DESIGN OF A MINIATURE INFRARED FTS FOR MARS OBSERVATION

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ABSTRACT

This work is devoted to the design of the miniaturized Fourier Transform Spectrometer “MicroMIMA” (micro Mars Infrared MAPper), intended to be mounted on a descending module to Mars of the ESA mission “ExoMars 2016. The scientific goal of the instrument is the spectral characterization and monitoring of the Martian atmosphere, bound to investigate its composition, minor species abundances and evolution during time. The spectral resolution of MicroMIMA is of 2 cm\(^{-1}\) (with the option to be extended up to 1 cm\(^{-1}\)) that allows to recognize the spectral features of the main elements of interest in the atmosphere and in particular to assess methane abundance with ppb resolution. The instrument mechanical design constraints are quite strict:

- limited mass, size and power budget;
- high stress resistance for the landing shock;
- withstanding of severe environmental conditions without any power for thermal control;
- resistance for strong vibrations of the high acceleration levels in wide frequency range.

The optimal instrument configuration has been set in order to achieve the highest sensitivity in the 2 to 5 \(\mu\)m spectral range, along with the reduction of possible noise, i.e. the Signal-to-Noise Ratio (SNR) has been used as figure of merit. The theoretical SNR has been maximized starting from the analytical expressions for Noise Equivalent Spectral Radiance. NESR reduction was achieved by means of the optical layout geometry optimization and by selection of optical elements that offer highest efficiencies for the instrument wavenumber range of interest. Afterwards for the proposed optical layout we performed evaluation of the theoretical SNR for different application cases: laboratory observations by the instrument on the Earth and actual acquisition of Martian atmosphere spectrum during the mission have been considered.

The instrument model design was supported by finite element analyses the static and dynamic loads during launch and landing of the system, as well as thermoelastic analysis for the thermal field during operating process and the resulting optical misalignments. Moreover, an optimization of the vibrational isolation system was performed.

An instrument mock-up has been created in order to evaluate the optical layout performances. This mock-up was simplified from the structural point of view but with detailed representation of mounting, regulation and positioning of optical elements and piezoactuator group. Its assembly, adjustment and a set of preliminary verifications has been made using the infrared lamp as a radiation source.

Also an innovative data treatment technique has been elaborated, which allows correcting the spectral data of FTS instruments from mechanical disturbance effects, starting from the single spectrum. Such a technique increases the spatial resolution of the mapping process and becomes crucial when the desired information is linked to a particular mapping area associated to an individual spectrum. An explicit analytical model was created to describe the formation process of vibration borne spectral ghosts, and a semi-blind deconvolution method was proposed for the data correction. It consisted in an iterative numerical algorithm of the series of consecutive deconvolutions. The general problem of the data post-processing was subdivided into three separate sub-problems: definition of the vibration kernel, recovering of the original spectrum from the distorted one and the results validation. Finally the technique was tested on the data from the PFS (Planetary Fourier Spectrometer onboard Mars Express 2003) and the algorithm proved to be consistent according to the selected efficiency criteria (coming from the available general information about the signal spectral shape).
L’obiettivo di questo lavoro è la progettazione di uno spettrometro a Trasformata di Fourier miniaturizzato, denominato MicroMIMA (micro Mars Infrared MApper). Lo strumento è stato progettato per essere montato su un modulo di discesa della missione ESA “ExoMars 2016”. Il suo scopo è osservare l’atmosfera marziana dopo l’atterraggio per studiare la composizione. La risoluzione spettrale dello strumento è 2 cm⁻¹ (con la possibilità di incrementarla fino a 1 cm⁻¹), che è sufficiente per riconoscere le linee di assorbimento dei principali componenti della atmosfera. I vincoli di progettazione meccanica dello strumento erano:

- peso, dimensioni e potenza limitati;
- elevata resistenza a stress meccanici per sopportare l’urto dell’atterraggio;
- sopportare le severe condizioni ambientali senza utilizzo di potenza per la regolazione termica;
- resistenza alle vibrazioni di ampiezza elevata in banda larga generate al lancio.

La configurazione ottimale dello strumento è stata concepita per ottenere la più alta sensibilità e il minor rumore possibile nell’intervallo spettrale fra 2 e 5 µm. La massimizzazione del rapporto segnale-rumore è stata raggiunta ottimizzando la geometria ottica e selezionando i componenti ottici con la maggiore efficienza. Il rapporto segnale/rumore per il layout proposto è stato valutato per le applicazioni di laboratorio sulla Terra e nella missione su Marte.

La progettazione del modello è stata supportata da analisi a elementi finiti simulando i carichi statici e dinamici durante il lancio e l’atterraggio del sistema e da analisi termo-elastiche per il campo termico durante il processo di funzionamento. In più è stata realizzata l’ottimizzazione del sistema d’isolamento dalle vibrazioni.

È stato progettato un modello dimostrativo per verificare le caratteristiche operative dello strumento, che è stato semplificato dal punto di vista strutturale, ma con la ricostruzione dettagliata del layout ottico. Sono stati eseguiti il suo assemblaggio, l’allineamento e i test preliminari.

È stata inoltre elaborata una tecnica innovativa per il trattamento dei dati dello spettrometro a Trasformata di Fourier con lo scopo di ridurre l’effetto delle vibrazioni meccaniche. Questa tecnica corregge gli spettri separatamente, consentendo di aumentando la risoluzione spaziale del processo di mappatura. Infine l’algoritmo è stato validato usando i dati del PFS (Planetary Fourier Spectrometer a bordo di Mars Express 2003).
# 1. INTRODUCTION

Fourier transform spectroscopy is a technique to obtain high resolution spectra of the light. The main element of the Fourier spectrometer is the interferometer which gives an interferogram of the observed radiation. This introduction describes the working principle of the Fourier spectrometer in general, mentioning as well its application on the micro-MIMA, including its scientific objectives, construction, design constraints and technical requirements.

## 1.1 FTS working principle

Fourier Transform Spectrometer (FTS) working principle is based on the Michelson interferometer. The last one consists of light source, two mirrors (fixed and moving ones) and a half-transparent mirror (beam splitter) at the 45° angle, which divides the coming beam into two perpendicular rays with 50% intensity. Those two rays afterwards are recombined (through the collecting lens, parabolic mirror, etc.) at the detector and create the interferogram picture. In case of equal optical pathlengths of split rays, they will arrive to the detector in-phase coherent creating the constructive interference. By shifting the moving mirror optical paths change their lengths and thus the interference picture is modified. The generic scheme of such interferometer is presented on the Fig. 1.1 [1].

![Michelson interferometer scheme](image)

Figure 1.1. Michelson interferometer scheme. Symbols $t_{BS}$, $r_{BS}$ and $r_m$ are beamsplitter transmission, beamsplitter external amplitude reflection and mirror overall reflection coefficients correspondingly.

The interferometer working principle can be easily described by the example of the monochromatic light source [2].

The incident light-wave amplitude being represented by $e^{i\omega t}$, the emergent wave amplitude towards the detector becomes:

$$A = e^{i\omega t} t_{BS} r_{BS} r_m (e^{-i2\pi\sigma x_1} + e^{-i2\pi\sigma x_2})$$ \hspace{1cm} (1.1),

where $x_{1,2}$ are the optical pathlengths of the split beams and $\sigma$ is the wavenumber.
The emergent time-averaged intensity is the square of the amplitude:

\[ I = |A|^2 = 2R_{BS}T_{BS}R_m\{1 + \cos(2\pi\sigma(x_1 - x_2))\} \quad (1.2), \]

where \(R_{BS}\) and \(T_{BS}\) are the beamsplitter reflectance and transmittance, and \(R_m\) is the mirror reflectance.

Redefining the optical system efficiency as the \(\eta_0 = 4R_{BS}T_{BS}R_m\) and the optical path difference (OPD) as the \(x = x_2 - x_1\), we obtain the following equation:

\[ I(x) = \eta_0 \left[ \frac{1 + \cos(2\pi\sigma x)}{2} \right] \quad (1.3). \]

### 1.1.1. Instrumental function of a FTS.

Considering the source spectrum being continuous and consisting of a wide band of wavenumbers \(E(\sigma)\) (Fig. 1.2) \([1]\) and at that point not taking into account the optical efficiency \(\eta_0/4\), at the given OPD \(x\) the interference signal of the infinitesimal spectral element between \(\sigma\) and \(\sigma + d\sigma\) will be:

\[ dF(x, \sigma) = 2E(\sigma)[1 + \cos(2\pi\sigma x)] \quad (1.4), \]

and thus the total signal (so-called interference record) will be defined as:

\[ F(x) = 2 \int_0^\infty E(\sigma)[1 + \cos(2\pi\sigma x)] d\sigma \quad (1.5). \]

A typical interference record is shown on Fig. 1.3.

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**Figure 1.2.** A wide-band continuous spectrum \(E(\sigma)\) and an infinitesimal monochromatic section of the width \(d\sigma\).

Subtracting from the interference record the constant term, we obtain the interferogram \(I(x)\):

\[ I(x) = 2 \int_0^\infty E(\sigma) \cos(2\pi\sigma x) d\sigma \quad (1.6). \]
Figure 1.3. An interference record $F(x)$.

Definition of $E(-\sigma) = E(\sigma)$ simplifies the computation to:

$$I(x) = \int_{-\infty}^{\infty} E(\sigma) \cos(2\pi \sigma x) d\sigma = \int_{-\infty}^{\infty} E(\sigma) e^{i2\pi \sigma x} d\sigma = \mathcal{F}\{E(\sigma)\}$$  

$$E(\sigma) = \mathcal{F}^{-1}\{I(x)\}$$  

In FTS the output of a measurement is the interference signal in $x$-domain, while the information of interest is obtained from the $\sigma$-domain spectrum, calculated from the signal by inverse Fourier Transform.

