectra is computed.
4. The RMS is converted into the corresponding number of averaging dwells N , according to Eq. 3.30.
5. The analysis is repeated with a different periodic fluctuation amplitude.

The number of averaging dwells N , resulting from point 4 of the processing, is used to check whether the periodic disturbances can have non negligible impact on the data quality after climate studies averaging. The results of this study are reported in Section 3.4.4.

3.4.4. Results: IDEM speed fluctuations impact

This section outlines the results relative to the impact of random and periodic speed fluctuations observed in the IDEM test campaign on the data quality. The tolerance level of the FSI to potentially higher disturbance level is investigated.

IDEM Random speed fluctuations impact

The IDEM random speed fluctuations, at 1σ confidence level, are 0.74% of the nominal IA scan speed. To study the relevance of this amplitude of fluctuation, a range of fluctuations from 0.5% to 2% has been investigated and compared to the arbitrary threshold of 1/10 of the NESR requirement. The resulting RMS of the error over the FSI observational bandwidth is reported in Figure 3.55. The speed fluctuation amplitude required to match the threshold of 1/10 of the NESR is identified at 2.1% and plotted.

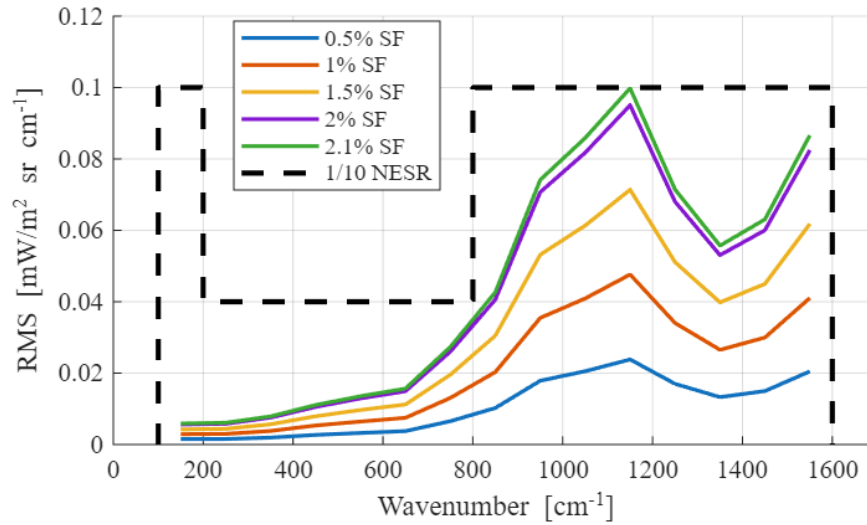


Figure 3.55: *Error due to random speed fluctuations over the bandwidth.*

As expected, larger errors are observed at higher wavenumbers. The IDEM fluctuations, at 0.74%, are well below the relevance threshold of 1/10 NESR, therefore they can be considered negligible and will be removed through the dwell averaging process. This analysis demonstrates that, even if the experimental fluctuations level increases by a factor of 2 or 3, the impact is can still be considered negligible.

By plotting the RMS error versus the percentage of fluctuation, (Figure 3.56) a linear relationship is observed. This correlation allows to approximate the impact of larger fluctuation amplitudes, in the unlikely event that, in the FSI flight model test campaign, the fluctuations will increase by a factor higher than 3 compared to the IDEM data.

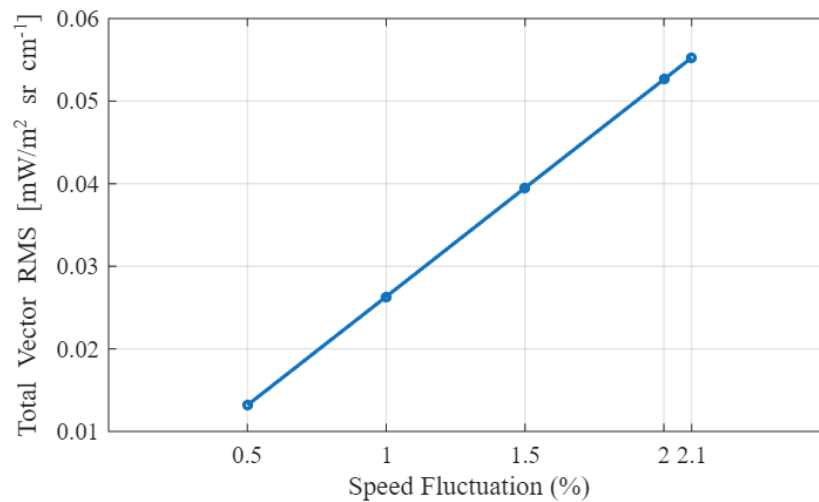


Figure 3.56: *Speed fluctuation amplitude and corresponding error on the data quality.*