Taking into account the fact that signal is sampled only in a finite region $x \in [-L, L]$ at $2N$ discrete points with a sampling interval $\Delta x$ (so that $L = N\Delta x$), we have:

$$E_L^{\Delta x}(\sigma) = \Delta x \sum_{j=-N}^{N-1} I_j e^{-i2\pi \sigma \Delta x}$$  

Truncation $I_L(x)$ can be represented as the product of the continuous interferogram $I(x)$ with the rectangular window $\Pi_{2L}(x)$, where

$$\Pi_{2L}(x) = \begin{cases} 1, & |x| \leq L, \\ 0, & |x| > L. \end{cases}$$

Spectrum from the truncated continuous interferogram will be:

$$E_L(\sigma) = \mathcal{F}^{-1}\{\Pi_{2L}(x)I(x)\} = \mathcal{F}^{-1}\{\Pi_{2L}(x)\} \ast \mathcal{F}^{-1}\{I(x)\} = W_L(\sigma) \ast E(\sigma)$$  

Spectrum from infinitely long sampled interferogram will be:

$$E^{\Delta x}(\sigma) = \Delta x \sum_{j=-\infty}^{\infty} I_j e^{-i2\pi \sigma j \Delta x} = \sum_{k=-\infty}^{\infty} \delta\left(\sigma - \frac{k}{\Delta x}\right) \ast E(\sigma)$$

Finally the spectrum from sampled truncated interferogram becomes:

$$E_L^{\Delta x}(\sigma) = \sum_{k=-\infty}^{\infty} \delta\left(\sigma - \frac{k}{\Delta x}\right) \ast W_L(\sigma) \ast E(\sigma) = W_L^{\Delta x}(\sigma) \ast E(\sigma)$$
where $W_L^{Δx}(σ)$ is the instrumental function of a Fourier transform spectrometer,

$$W_L^{Δx}(σ) = \sum_{k=-\infty}^{\infty} 2L \text{sinc} \left[ 2\pi \left( σ - \frac{k}{Δx} \right) L \right] \quad (1.13)$$

The above discussion was performed for the rays travelling along the instrument optical axis, what is not true in the generic case as the instrument is characterized by some field of view (FOV) according to its optical configuration parameters.

If the OPD of rays incoming from the source along the optical axis is $x$, then the OPD of rays travelling in the direction $α$ with respect to the optical axis is $x \cos α \approx x \left( 1 - \frac{Ω'}{2π} \right)$, where $Ω' = πα^2$ (Fig. 1.4).

![Figure 1.4. Rays’ travel inside the interferometer FOV.](image)

Having $β$ as the instrument FOV cone half-angle (and correspondingly $Ω=πβ^2$ its FOV solid angle) the direction of rays coming from source $α ∈ [0, β]$, in other words $Ω' ∈ [0, Ω]$.

The total interferogram is obtained by integrating over the FOV solid angle:

$$I_Ω(x) = \int_0^Ω I \left[ x(1 - \frac{Ω'}{2π}) \right] dΩ' = Ω \int_{-∞}^{∞} E(σ)\text{sinc} \left( \frac{σxΩ}{2} \right) e^{i2πσx(1-\frac{Ω'}{2π})} dσ \quad (1.14)$$

The spectrum computed from the interferogram will be:

$$E_Ω(σ) = \mathcal{F}^{-1}[I_Ω(x)] = W_Ω(σ) * E(σ) \quad (1.15),$$

where $W_Ω(σ)$ is the instrumental function due to the instrument FOV, in general it causes broadening of the spectral lines and their shift in the wavenumber.
1.1.2. Alternative FTS configurations.

Planar mirrors in the classical Michelson interferometer might be substituted by the cubic corner reflectors. The most generic scheme of such configuration is presented on Fig. 1.5.

Figure 1.5. Optical configuration of a double pendulum interferometer.

The working principle is the same (incoming light beam is divided in two, reflected on mirrors and an interferogram is obtained on the detector). In this case the optical retardation is provided by the rotation of both mirrors around the pendulum axis.

Such configuration has a list of advantages comparing with the classical scheme:

- usage of rotation movement instead of translation is more preferable in terms of tolerances (realization of usual bearing system is much easier than one of a linear guide);
- it also appears to be more compact for the mass and volume constraints.

Generally lots of more complicated FTS configurations were developed, each time based on the particular instrument requirements. As an example on Fig. 1.6 are presented some of such configurations.
Figure 1.6. Alternative configurations of a FTS instrument: a - alternative double-pendulum configuration; b – alternative Michelson configuration; c - Genzel interferometer; d – “The Web” (Genzel-type interferometer).

1.1.3. Sampling strategies in the FTS.

The Fourier Transform Spectrometer needs sampling at the constant optical path differences, not provided by the constant time sampling strategy in case of variations (e.g. caused by mechanical vibrations) in speed of interferometer mirrors. In such case non-constant OPD sampling would complicate the post-processing techniques as the spectra would not be provided by use of the usual FT algorithms for constant sampling.

The most common strategy that allows moving the interferogram acquisition from the time to the OPD domain, is usage of a reference laser source for triggering the data acquisition. In the interferometer the light from the laser travels through the same optics as the main beam of incoming radiation. The additional detector collects the laser signal at the output of the instrument. Then control electronics detect the zero-crossing of the laser interferogram and give a trigger signal for data acquisition on the main detectors. Being done at the each zero-crossing the sampling OPD step will be equal the laser half wavelength $\lambda_{laser}/2$.

The moments to notice in this strategy is that the laser line wavelength is a function of its temperature, thus the last has to be stabilized and under constant control. Another peculiarity relates to the different time delays in the acquisition chains of main and laser signal; in other words data acquisition is held not exactly at the zero-crossing of the laser interferogram, that in presence of speed variations would provide sampling step errors.
1.2. Aurora Programme: ExoMars missions.

The ESA Directorate of Human Spaceflight, Microgravity and Exploration developed the Aurora Programme in order to perform the future exploration of the Solar System using robot systems as well as human crews. Plan of Aurora consists of the several robotic missions, each well technologically equipped and ready to act as an independent building block (to ensure possible human presence in the exploration process). First goals to be investigated are Mars and Moon, then probably other near earth objects.

ExoMars programme is 1st in these series of missions. It is supposed to create the base for further exploration activities of ESA, with the fundamental scientific task as the main goal: search for extinct or extant life.

It was conceived in 2007 as divided into following 2 subsequent missions:

- one mission under ESA lead, launched in 2016 by a US launcher including a joint US-European Orbiter releasing a European EDL demonstrator;

- another mission under NASA lead, launched in 2018 by a US launcher including a European Rover and a US Rover both deployed by a US EDL system.

After the withdrawal of the NASA contribution in 2010 the US role was taken by the Russian Space Agency.

1.2.1. “ExoMars 2016: Orbiter and EDL demonstrator”.

ExoMars 2016 mission shall accomplish the following objectives:

- Technological objective: Entry, Descent and Landing (EDL) of a payload on the surface of Mars;
- Scientific objective: to investigate Martian atmospheric trace gases and their sources;

ESA will design, build and integrate a large Spacecraft Composite consisting of an ESA Orbiter which will carry the scientific trace gas payload instrumentation and an ESA EDL Demonstrator. The Spacecraft Composite will be launched in early January 2016 by a NASA and will arrive at Mars approximately 9 months later in mid-October of 2016. Prior to arrival at Mars the ESA EDL Demonstrator will be released from the ESA Orbiter and will enter the Mars atmosphere from a hyperbolic arrival trajectory. The release of the EDL Demonstrator will take place 3-5 days prior to the critical Mars Orbit Insertion manoeuvre by the ExoMars Orbiter. The sequence of manoeuvres following the separation will be designed to maximise the chance of receiving the UHF radio beacon signals from the EDL Demonstrator during its Entry, Descent and Landing phase. Subsequently, the ExoMars Orbiter will begin a series of manoeuvres to arrive at the science and communications orbit with an altitude in the range of 350 Km to 420 Km. The science operations phase is expected to begin at the earliest in May of 2017 (depending on the actual duration of the aerobraking phase) and last for a period of one Martian year.
**European Orbiter**

The Exomars Orbiter (Fig. 1.5) is built around the Spacebus telecommunication platform from TAS-F with an avionic module (or service module) located on the basis of the platform and a primary structure built around an 1194 mm central tube. The dry mass of the Orbiter is about 1000 kg. The nominal lifetime of the system is 7 years so the Orbiter will be operational till end of 2022, assuming its launch to be performed in January 2016.

The Orbiter configuration provides space to accommodate all science Instruments, in the area of the –Y panel also called Mars Nadir face (Fig. 1.7 A) and the +X panel looking at the cold space during the Mars orbit science phase (Fig. 1.7 B).

The total maximum mass allocated for all of the instruments is 125 kg. They shall be mounted on one of two mounting planes (Fig. 1.8).
Payload will include set of instruments to achieve following main scientific objectives of the mission:

- detection of a broad suite of atmospheric trace gases;
- characterization of their spatial and temporal variation;
- localization of source of key trace gases.

**European EDL demonstrator**

The EDL Demonstrator (Fig. 1.9) will provide Europe with the technology of landing on the surface of Mars with a controlled landing orientation and touchdown velocity. The design maximises the use of technologies already in development within the ExoMars programme.

These technologies include:

- Thermal Protection System Material;
- Parachute System;
- Radar Doppler Altimeter;
- Liquid propulsion controlled final braking.

The configuration of the ESA EDL Demonstrator will include engineering sensors for system performance evaluation during EDL phase. As the arrival of the Demonstrator might contemporize Mars Global Dust Storm all system will be designed to survive such severe environment.

Figure 1.9. ExoMars 2016 European EDL Demonstrator
After entry a single stage Disk Gap Band parachute will be deployed and the landing process will be controlled by closed-loop Guidance, Navigation and Control (GNC) system consisting of Radar Doppler Altimeter sensor and onboard Inertial Measurement Units (for liquid propulsion system).

The EDL Demonstrator is expected to survive on the surface of Mars for a short time by using the energy capacity of its primary batteries. So it will be equipped by the specific Instrumental Payload which will gather information about Martian atmosphere and environment conditions using available resources of Demonstrator without adding any additional systems for solar power generation or for thermal control. The *Infra-Red Fourier Spectrometer micro-MIMA* was initially designed as an element of the Demonstrator Payload, although afterwards it has not been selected.

**1.2.2. “ExoMars 2018: Rover and Pasteur Payload”**

Main scientific objectives of ExoMars2018 (listed in order of priority) are:

- search for any evidence of present/past life on Mars;
- acquire 3-dimensional water/geochemical environment of Mars surface;
- evaluation of the conditions for further human missions;
- subsurface and deep interior of the planet investigation (to make conclusions about habitability and evolution of Mars).

The ExoMars 2018 payload instrumentation will be located on two different vehicles: Pasteur payload – on the moving Rover (Fig. 1.10), Geophysics and Environment Package (GEP) Payload – on the fixed station (which also will perform functions of the lander of the rover). Rover Payload will follow 1st two of the named goals. It will be autonomic for regional mobility of several kilometers using solar energy as the power source.

![Fig.1.10 ExoMars 2018 Pasteur Rover](image-url)
1.2.3. Mission environmental conditions

Environmental conditions predicted for ExoMars 2018 Payload are following:

- non-working temperature variations around -100÷120°C,
- operative temperature up to about -70°C.

Comparing with Earth Mars environment is affected by higher levels of radiation:

- total ionizing radiation 2.5 krad (for 4 mm aluminum shielding);
- non-ionizing energy loss 5 107 MeV/g (for 4 mm aluminum shielding).

1.2.4. Mission dynamic loads

The dynamic loads listed in the ExoMars 2018 payload requirements [3] are the following:

- landing load: a quasi-static acceleration of 1000 m/s² related to the shock of landing on Mars surface;
- sweep sine: vibrations in a frequency range of 30-100 Hz;
- random excitation: an rms acceleration value of 170 m/s² spread in a frequency range between 20-2000 Hz.

1.3. MicroMIMA.

The Micro-MIMA (micro Martian Infrared Mapper) is a Fourier Transform Spectrometer, designed for the on-site atmospheric studies.

1.3.1. Objectives.

The Micro-MIMA is designed as a proposal for the European EDL Demonstrator scientific payload. It was supposed to be accommodated on mounting deck on the top Demonstrator, and its main scientific goal was the study of the planet atmosphere through the analysis of the absorption bands in the Sun Transmission Spectrum. Such information provides the data about the atmosphere gas-composition, useful to make conclusions about possible biological activity and to check the meteorological conditions at the landing site.

Therefore, MicroMIMA will detect presence and concentration of the CH₄, H₂O, N₂O, SO₂, CO, O₃ and other molecules. Special attention will be paid to the methane component due to the fact that its presence in Martian atmosphere has been firstly identified by observation of the Planetary Fourier Spectrometer onboard Mars Express 2003, but is still to be confirmed by other instruments. Hypothetical reasons for methane existence are either biological or related to volcanic activity. Both of those origins are not compatible with the present conception of Martian environment.

1.3.2. Working principle.

The MicroMima is a double pendulum Fourier Transform Spectrometer. In the classical Michelson interferometer the optical path difference is carried out by translating the moving mirror along a linear direction, while in MIMA, the OPD is produced by rotating a double pendulum system around its axis. Such a preference is explained by the fact that the double pendulum configuration allows mounting of the moving elements on a bearing system, which is much easier to realize in
comparison with a linear guide (considering the tolerances required by the interferometer). Also double pendulum scheme provides a more compact solution in terms of mass and volume.

As the MicroMIMA was intended to be mounted on the descending module mast, whose position and pointing cannot be predicted in advance [4], its optical layout requires a collecting elements of wide Field-of-View or a sun-tracking mechanism, in order to align the arbitrary directed incoming radiance with the instrument optical axis.

In order to sample the interferogram at the constant optical path difference steps, a reference laser interferogram is acquired in parallel, and its zero-crossings are used as a trigger for the main signal acquisition.

The full optical scheme and the instrument working principle will be discussed in details in the following chapters.

1.3.3. Micro-MIMA functional requirements

Following the scientific purposes the instrument is designed to measure atmosphere spectra with resolution sufficient to identify its gas content by analysis of spectral features of the acquired signal.

The summary of the instrument functional requirements is given below:

- spectral range 2.0-5 μm wavelength (2000 – 5000 cm\(^{-1}\) wavenumber);
- spectral resolution 2 cm\(^{-1}\) (leaving possibility for 1 cm\(^{-1}\));
- entrance optics FOV 140°;
- instrument FOV 1.8°;
- max optical path difference 5 mm (±2.5 mm double sided interferogram, leaving possibility for ±5 mm OPD in case spectral resolution of 1 cm\(^{-1}\));
- single PbSe detector;
- overall mass budget including electronics 250 g (note: max excess of 10%) with estimated quota of 50 g for instrument itself.
References CHAPTER 1.


2. PERFORMANCE OPTIMIZATION

In this chapter the optimal FTS configuration is derived for the maximum signal detection and reduction of noise. The optimization is held within the instrument performance requirements and mechanical budget limits. For the proposed optical layout the theoretical SNR is evaluated under different incident radiation conditions.


The FTS instrument is designed as the double-pendulum interferometer (Fig. 1.5). Its optical layout consists in the entrance optics, folding mirror, beamsplitter, corner cubic mirrors, collecting lens and photodetecting element (Fig. 2.1).

Figure 2.1. Optical layout scheme.

It is convenient to represent SNR of the instrument in the wavenumber domain, in other words:

\[ SNR(\sigma) = \frac{L_s(\sigma)}{NESR(\sigma)} = \frac{P_s(\sigma)}{NEP(\sigma)} \]  \hspace{1cm} (2.1)

where SNR is the signal-to-noise ratio; \( L_s(\sigma) \) is incident spectral radiance, \( W/(sr \ cm^2 \ cm^{-1}) \); NESR is the Noise Equivalent Spectral Radiance of the instrument, \( W/(sr \ cm^2 \ cm^{-1}) \); \( P_s(\sigma) \) is arriving to the detector power in the given wavenumber band, \( W \); NEP is the Noise Equivalent Power in the corresponding frequency band, \( W \).

2.1.1. Signal definition.

Signal power arriving to the detector can be expressed in terms of incident spectral radiance:

\[ P_s(\sigma) = \xi(\sigma)\Theta\Delta\sigma \frac{L_s(\sigma)}{2} \]  \hspace{1cm} (2.2)

where \( \xi(\sigma) \) is the instrument efficiency (overall transmittance), including reflection losses, transmittance of optical elements, modulation efficiency, and other losses due to aberrations, misalignment, instrument line shape etc.; \( \Theta \) is the instrument throughput, \( cm^2 \ sr \); \( \Delta\sigma \) is the instrument nominal spectral resolution, \( cm^{-1} \).
The instrument throughput can be defined as:

\[ \Theta = A\Omega = A\pi\beta^2 \]  

(2.3)

where \( A \) is the instrument pupil area, cm\(^2\); \( \Omega \) is the instrument FOV solid angle, sr; \( \beta \) is the instrument FOV cone half-angle, rad.

Calling back (1.x, 1.y, 1.z) we can define the instrument efficiency \( \xi \) as:

\[ \xi(\sigma) = \eta_0 m_{2L,\Omega}(\sigma)m_1(\sigma u) \]  

(2.4)

where \( \eta_0 \) is the instrument optical efficiency; \( m_{2L,\Omega}(\sigma) \) is the modulation factor due to the instrument line shape, caused by the \([-L; L]\) truncation of interferogram and variations of OPD for rays inside the FOV; \( m_1(\sigma u) \) is the modulation factor due to optical misalignments \( u \) (for the perfectly aligned instrument \((u = 0)\) we have \( m_1(0) = 1 \)).

Referring to (1.y, 1.z) and neglecting the frequency shift, the signal modulated by the instrumental function can be represented as following:

\[ P_{L,\Omega}(\sigma) = W_{\Omega}(\sigma) * W_{L}(\sigma) * P(\sigma) \]  

(2.5.1)

\[ W_{\Omega}(\sigma) = \mathcal{F}^{-1} \left[ \Omega \cdot \text{sinc}(\frac{\sigma \Omega}{2}) \right] \]  

(2.5.2)

\[ W_{L}(\sigma) = 2L \cdot \text{sinc}(2\pi\sigma L) \]  

(2.5.3)

where \( W_{\Omega}(\sigma) \) is the instrument function due to FOV modulation effect (Fig. 2.2, a); \( W_{L}(\sigma) \) is the instrument function due to interferogram truncation (Fig. 2.2, b).