IDEM Periodic speed fluctuations impact

The periodic fluctuations observed in the IDEM data result in a systematic error on the L1b products. Therefore, the results relative to their impact are presented both in terms of RMS difference over the bandwidth and with the number of averaging dwells according to Eq 3.30. This allows to assess if such disturbance represents a non-negligible contributor in the envisaged climate studies of FORUM.

From Figure 3.57, the periodic fluctuation contribution appears to be extremely low. The RMS over the bandwidth is here compared to 1/100 of the NESR requirement, not 1/10 as for the random fluctuations. Since the error level is below this threshold, the impact of periodic speed fluctuation is fully negligible. To assess the tolerance of the FSI to a larger fluctuation, the same analysis is repeated with an amplitude increased by a factor of 10. Even under such an unlikely increase, the error over the bandwidth is still negligible.

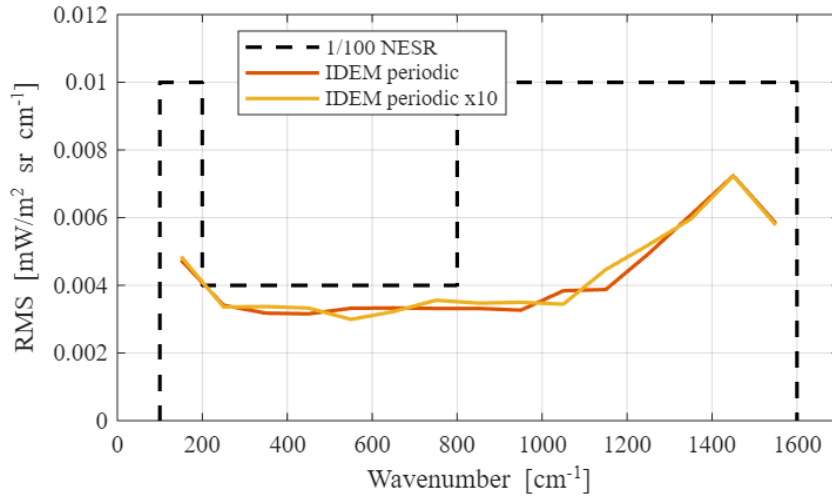


Figure 3.57: Errors due to periodic speed fluctuations over the bandwidth.

The RMS of the error over the whole band is $0.0045 \text{ mW/m}^2 \text{ sr cm}^{-1}$ for the simulation with the IDEM amplitude and $0.0046 \text{ mW/m}^2 \text{ sr cm}^{-1}$ for the 10 times higher amplitude fluctuation, showcasing the minimal difference. The errors due to IDEM periodic fluctuations are converted into their associated number of dwells according to Eq 3.30, resulting in the distribution of Figure 3.58.