It is convenient to separate the FOV and truncation effects by definition of corresponding modulation factors \( m_{\Omega} \) and \( m_{2L} \):

\[ m_{2L,\Omega} = m_{2L}m_{\Omega}(\sigma) \]  

(2.6)

Actually values \( m_{2L} \) and \( m_{\Omega} \) will depend on the observed signal. For the general one they can be assumed as:
\[ m_{2L} = \frac{A_{trunc}}{A_I} \]  
\[ m_{\Omega} = \frac{A_{\Omega}}{A_{II}} \]

Where \( A_{trunc}, A_{\Omega}, A_I, A_{II} \) are the areas as shown on the Fig. 2.2.

\[ A_{trunc} = \int_{\frac{\Delta \sigma}{2}}^{\frac{\Delta \sigma}{2}} W_L(\sigma) d\sigma = \int_{-\frac{1}{4L}}^{\frac{1}{4L}} 2L \text{sinc}(2\pi \sigma L) d\sigma = \frac{2}{\pi} \text{Si} \left( \frac{\pi}{L} \right) \]  
\[ A_{\Omega} = \int_{-L}^{L} W_\Omega(x) dx = \int_{-L}^{L} \text{sinc} \left( \frac{\sigma \Omega}{2} \right) dx = \frac{4}{\sigma} \text{Si} \left( \frac{\sigma \Omega}{2} \right) \]  
\[ A_I = 2L \Delta \sigma = 1 \]  
\[ A_{II} = 2L \Omega \]

Finally we obtain:

\[ m_{trunc} \approx 0.87 \]

\[ m_{\Omega} = \frac{2}{\sigma \Omega L} \text{Si} \left( \frac{\sigma \Omega L}{2} \right) \]

where \( \text{Si} \) is the sinc integral function.

### 2.1.2. Noise definition.

The detection sensitivity is generally described by the detector NEP and Detectivity \( (D^*) \). NEP is the minimum detectable signal power, that is the quantity of the incident light equal to the intrinsic noise level of a detector-instrument system. In other words, this is the quantity of incident light when the SNR is equal to 1. Detectivity refers to the photo sensitivity per unit active area of a detector.

The NEP and Detectivity are described by the noise mechanisms on the detector and are related to each other:

\[ D^*(\sigma) = \sqrt{\frac{A_d \Delta f}{\text{NEP}(\sigma)}} \]  
\[ \Delta f = \frac{1}{t} \]

where \( A_d \) is the detector active area, \( \Delta f \) is the frequency band where NEP is calculated, \( t \) is the single scan time.

Main noise sources occurring during detecting IR radiation:

- operating circuits;
- infrared detector itself;
- the radiation noise (coming from the signal or background fluctuations).

**Operating circuits** cause the post detector electronic noise. Sometimes the circuitry after the detector determines the lowest measurable signal, particularly for detectors which do not provide some internal
amplification of the photocurrent. By contrast, the almost noise-free internal amplification of photomultipliers accounts for their superb performance.

Types of **IR detector intrinsic noise**, characteristic for different detector types:

- **Generation-recombination noise.** It is seen in photo-conductors in which the absorbed photons produce both positive and negative charge carriers. Some of the free carriers may recombine before they are collected. Thermal excitation may generate additional carriers. Both the generation and recombination occur randomly, resulting in noise fluctuations in the output current.

- **Johnson noise (thermal),** caused by the random motion of carriers in a conductor. The result is fluctuations in the detector’s internal resistance, or in any resistance in series with the detector's terminals.

- **Flicker or 1/f noise,** which is not well understood. It occurs in detectors such as photoconductors which require a biasing current. Its magnitude is proportional to $1/f^B$ where $B$ is usually between 0.8 and 1.2.

- **Readout noise** for array detectors, associated with the uncertainties introduced during the transfer of charges between storage registers.

The radiation has a discreet nature as it is composed of photons arriving randomly in time. Absorbed photons produce photoelectrons at random intervals, and this variation in current appears as noise – the so-called **shot noise.** This noise can be generated by actual desired signal photons or by background photon flux. In case of low noise detectors and circuits, the photodetection will be described as **signal or background limited** (depending which radiation flux is prevailing).

The detectivity in such situation is described by formula:

$$D^*(\lambda) = \frac{\lambda\sqrt{\eta}}{\zetahc\sqrt{Q}}$$  \hspace{1cm} (2.10)

where $\lambda$ is the wavelength; $\eta$ is the detector quantum efficiency; $h$ is the Planck constant; $c$ is the speed of light; $Q$ is the photon flux density of signal or background radiation; $\zeta$ is the coefficient dependent on the used type of detector ($2$ for photoconductive detectors and $\sqrt{2}$ for the photovoltaic ones).

The additional of noise sources:

- **Microphonic noise,** caused by vibration or shock.
- **Temperature noise** on the detector caused by fluctuations in their temperature.

2.2. **Signal to noise ratio optimization.**

The SNR optimization can be performed in two different manners: by means of maximization of the signal arriving at the detector, and by reduction of generated noise. Both techniques will be covered in this section, taking the provided mechanical constraints as the imposed limits for optimization.
2.2.1. Signal maximization.

From the (2.2 – 2.4) it is seen that the detector incident radiation strongly depends on the instrument configuration. Under the same illumination conditions different signal levels would be detected according to the size and efficiency of the optical elements.

In other words increase of area of instrument pupil (i.e. the collecting lens) leads to the gain in the incoming signal, the proper detector size provides the optimal FOV of the instrument, various entrance optics configurations provide different optical efficiency, and finally materials are to be chosen according to their optical performances in the wavenumber band of interest.

Optics material choice.

The optical efficiency $\eta_o$ of the instrument depends on the optical properties of its elements.

The following parameters are to be optimized by the appropriate material choice:

- transmittance of substrate (lenses, beamsplitter);
- reflectance of optical coating (mirrors, beamsplitter).

The wavelength range of instrument application is 2..5 $\mu$m. On Fig. 2.3 transmittance of various optical materials is presented as a function of wavelength.

![Figure 2.3. Optical materials transmittance [1].](image)

From the above plot it is seen that $\text{CaF}_2$ substrate provides the highest transmittance characteristics for the wavelength range of interest.

Regarding beamsplitter, the available off-the-shelf choices are presented in the Table 2.1.
<table>
<thead>
<tr>
<th>Beamsplitter substrate</th>
<th>Beamsplitter coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV Fused Silica</td>
<td>250 – 450 nm</td>
</tr>
<tr>
<td></td>
<td>400 – 700 nm</td>
</tr>
<tr>
<td></td>
<td>700 – 1 100 nm</td>
</tr>
<tr>
<td></td>
<td>350 – 1 100 nm</td>
</tr>
<tr>
<td></td>
<td>600 – 1 700 nm</td>
</tr>
<tr>
<td></td>
<td>1.2 – 1.6 µm</td>
</tr>
<tr>
<td>IR Fused Silica</td>
<td>0.9 – 2.6 µm</td>
</tr>
<tr>
<td>Calcium Fluoride</td>
<td>2 – 8 µm</td>
</tr>
<tr>
<td>Zinc Selenide</td>
<td>7 – 14 µm</td>
</tr>
</tbody>
</table>

Table 2.1. Broadband plate beamsplitter guide [2].

The preferred solution will be the \( \text{CaF}_2 \), as for other optical elements. Transmittance and reflectance curves for the beamsplitter plate are given on the Fig. 2.4.

The mirror coatings characteristics are given in the Table 2.2.

<table>
<thead>
<tr>
<th>Coating type (metallic)</th>
<th>Wavelength range, nm</th>
<th>Per-surface reflectance*, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enhanced aluminium</td>
<td>400 – 700</td>
<td>93</td>
</tr>
<tr>
<td>IR-enhanced aluminium</td>
<td>600 – 1 600</td>
<td>89</td>
</tr>
<tr>
<td>Protected aluminium</td>
<td>400 – 750</td>
<td>87</td>
</tr>
</tbody>
</table>

Figure 2.4. Beamsplitter characteristics: \( a \) – transmittance, \( b \) – reflectance [2].
<table>
<thead>
<tr>
<th></th>
<th>Reflectance</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare aluminium</td>
<td>225 – 10 000</td>
<td>90</td>
</tr>
<tr>
<td>UV-enhanced aluminium</td>
<td>225 – 700</td>
<td>89</td>
</tr>
<tr>
<td>Protected silver</td>
<td>450 – 10 000</td>
<td>96</td>
</tr>
<tr>
<td>Protected gold</td>
<td>650 – 16 000</td>
<td>97</td>
</tr>
<tr>
<td>Bare gold</td>
<td>650 – 20 000</td>
<td>97</td>
</tr>
</tbody>
</table>

Table 2.2. Characteristics of CCM coatings [3].

As it is seen from the table above, protected and bare gold coatings provide the higher reflectance. The Fig. 2.5 represents reflectance as a function of wavelength for those coatings.

![Figure 2.5. Optical coatings reflectance: a – protected gold, b – bare gold [3].](image)

The **bare gold coating**, unlike the protected gold one, does not show any drops in the reflectance and is picked as the optical material choice.

**Entrance optics configuration choice**

The proposed configurations for the entrance optics are the Fish-Eye system of lenses and the Pointing mechanism (Fig. 2.6).

![Figure 2.6. Entrance optics proposed configurations: a – Fish-Eye scheme; b – Pointing mechanism scheme.](image)
Each configuration represents an advantage: for the same instrument pupil size, the Fish-Eye system offers lower mass and volume and intrinsic reliability having no moving parts, the Pointing mechanism besides provides a higher optical efficiency.

It must be noticed that the Fish-Eye advantage in throughput is valid for extended sources, if the instrument FOV is larger than the source one (i.e. in Sun observations under clear sky), the throughput is actually driven by the source FOV (Table 2.3).

The optical efficiency of the Fish-Eye system \( \eta_o \) is about 15% while the Pointing mechanism \( \eta_o \) depends on the number of used mirrors \( N \) and on the reflectivity of their coating \( R_M \):

\[
\eta_o \text{PM} = R_M^N \quad (2.11)
\]

<table>
<thead>
<tr>
<th>Entrance optics configuration</th>
<th>Optical efficiency</th>
<th>Throughput for extended source (( A ) – instrument pupil area, ( \Omega_s ) – detector solid angle FOV, ( A_{\text{FISH-EYE}} ) – fish-eye area)</th>
<th>Throughput for small FOV sources (( A ) – instrument pupil area, ( \Omega_s ) – source solid angle FOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fish-Eye system ( (A_{\text{FISH-EYE}} )–area of system aperture)</td>
<td>0.15</td>
<td>( \theta = \Omega_{\text{FISH-EYE}} A_{\text{FISH-EYE}} )</td>
<td>( \theta = \Omega_s A_{\text{FISH-EYE}} )</td>
</tr>
<tr>
<td>Pointing mechanism ( (N = 2, R_M = 95%) )</td>
<td>0.9</td>
<td>( \theta = \Omega_d A )</td>
<td>( \theta = \Omega_s A )</td>
</tr>
</tbody>
</table>

Table 2.3. Optical efficiency and instrument throughput for different entrance optics configurations.

Signal power passing through the entrance optics can be expressed as following:

\[
P_{\text{SIGNAL}} = \eta_o \theta L_s \quad (2.12)
\]

where \( \eta_o \) is the entrance optical efficiency and \( L_s \) is the source spectral radiance.

As said above, the Pointing mechanism mass is expected to be larger than the corresponding Fish-Eye system thus, it is necessary to perform a tradeoff between required mass and efficiency of the entrance optics, taking into account also the source characteristics and the instrument FOV angles. As an option of mass reduction for instruments with large aperture, it can be adopted alternative configuration without any pointing system, as the sufficient signal level will be achieved anyway.

**Optics size optimization**

To make the optimal choice of the optical elements size a rough instrument design, meeting the mechanical environment requirements has been performed along with the tradeoff analysis between the optical performance (SNR) and the instrument mass.

With the given mass constraint the best SNR figure was achieved with an interferometer having a pupil diameter 12 mm and the fisheye foreoptics.
The final optical scheme is shown on Fig. 2.7.

**Figure 2.7. Optical elements size, mm.**

**Detector size optimization.**

The size of detector is another parameter to be optimized in order to obtain maximum signal level. Basically it determines the instrument FOV angle $\Omega$, and as it is seen from (2.5.1-2.5.2) the signal power is strongly correlated to the $\Omega$ value. The optimal FOV corresponds to the maximum area $A_\Omega$ under the $W_\Omega$. As the area $A_\Omega$ is function not only of FOV angle, but also of the component wavenumber $\sigma$ (2.7.4), the maximization of $A_\Omega$ for different $\sigma$ will provide different optimal $\Omega$.

As the optimization criteria we choose maximization of signal power for the maximum wavenumber in the range of interest:

$$
\max(A_\Omega) = \max \left( \frac{4}{\sigma_{\max}} \text{Si} \left( \frac{\sigma_{\max} \Omega L}{2} \right) \right) = A_\Omega \bigg|_{\Omega = \Omega_{opt}} = \frac{4}{\sigma_{\max}} \text{Si} \left( \frac{\sigma_{\max} \Omega_{opt} L}{2} \right) \quad (2.13.1)
$$

$$
\max \left( \frac{4}{\sigma_{\max}} \text{Si} \left( \frac{\sigma_{\max} \Omega L}{2} \right) \right) = \frac{4}{\sigma_{\max}} \text{Si}(\pi) \quad (2.13.2)
$$

$$
\Omega_{opt} = \frac{2\pi}{\sigma_{\max} L} \quad (2.13.3)
$$

The maximum OPD $2L$ can be found as the inverse of the spectral resolution $\Delta\sigma$:

$$
2L = \frac{1}{\Delta\sigma} \quad (2.14)
$$

Then for the spectral resolution of $2\text{cm}^{-1}$ and wavenumber range of interest $\sigma \in [2000, 5000] \text{ cm}^{-1}$ we get the optimal FOV solid angle $\Omega_{opt} = 0.005 \text{ sr}$.

The instrument FOV is determined by the gathering lens focal length and the detector size (Fig. 2.8).
The instrument half-cone FOV $\beta$ can be calculated as following:

$$\beta \approx \arctan\left(\frac{d}{2L_f}\right) \quad (2.15)$$

where $d$ is the detector size and $L_f$ is the gathering lens focus length.

Instrument FOV solid angle in its turn will be:

$$\Omega = \pi\beta^2 \quad (2.16)$$

From (2.15) and (2.16) we can find the detector size for the FOV optimization:

$$d = 2L_f \tan\left(\sqrt[2]{\frac{\Omega_{\text{opt}}}{\pi}}\right) \quad (2.17)$$

For the chosen lens focal length of 20 mm we get the recommended detector size of 1.6 mm.

It has to be noted that above calculations are valid for the extended radiation source. In case of non-extended source ($\Omega_{\text{source}} < \Omega_{\text{instrument}}$) detector size can be evaluated according to the following expression:

$$d = 2L_f \tan\left(\sqrt[2]{\frac{\Omega_{\text{source}}}{\pi}}\right) \quad (2.18)$$

### 2.2.2. Noise reduction

The noise reduction problem is solved by means of choice of the appropriate type of the photodetector, additionally optimizing its operating conditions to achieve the highest photodetection performance.

**Detector type choice**

The information about available infrared photodetectors is summarized on the Table 2.4. There is a number of detectors efficient in our wavelength range of interest (2.5 $\mu$m): PbSe, InSb, HgCdTe, quantum extrinsic type ones. However with regards to the power budget limitation up to 5W, we are forced chose the PbSe detector as the one of the highest operating temperature – and thus with the minimum cooling power required.
Having the detectivity increasing with decrease of operating temperature, we use the one-stage thermoelectric cooling ($\Delta T = -50^\circ C$) as the superior within the limits for the cooling power budget.

Calling back equations (2.9.1-2.9.2), for the given spectral resolution the noise reduction problem is a trade-off solution between the detector detectivity $D^*$ and the scan time $t$. On the other hand the final SNR can be increased by means of averaging $N$ subsequent scans, obtaining:

$$SNR_{TOTAL} = SNR_{single \ scan} \sqrt{N} = \frac{L_s(\sigma)}{\text{NESR}(\sigma)} \sqrt{N} = L_s(\sigma) \frac{D'(\sigma) \xi(\sigma) \theta \Delta \sigma \sqrt{t}}{2 \sqrt{A_D}} \sqrt{N}$$

$$N = \frac{t_{tot}}{t}$$

(2.19.1)

(2.19.2),

where $t_{tot}$ is the time of $N$ scans,

$$SNR_{TOTAL} = L_s(\sigma) \frac{D'(\sigma) \xi(\sigma) \theta \Delta \sigma}{2 \sqrt{A_D}} \sqrt{t_{tot}}$$

(2.19.3)

Finally the optimization of the SNR does not require a trade-off analysis on $t$ and the problem is reduced to the $D^*$ maximization.

**Main noise sources.**

Main noise sources occurring during detecting IR radiation are:

- noise generated by the electronic circuit for signal conditioning and ADC;
- the intrinsic radiation noise (coming from the signal or background fluctuations);
- detector noise.

Electronic **circuits** cause the post detector electronic noise, its reduction below the detector noise is the goal of the electronic chain design which is not addressed in this work, it will be assumed that it is negligible in comparison with the other sources.

---

**Table 2.4. Types of infrared detectors and their characteristics [1].**

<table>
<thead>
<tr>
<th>Type</th>
<th>Detector</th>
<th>Spectral response (µm)</th>
<th>Operating temperature (K)</th>
<th>$D'(\text{cm} \cdot \text{Hz}^{1/2} / \text{W})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple · Thermopile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boloimeter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pneumatic cell</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyroelectric detector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Golog cell, condenser-microphone</td>
<td>Depends on window material</td>
<td>300</td>
<td>$D'(\lambda,10,1) = 6 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$D'(\lambda,10,1) = 1 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$D'(\lambda,10,1) = 2 \times 10^3$</td>
</tr>
<tr>
<td>Intrinsic type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photocondoctive type</td>
<td>PbS</td>
<td>1 to 3.6</td>
<td>300</td>
<td>$D'(500,600,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>PbSe</td>
<td>1.5 to 5.8</td>
<td>300</td>
<td>$D'(500,1200,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>2 to 6</td>
<td>213</td>
<td>$D'(500,1200,1) = 2 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>HgCdTe</td>
<td>2 to 16</td>
<td>77</td>
<td>$D'(500,1000,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td>Photovoltaic type</td>
<td>Ge</td>
<td>0.8 to 1.9</td>
<td>300</td>
<td>$D'(500,600,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>InGaAs</td>
<td>0.7 to 1.7</td>
<td>300</td>
<td>$D'(500,600,1) = 5 \times 10^3$</td>
</tr>
<tr>
<td></td>
<td>Ex. InGaAs</td>
<td>1.2 to 5.55</td>
<td>253</td>
<td>$D'(500,1200,1) = 2 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>InAs</td>
<td>1 to 3.1</td>
<td>77</td>
<td>$D'(500,1200,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>1 to 5.5</td>
<td>77</td>
<td>$D'(500,1200,1) = 2 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>HgCdTe</td>
<td>2 to 16</td>
<td>77</td>
<td>$D'(500,1000,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td>Extrinsic type</td>
<td>Ge : Au</td>
<td>1 to 10</td>
<td>77</td>
<td>$D'(500,600,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>Ge : Hg</td>
<td>2 to 14</td>
<td>4.2</td>
<td>$D'(500,600,1) = 8 \times 10^8$</td>
</tr>
<tr>
<td></td>
<td>Ge : Cu</td>
<td>2 to 30</td>
<td>4.2</td>
<td>$D'(500,600,1) = 5 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>Ge : Zn</td>
<td>2 to 40</td>
<td>4.2</td>
<td>$D'(500,600,1) = 5 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>Si : Ga</td>
<td>1 to 17</td>
<td>4.2</td>
<td>$D'(500,600,1) = 5 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>Si : As</td>
<td>1 to 23</td>
<td>4.2</td>
<td>$D'(500,600,1) = 5 \times 10^5$</td>
</tr>
</tbody>
</table>
The second cause is related to the radiation discrete nature as it is composed by photons arriving randomly in time, this generates a variation in signal called the shot noise. In case of low noise detectors and circuits, the photodetection will be described as signal or background limited depending on which of the two radiation flux is prevailing.