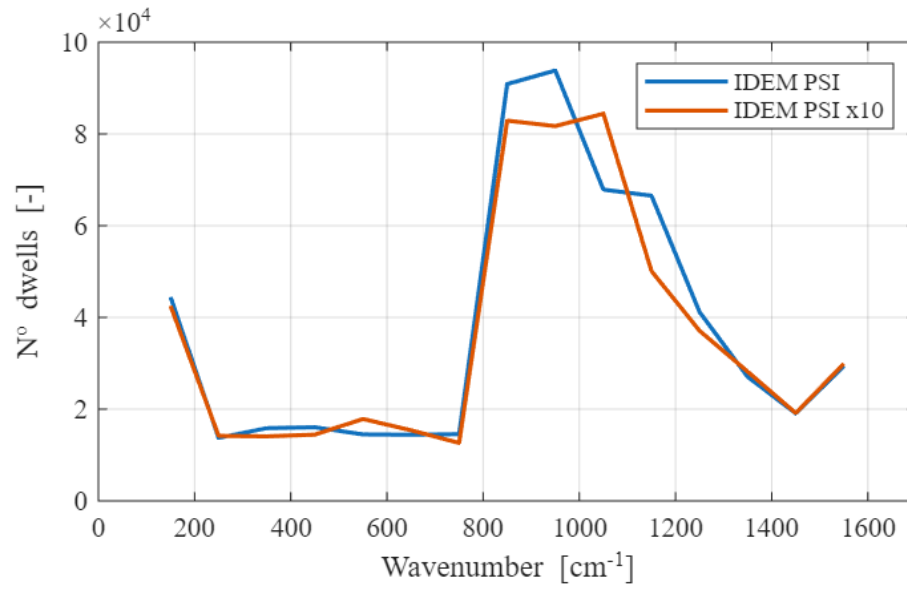


Figure 3.58: Number of averaging dwells for periodic fluctuation error relevance on climate studies. As expected, the simulation with a higher speed fluctuation, is associated on average to a lower number of dwells.

The associated averages are well above the threshold of 10^4 identified in Section 3.1.1 over the whole spectral band, thus confirming that the periodic speed fluctuations observed in the IDEM are fully negligible.

4 | Discussion

The performance results detailed in Chapter 3 represent the basis for an analysis on the robustness of the FSI design to the disturbances considered. The aim of this Chapter is to distinguish the validated and robust design aspects of the FSI from those requiring improvements. Given the limited feasibility of implementing significant design modifications at the current development stage, the discussion also investigates potential enhancements for a potential successor to the FORUM mission.

4.1. FSI design robustness against disturbance sources

The robustness of the FSI design against disturbances was evaluated considering four key aspects: sub-optimal and differing NEP on both detectors and the speed fluctuation effects, in relation to the BTDA Transfer Function knowledge and the IDEM experimental measurements.

The current instrument design has proven to be highly robust against random and periodic speed fluctuations. Periodic fluctuations require specific considerations because the resulting error, though low, is not removed by the averaging processes. While periodic fluctuations are present in the IDEM and expected in the flight model of the FSI, their impact remains limited. Even when simulated with a factor of 10 increase their effect is still negligible, allowing to safely assume that their impact on final data quality is not relevant. Random fluctuations introduce a larger mean error across the spectral range, approximately ten times higher than the periodic contributors; however, their effect remains a minor contributor to the overall noise and will be effectively suppressed through averaging, therefore it does not constitute a reason for concern at this stage.

The effect of BTDA TF knowledge inaccuracies are strictly related to the fine characterization of the flight model BTDA TF. Considering the currently envisaged accuracy of characterization, the effect of this disturbance appears to be fully negligible.

These considerations on the robustness of the FSI to speed fluctuations are relative to the IDEM data and the current estimates on the BTDA TF, that are not however fully representative of the FSI flight model. These analyses should be repeated with more representative experimental data collected during the future test campaigns. Nevertheless, sufficient margins and degradations have been considered through the analyses to showcase that, in the unlikely event that the disturbance level will be higher in the flight model, the instrument is still able to tolerate the effect of speed fluctuations, as the data quality is only partially degraded.

On the contrary to the speed fluctuations, whose effect can be considered as a minor contributor to the radiometric noise, the same does not hold for the detectors' NEP. The NESR performance is dominated by the sub-optimal detector noise, resulting in significant non-compliances. Exploiting the different NEP of the flight detectors for signal recombination improvements brings partial advantages, that are however not sufficient to lower significantly the non-compliance. Nevertheless, the capability to perform a weighted average of the L1b products has proven to be advantageous, and represents a useful feature to adopt during the mission operational life. For example, in the event of a differential degradation over time of the performances of the two detectors, the NEP gap might increase sufficiently to bring significant advantages in terms of NESR if a weighted average is performed. Among all the signal recombination strategies, the most robust approach is to identify a wavenumber-dependent weighted average for optimum NESR, as this method yields more significant performance advantages and is independent of the observed scene.

The suboptimal NEP, root cause of the NESR non-compliance, can be counterbalanced effectively only through a modification of the FSI acquisition strategy. Multiple alternatives have been explored, adopting lower interferometer movements and trades with other performance parameters, to improve the current NESR estimates.

The most effective strategy to improve the data quality (without introducing other performances degradations) is the reduction of the interferometer speed. This modification directly affects the NEP band of interest and is the most effective method, at the current design stage, to improve the NESR while maintaining the current hardware design. However, the modification of the interferometer speed alone is not sufficient to bring the desired improvements.

Spectral resolution and SSD were identified as the performance parameters whose adjustment is associated to a NESR performance increase. Among the two, the most effective modification is the partial degradation of the spectral resolution, that can yield improvements of up to 20% of NESR (always combined with a reduced interferometer speed).

This is achieved by decreasing the interferometer range of motion, introducing a partial spectral resolution non-compliance of 5% limited to a portion of the total spectral band. The relatively modest degradation compared to the significant NESR improvements suggest that this option might be worth exploring for future implementations.

A modifications of the SSD, achieved with an increase of acquisition time, theoretically improves the NESR performance by approximately 10%. However, the associated SSD performance degradation is more significant compared to the spectral resolution degradation of 5% previously discussed. Nevertheless, if the spectral resolution shall not be modified for technical or scientific reasons, the introduction of a limited non-compliance on the SSD is a valid alternative for NESR improvements.

To effectively remove the NESR non-compliance, a dual degradation of SSD and spectral resolutions has proven to be a valid alternative. With modifications compatible with the current design margins, and through the introduction of limited non-compliances on SSD and spectral resolution, the NESR can be reduced to almost a perfect full compliance. If the largest possible NESR improvement is desired, then this strategy is a valid alternative to be explored and implemented.

Significant NESR improvements result also from the implementation of a single sided interferogram acquisition strategy. However, at the stage of development of the FSI, this can be achieved only by introducing a significant ARA degradation. Recalling that FORUM's primary objective is to provide high accuracy infrared measurements, this option is not desirable as it could strongly lower the scientific products accuracy. At an earlier development stage, this option could have been implemented with a partial configuration modification, to remove the radiometric errors affecting the ARA, resulting in large NESR gains without degradation of SSD or spectral resolution.

Overall, the FSI under the influence of external and internal disturbances is partially suited to satisfy the mission objectives; multiple improvement strategies are identified to potentially enhance its data quality through minor modifications compatible with the current design margins.

The results presented here are based on worst-case EOL performance estimates. These projections shall be refined once the flight model is fully characterized, replacing theoretical estimates with measured data. If the measured NESR aligns with the best-case scenario, no further modifications may be required. Nevertheless, the proposed strategies provide a solid alternative if the instrument's actual performance resemble the worst-case estimations. Moreover, if the in-flight NESR is subject to an unexpected degradation, the performance could be improved by implementing the proposed modification strategies, as they do not require any hardware modification.

4.2. Design enhancements for a potential FORUM 2 Mission

As FORUM approaches the closure of the detailed design phase, the possibility to implement design modifications is increasingly limited. Nevertheless, considerations on the FSI development provide critical insights for a potential successor mission. Earth Explorer missions frequently serve as technological pathfinders for operational programs, such as Copernicus and MetOp. Consequently, identifying potential design enhancements guarantees that future operational systems can fully leverage on the scientific and technological heritage established by FORUM.

This document established that the current FSI design is suited to achieve high accuracy and spectrally resolved far-infrared measurements. The robustness of the FSI to disturbances such as speed fluctuations has been proved. The critical area that shall be improved in a potential FORUM 2 mission is the radiometric noise. The pyroelectric FSI detectors, responsible for the sub-optimal noise, were selected due to their large observation bandwidth, a major requirement of FORUM measurements. The drawback of this detectors category is that their typical NEP is relatively high and they can operate only at room temperature, thus removing the possibility to cool them for noise reduction purposes. For a potential FORUM 2 mission, this limitation could be addressed by reconfiguring the dual-output IA architecture to utilize spectral splitting. By assigning a distinct, narrower bandwidth to each output port, the total observational range is maintained while relaxing the constraints on individual detectors. This approach broadens the pool of candidate sensors, enabling the selection of technologies with advantageous NEP and potential cooling options. Schematic representation in Figure 4.1.