The detector intrinsic $1/f$ noise (flicker noise) can be evaluated through the detector specific detectivity as a function of the chopping frequency $f$. For the chosen PbSe photoconductive detector this kind of noise is usually the prevailing one, and thus we mostly focus on it.

However we also evaluate Signal-to-Noise Ratios for the signal and background limited photodetection cases, to ensure that $1/f$ noise domination.

\textit{Detectivity: shot noise.}

The the ideal situation, when the noise of the detector is determined entirely by the noise of the signal photons, can be described by the following formula:

\begin{equation}
D^*(\sigma) = \frac{1}{2hc\sigma} \left( \frac{\eta_q}{\Phi_s(\sigma)} \right)^{1/2}
\end{equation}

\begin{equation}
\Phi_s(\sigma) = \frac{P_s(\sigma)}{hceA_d}
\end{equation}

where $\Phi_s(\sigma)$ is the signal radiation photon flux density, $\eta_q$ is the detector quantum efficiency, $h$ is the Plank constant and $c$ is the speed of light.

Regarding to the quantum efficiency of the detector, one can evaluate it from reflectivity $r$ and the absorption coefficient $\alpha$ of the semiconductor:

\begin{equation}
\eta_q = (1 - r)(1 - e^{-\alpha x})
\end{equation}

where $x$ is penetration depth.

Having the reflectivity of the semiconductor surface reduced by means of the appropriate coating and the absorption coefficient of PbSe of order of $10^3..10^4$ for $2..5 \ \mu$m wavenumber range (Fig. 2.9), the achieved quantum efficiency of the detector is above 0.9 [4], and for the rough characterization of signal/background limited photodetection we assume it to be of value of 1.
Figure 2.9. Absorption coefficient for various photodetector materials [4].

Usually, the noise due to optical signal flux is small, but for MicroMIMA application conditions (direct Sun observations) it might be significant due to the high expected signal levels and cannot be neglected without evaluation.

Background radiation frequently is the main source of noise in a detector. To reduce the background flux on the detector, we use the cold baffle to limit the background FOV of the detector to the FOV of the instrument optical system.

For background limited photodetection the specific detectivity can be evaluated from the following formula:

\[ D^*(\sigma) = \frac{1}{2hc\sigma} \left( \frac{\eta_q}{\Phi_{BG}(\sigma)} \right)^{1/2} \]  

(2.21.1)

\[ \Phi_{BG}(\sigma) = \frac{P_{BG}(\sigma)}{h\sigma A_d} \]  

(2.21.2)

where \( \Phi_{BG}(\sigma) \) is the signal radiation photon flux density, \( P_{BG}(\sigma) \) is the background radiation power.

**Detectivity: 1/f noise**

The detectivity \( D^*(\sigma) \) is a function of chopping frequency \( f \) and detector temperature \( T \):

\[ D^*(f, T) = \frac{K(T) \sqrt{f}}{\sqrt{1+4\pi f^2 \tau^2(T)}} \]  

(2.22)

where \( \tau \) is the detector time constant and \( K \) is a scaling coefficient (provided in the detector datasheets). It has to be noticed that both \( \tau \) and \( K \) are functions of \( T \).
Regarding the detector specific detectivity, the main dependencies of the chosen PbSe detector are represented in Fig. 2.10.

Figure 2.10. PbSe detector dependencies: a – specific detectivity versus detector temperature; b – relative detectivity versus chopping frequency; c – detector time constant versus temperature [5].

The maximum $D^*$ can be obtained by lowering the temperature $T$ to a minimum within the detector cooling system capabilities; having the cooling capability of $\Delta T = 50{\degree}C$, and taking the ambient temperature as $25{\degree}C$, the detector operating temperature will be of $-25{\degree}C$. This is the ground condition but incidentally it corresponds also to the worst hot case for Martian surface operation.

Moreover, $D^*$ can be maximized using the optimal chopping frequency $f_{\text{OPTIMAL}}$ for the given temperature (where $\frac{\partial D^*}{\partial f} = 0$), given by:

$$f_{\text{OPTIMAL}} = \frac{1}{\sqrt{4\pi t^4}}$$  \hspace{1cm} (2.23)

For the double-pendulum interferometer scheme the relation between the chopping frequency $f$ and the cubic corner mirror speed $v_{\text{CCM}}$ can be obtained from:
\[ f = 4 \nu_{CCM} \]  \hspace{1cm} (2.24)

Knowing the wavenumber range of interest \([\sigma_{\text{min}}, \sigma_{\text{max}}]\) and locating \(f_{\text{OPTIMAL}}\) in the middle of that range, the optimal mirror speed \(v_{CCM\text{ OPTIMAL}}\) is derived as:

\[ v_{CCM\text{ OPTIMAL}} = \frac{f_{\text{OPTIMAL}}}{2(\sigma_{\text{max}}+\sigma_{\text{min}})} \]  \hspace{1cm} (2.25)

2.3. Theoretical SNR evaluation

After the optimization procedure has determined the instrument configuration, the theoretical instrument efficiency, expressed by the expected SNR for the different observation modes can be determined.

2.3.1. Terrestrial generic spectrum.

As first step we calculate the SNR for laboratory observations of terrestrial atmospheric spectrum under solar illumination conditions of clear sky. As signal we use the Direct + Circumsolar irradiance from the Reference Solar Spectrum ASTM G173-03, Air Mass 1.5 (Fig. 2.11), originally defined as \(E_{\lambda}(\lambda)\) and recalculated as \(E_{\sigma}(\sigma)\) using the following the relation:

\[ E_{\sigma}(\sigma) = \lambda^2 E_{\lambda}(\lambda), \]  \hspace{1cm} (2.26)

Note: Direct is the Direct Normal Irradiance (nearly parallel (0.5 deg divergent cone) radiation on surface with surface normal tracking (pointing to) the sun, excluding scattered sky and reflected ground radiation) and Circumsolar is the spectral irradiance within +/- 2.5 degree (5 degree diameter) FOV centered on the 0.5 deg diameter solar disk, but excluding the radiation from the disk.

Figure 2.11. Reference Solar Spectrum (Air Mass 1.5)

In case of terrestrial solar spectrum observation, the source FOV is quite small:

\[ \beta_{\text{Sun-Earth}} = \arctg \left( \frac{R_{\text{Sun}}}{D_{\text{Sun-Earth}}} \right) \approx 0.00465 \text{ rad} \] \hspace{1cm} (2.27.1)

\[ \Omega_{\text{Sun-Earth}} = \pi \beta_{\text{Sun-Earth}}^2 = 6.84 \times 10^{-5} \text{ sr} \] \hspace{1cm} (2.27.2)

where \(R_{\text{sun}}\) is the Sun radius, \(R_{\text{sun}} = 6.96 \times 10^8\) m and \(D_{\text{Sun-Earth}}\) is the Sun-Earth distance, \(D_{\text{Sun-Earth}} = 1.496 \times 10^{11}\) m.
In fact, the $\Omega_{\text{source}} < \Omega_{\text{instrument}}$, and under the optimal illumination conditions of clear sky and direction of Sun radiation coinciding with the instrument optical axis, the FOV modulation factor will be recalculated according to the source FOV, therefore $\Omega_{\text{source}} = \Omega_{\text{Sun-Earth}}$:

$$m_{\Omega_{\text{source}}} = \frac{2}{\sigma \Omega_{\text{Sun-Earth}} L} \sin \left( \frac{\sigma \Omega_{\text{Sun-Earth}} L}{2} \right)$$

(2.28)

In generic illumination conditions (diffused light) we take the instrument FOV for the modulation factor calculations.

**Signal limited photodetection (SLIP).**

For the SLIP case the resulting SNR plot for one of the selected detectors (BXT1-18T CalSensors, PbSe detector SN1022-001, the lower detectivity one) for 1 cm$^{-1}$ spectral resolution is shown in Figure 2.12.

![Figure 2.12. SNR_{SLIP} for terrestrial solar spectrum observation, optimal illumination conditions, spectral resolutions of 1 cm$^{-1}$](image)

For the terrestrial observations, the minimum expected SNR$_{\text{SLIP}}$ for the continuum is about $1.3\times10^5$.