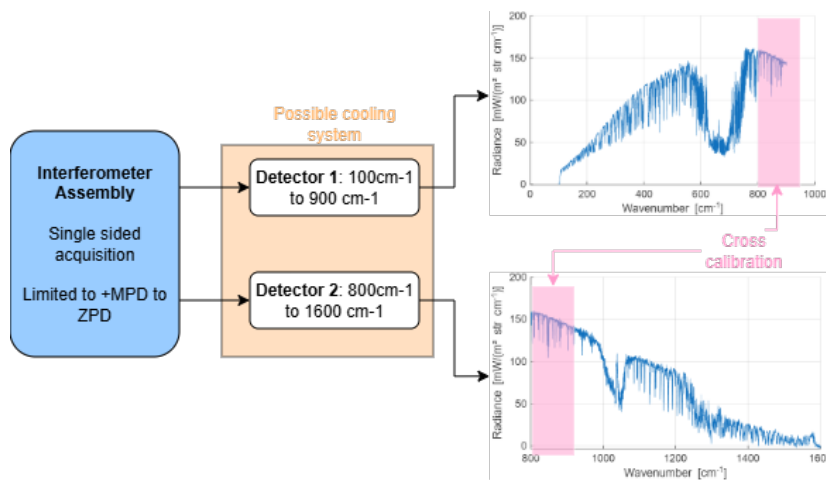


Figure 4.1: Proposed alternative configuration for the IA for a possible FORUM 2 mission, heir of the lessons learned from the FSI development.

The two detectors could be selected to have partially overlapping bandwidths, for cross calibration purposes. Additionally, a narrower band simplifies the BTDA TF design process, as it is easier to achieve a relative flatness of the group delay with a shorter bandwidth. This would reduce even more the susceptibility of the FSI to speed fluctuations, as the group delay would be less variable over the bandwidth.

Data quality could be further enhanced by adopting a single-sided interferogram acquisition strategy, which supports high spectral resolution and maintains SSD while lowering the effective NEP. This approach necessitates a reconfiguration of the BBU and cold space baffles, to ensure that they are encompassing the FOV of the FSI when the SCU is oriented on the centreburst acquisition position (see Section 3.1.6 for the rationale of this alignment). A potential layout modification for the deep space baffle, designed to guarantee this alignment, is shown in Figure 4.3 and compared to the baseline configuration of Figure 4.2.

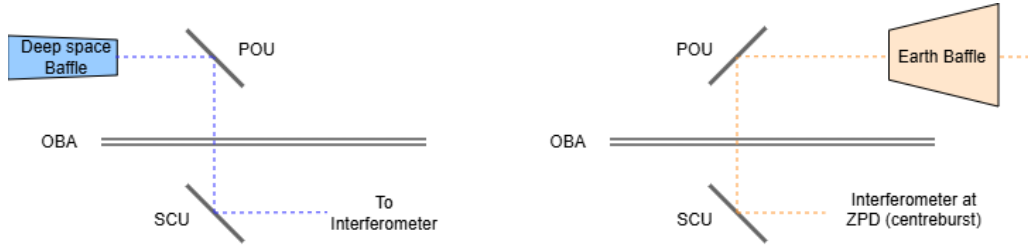


Figure 4.2: *Baseline configuration during deep space calibration (left) and Earth centreburst acquisition (right) [18].*

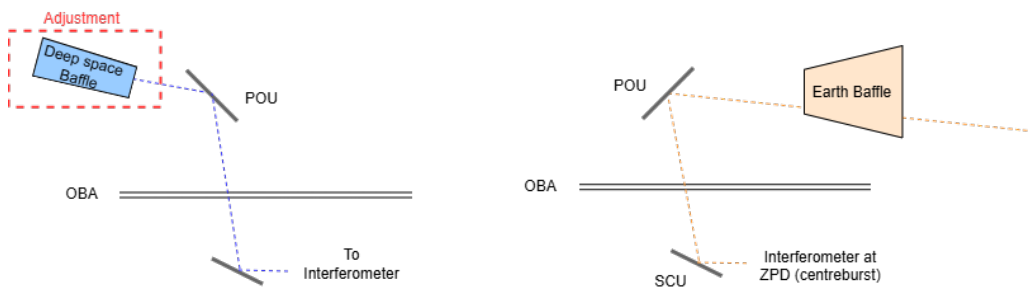


Figure 4.3: *Proposed alternative configuration for the deep space baffle to avoid SCU angle mismatch during calibration (left) and Earth centreburst acquisition (right).*

This configuration would allow to have an extremely high data quality, without any sacrifice on ARA, spectral resolution and SSD, thus constituting an alternative worth exploring for future operational missions.