**Background limited photodetection (BLIP).**

For the BLIP case we evaluate the background radiation flux from the spectral radiance of blackbody $L_{BG}(\sigma)$ having the instrument at expected ground temperature $T_{BG}$ of 25°:

$$L_{BG}(\sigma) = \frac{2 \pi \sigma^3 c^2}{\exp\left(\frac{hc\sigma}{k_B T_{BG}}\right)-1}$$

(2.29)

where $k_B$ is the Boltzmann constant.

For the cold-baffle isolated detector the incoming radiation power can be found by the following formula:

$$P_{BG}(\sigma) = \Theta \Delta \sigma \frac{L_{BG}(\sigma)}{2}$$

(2.29)

where $\Theta$ is the instrument optical system throughput.
The resulting SNR plot for one of the selected detectors (BXT1-18T CalSensors, PbSe detector SN1022-001, the lower detectivity one) for 1 cm\(^{-1}\) spectral resolution is shown in Figure 2.13.

![Figure 2.13. SNR\(_{BLIP}\) for terrestrial solar spectrum observation, optimal illumination conditions, spectral resolutions of 1 cm\(^{-1}\).](image)

For the terrestrial observations, the minimum expected SNR\(_{BLIP}\) for the continuum is about \(2 \times 10^8\).

**1/f limited photodetection.**

For the detector intrinsic noise prevailing case the resulting SNR plot for one of the selected detectors (BXT1-18T CalSensors, PbSe detector SN1022-001, the lower detectivity one) for 1 cm\(^{-1}\) spectral resolution is shown in Fig. 2.14.

![Figure 2.14. SNR for terrestrial solar spectrum observation, optimal illumination conditions, spectral resolutions of 1 cm\(^{-1}\)](image)
For the terrestrial observations, the minimum expected SNR for the continuum (generic illumination conditions and spectral resolution of 1 cm\(^{-1}\)) is about \(2 \cdot 10^4\).

As it has been proved in this section, the \(1/f\) noise is the dominating one, and it was used for the characterization of the following instrument application cases.

### 2.3.2. Martian approximate spectrum.

The second step of the efficiency evaluations concerns the calculation of the SNR for the acquisition of the Martian atmospheric spectrum in transmission mode during the mission. The adopted reference signal is the solar spectrum as black body radiation source at the Martian surface. As in case of terrestrial solar spectrum, for the Martian observation mode we have quite small source FOV, that is \(\Omega_{\text{Sun-Mars}}\) of about \(3.02 \cdot 10^{-5}\) sr. The resulting SNR plot for lower detectivity detector is given on Fig. 2.15.

![SNR for Martian observations of solar spectrum](image)

**Figure 2.15. SNR for Martian observations of solar spectrum (black-body model): optimal illumination conditions, spectral resolutions of 1 cm\(^{-1}\).**

For Martian observations, the minimum expected SNR for the continuum is about \(7 \cdot 10^3\).

### 2.3.3. Gas tracking problem.

Finally instrument capability of tracking the abundance of gases at low concentrations has been evaluated. The analysis was carried out on the methane component as the most representative one, with the expected concentration in atmosphere about 10-20 ppbv, using the absorption band at the wavenumber of 3018 cm\(^{-1}\) (Fig. 2.16) [6-8]. For the SNR calculations the case of minor concentration (10 ppbv) and observations with Sun in Zenith, (i.e. the worst conditions for the gas detection) was considered.
For the spectral resolution of $2\text{ cm}^{-1}$ the above spectrum will be smoothed, making the methane band hardly discernible due to the presence of stronger absorption line in the close neighborhood at $3015-3016 \text{ cm}^{-1}$. However, we can evaluate the SNR of the absorption band at $3018 \text{ cm}^{-1}$ with respect to the continuum at $3020 \text{ cm}^{-1}$ as:

$$SNR_{CH_4} = \frac{\Delta E_{CH_4}}{SNR_{Mars}(3018 \text{ cm}^{-1})}$$

(2.30.1)

$$\Delta E_{CH_4} = \frac{Emars(3020 \text{ cm}^{-1}) - Emars(3018 \text{ cm}^{-1})}{Emars(3020 \text{ cm}^{-1})}$$

(2.30.2)

where $\Delta E_{CH_4}$ is the relative depth of the methane absorption band with respect to the continuum at the adjacent wavenumber and $SNR_{Mars}$ the previously evaluated SNR of the continuum for the approximate Martian observation spectrum with spectral resolution of $2\text{ cm}^{-1}$. $\Delta E_{CH_4}$ is equal to 0.0054. For the lower performance detector SN1022-01, the $SNR_{Mars}(3018 \text{ cm}^{-1})$ is equal to $1.84 \times 10^4$ and thus the expected SNR of absorption band detection is about 100.

For the spectral resolution of $1\text{ cm}^{-1}$ the spectrum will be less smoothed, with methane absorption band better distinguishable from the strong neighboring band and a higher relative depth with respect to the continuum, i.e. $\Delta E_{CH_4}$ equal to 0.009. Considering again the lower performance detector, we have a SNR (for the spectral resolution $1\text{ cm}^{-1}$) of about $1.18 \times 10^4$ and thus a relative SNR for the absorption band detection of about 110.

2.4. Conclusions.

In this chapter the MicroMIMA Fourier spectrometer optimization has been carried out improving Signal to Noise Ratio performance characteristics with the reduced mass and power budgets. Optimization of the optical layout performance has been performed as a tradeoff between the achievable performance and the required mass for the optical layout. Between the two studied
configurations, i.e. Fish-eye and Pointing mechanism systems, the Fish-eye type demonstrated to perform better. Moreover, considerations about the system reliability make it more appealing.

The optimized layout performances were analyzed and achievable Signal to Noise Ratios were evaluated for different observation modes, i.e. terrestrial and Martian cases. In both cases good performances are achieved providing signal to noise ratios in the range of $10^4$. Moreover, the instrument gas detection capability was evaluated showing that the instrument allows to evaluate the presence of CH$_4$ in the Martian atmosphere with both nominal and enhanced spectral resolutions.
References CHAPTER 2.


3. DATA POSTPROCESSING

In this chapter, an analytical model of the data distortion by mechanical vibrations is derived. The single spectrum based correction algorithm is proposed and tested on the spectral data coming from the PFS (Planetary Fourier Spectrometer onboard Mars Express 2003).

3.1. Analytical formulation of vibration borne spectral distortions.

In the previous chapter the SNR was evaluated considering as signal the incoming radiance. However the data read on the detector will differ from one coming from the ideal instrument because of the source (i.e. due to mechanical distortions, detector nonlinearity, etc.).

The sensitivity of the FTS family instruments to the mechanical vibrations is a well-known phenomenon. Vibration generated spectral distortions are especially critical for FTS devoted to atmospheric studies (as the designed MicroMIMA spectrometer), as the gas composition determination is based on the matching of spectral features deriving from absorption bands that for the low concentration element are comparable with the instrument spectral noise. The adopted techniques aiming at the reduction of the vibration sensitivity (such as the constant optical path step sampling based on reference laser signal trigger), suffer of limitations in the practical implementation: time delays in the acquisition chain [1-5] and cyclical fluctuations of optical misalignments [6] lead to residual vibration induced modulations of the interferogram and eventually to the so-called ghosts in the spectra. Moreover as it is often impossible to measure the vibrations during the FTS measurement, the position and magnitude of these ghosts cannot be evaluated.

3.1.1. Direct model: general formulation.

As pointed out above the final spectrum is affected by mechanical disturbances through two main effects [1]:

- the implemented sampling system vibration borne sampling step errors due to the time delays in the acquisition systems;
- the cyclic misalignments induced by the vibrations.

In the following the effects on a monochromatic radiation entering the spectrometer subject to a purely harmonic vibration will be analyzed to derive then the effect on any complex spectrum.

The interferogram of a monochromatic source in a perfect interferometer can be represented as follows:

\[ I_{\sigma_s}(x_k) = m I_s \cos(2\pi \sigma_s x_k), \]  

where \( x_k \) is the OPD at the \( k \)th zero-crossing of the reference signal, \( \sigma_s \) is the wavenumber of the observed line and \( m \) is the modulation factor referred to the misalignments of the optical system from its ideal position, \( I_s \) the source half-intensity.

The pure harmonic vibration component generated at the source can be described by:

\[ y = y_d \sin(\omega_d t + \varphi_d), \]  

where \( y \) is the output signal, \( y_d \) is the vibration amplitude, \( \omega_d \) is the angular frequency and \( \varphi_d \) is the phase shift.
where \( \mathbf{y} \) represents the vector of the vibration component generated at the source and is characterized by its angular frequency \( \omega_d = 2\pi f_d \) and phase \( \varphi_d \). It has to be noticed that the phase is a random variable for each interferogram (though defined for each \( \omega_d \)) and usually follows a uniform distribution, in the 0-2\(\pi\) interval, through the set of the measurements.

Taking coordinates \( x \) and \( u \) respectively along and perpendicular to the optical axis of cube corner, we obtain the vibration components \( \Delta x \) and \( \Delta u \) responsible for the mirror speed alternations and optical misalignments in the PFS:

\[
\Delta u = u_d \sin(\omega_d t + \varphi_d^{u*}), \\
\Delta x = x_d \sin(\omega_d t + \varphi_d^{x*}),
\]

where phases \( \varphi_d^{u*} \) and \( \varphi_d^{x*} \) generally can be different, since the vector components of the transfer function of vibration propagation from the source to the interferometer in general will differ.