In summary:

- The overall architecture of the instrument could be maintained as it was proved to be suited for high accuracy and spectrally resolved measurements.
- The output ports of the interferometer should each be assigned to a different bandwidth.
- The FSI detectors should have a narrower bandwidth compared to the current one, allowing the selection of sensors with lower NEP and cooling capabilities.
- The measurements could be achieved with single sided interferograms, to strongly improve the NESR without degradation of spectral resolution and SSD.
- Partial configuration modifications related to the baffle orientation would be required to minimize the radiometric errors of the calibrations.

These modifications are only preliminary suggestions based on the outcome of the research presented in this document, and drawbacks not envisaged at this stage might be present.

5 | Conclusions and Recommendations

This thesis examined the impact of several critical disturbance sources on the data quality of the FORUM Sounding Instrument (FSI) scientific products. The FSI design was inspected to assess its tolerance level to these disturbances, validating the robustness of the current baseline and exploring potential improvement strategies.

This research demonstrated that the FSI radiometric noise performance is strongly driven by the Noise Equivalent Power (NEP) of the detectors. Within the constraints of the current design, several strategies were identified to optimize this performance metric, suggesting viable modifications to secure high data quality even in the presence of sub-optimal NEP. Furthermore, the potential data degradation caused by interferometer speed fluctuations was simulated and quantified. This analysis enabled the identification of critical sensitivity areas, highlighting the necessity for careful experimental characterization of the transfer function and representative speed fluctuations.

Notably, the experimental data sets and estimation tools utilised in this work provide a partially representative simulation of the FSI behaviour. The accuracy of this findings is inherently limited by the approximations introduced within the simulation environment. Consequently, these results shall be viewed as theoretical estimations, establishing a baseline for further validations with experimental measurements.

Future work should focus on refining these findings through the development of a complete end-to-end platform and instrument simulator, capable of providing higher-fidelity estimations of coupled disturbances. Ultimately, the theoretical results of this research must be validated against experimental measurements, acquired from the FSI flight model test campaign.

Overall, the findings of this document confirm the robustness of the current FSI design and demonstrate that the ambitious scientific objectives of the FORUM mission are within the reach of the current hardware and software capabilities.

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A | FTS instruments advantages

The unique working principle of FT spectrometers, presented in Section 2.2, brings two main advantages with respect to dispersive or filter based spectrometers. These advantages are:

Throughput or Jacquinot's advantage

In a FTS instrument the amount of light collected is limited by the optical throughput of the instrument, defined as:

$$\Theta = A \Omega \quad (\text{A.1})$$

where A is the aperture area and Ω the solid angle formed by the collimating optics. If we define the resolving power R as:

$$R = \frac{\sigma_{max}}{\Delta\sigma} \quad (\text{A.2})$$

where σ_{max} is the maximum wavenumber analysed and $\Delta\sigma$ the spectral resolution, then we can compare the throughput of an FTS and a dispersive spectrometer:

$$\Theta_{\text{FTS}} = \frac{\pi A}{R} \quad \Theta_{\text{dispersive}} = \frac{lA}{fR} \quad (\text{A.3})$$

where l is the height of the slit for the dispersion and f the focal length. In most cases, l/f does not exceed $1/20$ in modern spectrometers therefore the amount of light collected by an FTS is 20π more than their dispersive counterpart [13]. This positively impacts the Signal to Noise Ratio (SNR) of the FTS instrument.

Multiplex or Fellgett's advantage

The instrument is affected by several sources of noise. In Fourier Transform Spectrometers, the detector noise is typically the dominant contributor [13, 14]; in this case, the instrument is said to be detector-noise limited. When operating under this condition, an

FTS achieves a higher signal-to-noise ratio (SNR) than a dispersive spectrometer. This advantage arises because, in an FTS, all spectral elements are measured simultaneously, whereas in a dispersive spectrometer each spectral band is measured sequentially. For a spectrum divided into N independent spectral elements, the SNR relationship between the two instruments is:

$$\text{SNR}_{\text{FTS}} = \sqrt{N} \text{SNR}_{\text{dispersive}} \quad (\text{A.4})$$

This relation follows from the statistical nature of purely random noise, whose contributions combine in quadrature, meaning that total noise power scales with the square root of the number of averaged samples rather than linearly [26].

B | FSI additional components description

This appendix provides a description of additional FSI components. While these elements are not critical to the core analyses presented in Chapter 3, they offer a complementary overview of the FSI's overall structure and operational principles.

FTU: Front Telescope Unit

The Front telescope Unit is placed between the SCU and the IA, to optically condition the incoming beam of light for the Interferometer Assembly. The FTU exploits reflective optics only, with three mirrors in sequence; the optical configuration introduces a magnification factor and collimates the input beam. The FTU assembly is presented in Figure B.1.

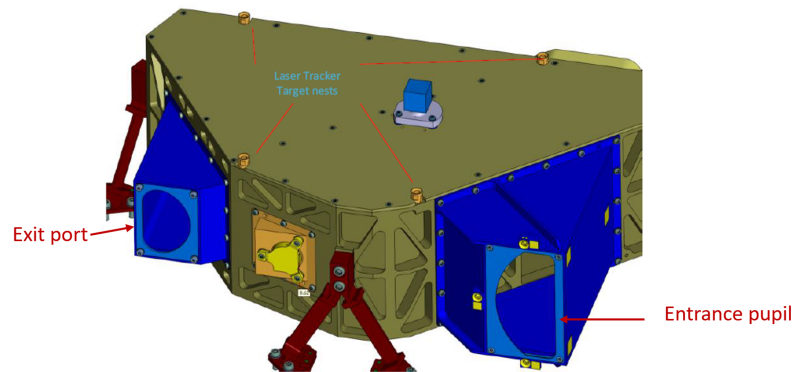


Figure B.1: *Front Telescope Unit (FTU), courtesy of OHB System AG & KTO.*

SPBB: Second Port Black Body

The Mach–Zehnder configuration of the IA features two input ports and produces two output beams, meaning the interferometer is sensitive to radiation entering both inputs. Since the Earth/BBU/deep space scene enters only one of the two ports, the second

port must be fed with a stable and well-known radiance. A Second Port Black Body (SPBB) is installed at Input Port 2, providing a constant and accurately characterised reference radiance. This ensures that its contribution can be reliably removed during post-processing. Using deep space as a second input would not be viable, as occasional Sun intrusions or background fluctuations would introduce undesired signals that could potentially damage the IA detectors.

ICU: Instrument Control Unit

The ICU serves as the central control element. It manages power distribution, thermal regulation, and operational control, interfaces and handles both telemetry and telecommands as well as the data generated by the payload. It represents the main interface with the platform.

FEI: FORUM Embedded Imager

The FORUM Embedded Imager is a thermal camera operating at $10.5\text{ }\mu\text{m}$ with a FWHM of $1.5\text{ }\mu\text{m}$. The role of the FEI is to provide scene heterogeneity characterization by acquiring radiometric images at high spatial resolution (600 m) and with a FOV larger than the FSI's (36 km vs 15 km). To be sensitive to surface properties, both during day and night, the observational band is chosen in the IR atmospheric windows, where little to none atmospheric attenuation is expected. The FEI shares the pointing and scanning units with the FSI, to characterize the observed scene heterogeneity [12].

The FEI is composed by an Optical Head and Front End Electronics. The Optical head is a refractive telescope paired with a micro bolometer, a detector sensible to thermal radiation in the required spectral band.

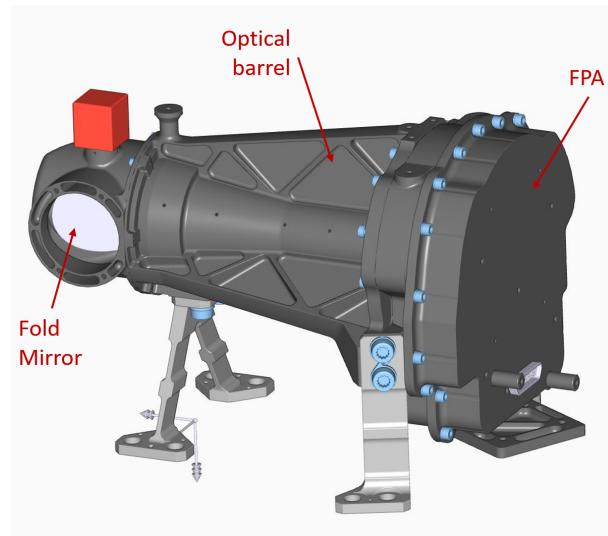


Figure B.2: *FORUM Embedded Imager - Optical Head, courtesy of Leonardo S.p.A.*

OBA: Optical Bench Assembly

The OBA is a rigid structure that provides mechanical support with high accuracy surface planarity and thermal stability, as it holds the components within the specified aligned margins while minimizing the distortions due to thermal expansions. Titanium bipods connect the OBA with the platform and provide thermal decoupling of the FSI.

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List of Acronyms

ADC Analog-to-Digital Converter

ARA Absolute Radiometric Accuracy

BB Blackbody

BBU Blackbody Unit

BC Best Case

BOL Beginning of Life

BS Beamsplitter

BTDA Back Telescope Detector Assembly

CDR Critical Design Review

D1 Detector 1

D2 Detector 2

DS Deep Space

EE Earth Explorer

EO Earth Observation

EoL End of Life

ERB Earth Radiation Budget

ESA European Space Agency

FEI FORUM Embedded Imager

FEE Front End Electronics

FFT Fast Fourier Transform

FIR	Far-Infrared
FORUM	Far-infrared-Outgoing-Radiation Understanding and Monitoring
FOV	Field of View
FSI	FORUM Sounding Instrument
FT	Fourier Transform
FTS	Fourier Transform Spectrometry
FTU	Front Telescope Unit
FWHM	Full Width Half Maximum
GCOS	Global Climate Observing System
IA	Interferometer Assembly
IASI	Infrared Atmospheric Sounding Interferometer
ICE	Interferometer Control Electronics
ICU	Instrument Control Unit
IDEM	Instrument Demonstrator
IFFT	Inverse Fast Fourier Transform
IGM	Interferogram
ILS	Instrument Line Shape
ISM	Instrument Simulation Module
ISRF	Instrument Spectral Response Function
L0	Level 0
L1	Level 1
L1PM	Level 1 Processing Module
MAG	Mission Advisory Group
METOP-SG	Meteorological Operational Satellite - Second Generation
MIR	Mid-Infrared
MLI	Multi-Layer Insulation

MPD	Maximum Path Difference
NEP	Noise Equivalent Power
NESR	Noise Equivalent Spectral Radiance
OBA	Optical Bench Assembly
OLR	Outgoing Longwave Radiation
OPD	Optical Path Difference
POU	Pointing Unit
PSF	Point Spread Function
RMS	Root Mean Square
RSS	Root Sum Squared
S/C	Spacecraft
SCE	Scan Control Electronics
SCU	Scanning Unit
SNR	Signal-to-Noise Ratio
SPBB	Second Port Blackbody
SRL	Scientific Readiness Level
SSD	Spatial Sampling Distance
s.t.	Such That
TF	Transfer Function
TRL	Technology Readiness Level
WC	Worst Case
ZPD	Zero Path Difference

List of Symbols

Variable	Description	SI unit
c	Speed of light	m s^{-1}
f	Frequency	Hz
G	Throughput (Etendue)	$\text{m}^2 \text{sr}$
k_B	Boltzmann's constant	J K^{-1}
N	Number of observations	—
R	Radius	m
T	Temperature	K
t	Time	s
v	Speed	m s^{-1}
w	Weight factor	—
x	Displacement	m
h	Altitude	m
α	Off-axis angle	deg
δ	Phase difference	deg
Δ_{rms}	Root Mean Square difference	—
$\Delta\sigma$	Spectral resolution	cm^{-1}
η	Instrument efficiency	—
θ	Viewing angle	deg
λ	Wavelength	μm
σ	Wavenumber	cm^{-1}
σ_f^2	Variance	—