The modulation factor \( m \) is a function of Cubic Corner Mirror (CCM) position error \( u \) along any direction perpendicular to its optical axis and, as first order approximation, it can be written in the form

\[
m(\sigma_s u) = m(\sigma_s u_0) + \frac{\hat{m}}{\sigma(\sigma_s u_0)} u \approx \sigma_s \Delta u + E(\sigma_s u),
\]

\[
m(\sigma_s, u) \approx m_0(\sigma_s, u_0) + \sigma_s a(\sigma_s, u_0) \cdot \sin(\omega_d t + \varphi_d^{u*}),
\]

where \( E(\sigma_s u) \) is the series truncation error, \( a \) is proportional to the vibration amplitude \( u_d \) and depends on the wavenumber \( \sigma_s \) of the modulated component and the initial interferometer alignment quality \( u_0 \) (would be zero for a perfectly aligned instrument with \( u_0=0 \)). Similarly, for the effect of the “along the axis” vibration component it was shown that the sampling steps first order approximation take the expression [1]:

\[
x_k = k \frac{\lambda_r}{2} + v_m T_D + v_o T_D \cos(\omega_d t_k + \varphi_d^{x}).
\]

Where \( T_D \) is the time delay in the sampling chain, \( \lambda_r \) is the reference laser wavelength, \( t_k \) is the time corresponding to the \( k \)th sampling while \( v_o \) is the vibration amplitude expressed as speed (i.e \( v_o = \omega_d x_d \))

By substituting Eq. (3.5.2) and Eq. (3.6) in Eq. (3.1) one obtains:

\[
I_{\sigma_s}(x_k) = \left[ m_0(\sigma_s, u_0) + a(\sigma_s, u_0) \sigma_s \sin(\omega_d t_k + \varphi_d^{u*}) \right] I_s
\times \cos \left[ 2\pi \sigma_s \left( \frac{k \lambda_r}{2} + T_D v_m \right) + 2\pi \sigma_s v_o T_D \cos(\omega_d t_k + \varphi_d^{x}) \right].
\]

For further simplification the following substitutions will be applied:

- the time within the sine function can be written \( t_k \approx k \lambda_r/(2 v_m) \);
- \( \varphi_\sigma_s = 2\pi \sigma_s v_m T_D \);
- \( \omega_d/v_m = 2\pi f_d/v_m = 2\pi \sigma_d, \sigma_d = f_d/v_m \).

Developing cosine into Taylor series up to 1st order we can rewrite Eq. (3.7) as:
\[ I_{\sigma_s}(x_k) = \left\{ m_{\sigma_s}(\sigma, u_o) + a(\sigma, u_o)\sigma \sin \left[ 2\pi \sigma_d \left( \frac{k\lambda_r}{2} + \varphi^u_d \right) \right] \right\} \]
\[ \times I_s \left\{ \cos \left[ 2\pi \sigma_s \left( \frac{k\lambda_r}{2} \right) + \varphi_{\sigma_s} \right] \right\} \]
\[ -2\pi \sigma_s v_o T_D \sin \left[ 2\pi \sigma_s \left( \frac{k\lambda_r}{2} \right) + \varphi_{\sigma_s} \right] \cos \left[ 2\pi \sigma_d \left( \frac{k\lambda_r}{2} \right) + \varphi^x_d \right] \right\}. \]  

(3.8)

The ghost studies performed on PFS spectra demonstrated that the sampling error term is prevailing [7]. Therefore as first approximation we neglect the \( m_{\sigma} \) and \( a \) coefficients dependence on wavenumber \( \sigma \). Such assumption generally can be valid or not depending on the initial misalignment \( u_o \).

Developing the product and remembering that the factor "2\( \pi \sigma_s v_o T_D a \)" is a second order infinitesimal and so it is negligible with respect to the other terms, we obtain:

\[ I_{\sigma_s}(x_k) = m_{\sigma} I_s \cos \left[ 2\pi \sigma_s \left( \frac{k\lambda_r}{2} \right) + \varphi_{\sigma_s} \right] \]
\[ + a \sigma I_s \sin \left[ 2\pi \sigma_d \left( \frac{k\lambda_r}{2} \right) + \varphi^u_d \right] \cos \left[ 2\pi \sigma_s \left( \frac{k\lambda_r}{2} \right) + \varphi_{\sigma_s} \right] \]
\[ -2\pi \sigma_s v_o T_D m_{\sigma} I_s \sin \left[ 2\pi \sigma_s \left( \frac{k\lambda_r}{2} \right) + \varphi_{\sigma_s} \right] \cos \left[ 2\pi \sigma_d \left( \frac{k\lambda_r}{2} \right) + \varphi^x_d \right]. \]  

(3.9)

Substituting \( A_s = m_{\sigma} I_s \), \( A_1 = a/(2m_{\sigma}) \), \( A_2 = \pi v_o T_D \) and grouping the terms by the ghosts they describe, one can rewrite the Eq. (3.9) as follows:

\[ I_{\sigma_s}(x_k) = A_s \cos \left[ 2\pi \sigma_s \left( \frac{k\lambda_r}{2} \right) + \varphi_{\sigma_s} \right] \]
\[ + A_1 \sigma_s A_s \cos \left[ 2\pi (\sigma_d + \sigma_s) \left( \frac{k\lambda_r}{2} \right) + (\varphi^u_d + \varphi_{\sigma_s} - \frac{\pi}{2}) \right] \]
\[ + A_2 \sigma_s A_s \cos \left[ 2\pi (\sigma_d + \sigma_s) \left( \frac{k\lambda_r}{2} \right) + (\varphi^x_d + \varphi_{\sigma_s} + \frac{\pi}{2}) \right] \]
\[ + A_1 \sigma_s A_s \cos \left[ 2\pi (\sigma_s - \sigma_d) \left( \frac{k\lambda_r}{2} \right) + (\varphi_{\sigma_s} - \varphi^u_d + \frac{\pi}{2}) \right] \]
\[ + A_2 \sigma_s A_s \cos \left[ 2\pi (\sigma_s - \sigma_d) \left( \frac{k\lambda_r}{2} \right) + (\varphi_{\sigma_s} - \varphi^x_d + \frac{\pi}{2}) \right] \]
\[ = I_{\sigma_s} \text{original signal} + I_{\sigma_s} \text{right ghost} + I_{\sigma_s} \text{left ghost} \]  

(3.10)

Note: it does not change physical sense of the expression if we replace \( \varphi^u_d - \pi/2 \) by simply \( \varphi^u_d \) as it is generally a random unknown value.

In wavenumber domain Eq. (3.10) can be represented as:

\[ I(\sigma) = A_s \exp(i\varphi_{\sigma_s}) \delta(\sigma - \sigma_s) \]
\[ + A_s \left\{ A_1 \sigma_s \exp[i(\varphi_{\sigma_s} + \varphi^u_d)] + A_2 \sigma_s \exp \left[ i(\varphi_{\sigma_s} + \varphi^x_d + \frac{\pi}{2}) \right] \right\} \delta(\sigma - (\sigma_s + \sigma_d)) \]
\[ + A_s \left\{ A_1 \sigma_s \exp[i(\varphi_{\sigma_s} - \varphi^u_d)] + A_2 \sigma_s \exp \left[ i(\varphi_{\sigma_s} - \varphi^x_d + \frac{\pi}{2}) \right] \right\} \delta(\sigma - (\sigma_s - \sigma_d)), \]  

(3.11)
Using the $B \exp(i\varphi_{\sigma B})$ and $C \exp(i\varphi_{\sigma C})$ expressions (see Annex 3.1) we can rewrite Eq. (3.11) as following:

$$I(\sigma) = A_s \exp(i\varphi_{\sigma s}) \delta(\sigma - \sigma_s) +$$

$$[\sigma_s A_s \exp(i\varphi_{\sigma s}) \delta(\sigma - \sigma_s)] \{ B \exp(i\varphi_{\sigma B}) \delta[\sigma - (+\sigma_d)] + C \exp(i\varphi_{\sigma C}) \delta[\sigma - (-\sigma_d)] \}$$

$$= I_{\text{signal}}(\sigma) + [\sigma_s I_{\text{signal}}(\sigma)] * K_{\sigma d}(\sigma), \quad (3.12)$$

where $I_{\text{signal}}(\sigma)$ is the undistorted spectrum and $K_{\sigma d}(\sigma)$ is the single harmonic vibration kernel, “$\delta$” and “$*$” are respectively the Dirac’s function and the convolution operator.

The combined modulation effect can be evidenced as on Fig. 3.1.

---

**Figure 3.1.** Monochromatic line modulation by pure harmonic vibration; **a** – initial spectrum, **b** – vibration kernel, **c** – modulated spectrum.

The above reasoning can be extended for any non-monochromatic input spectra and arbitrary vibration component shape (see Annex 3.2):

$$I(\sigma) = I_{\text{continuum}}(\sigma) + [\sigma I_{\text{continuum}}(\sigma)] * K(\sigma) \quad (3.13)$$

$$K(\sigma) = \sum_j \left\{ B_j \exp\left[i\varphi_{\sigma Bj}(\sigma)\right] \delta\left[\sigma - (+\sigma_d)\right] \right\}$$

$$+ C_j \exp\left[i\varphi_{\sigma Cj}(\sigma)\right] \delta\left[\sigma - (-\sigma_d)\right] \quad (3.14)$$
The last observation becomes important as the general vibration kernel does not consist of single vibration component but a whole set of them, each appearing as the bell-shaped function in the wavenumber domain, although being a pure harmonic in the time domain. This peculiarity is caused by the uneven sampling: because of non-constant mirror speed, the equal OPD step does not correspond to the equal time step.

3.1.2. Direct model: laser straylight modulation.

The above discussion concludes that to each harmonic of vibrations two ghosts are obtained of every spectral feature: one on its right and the other on its left. A particular case will be generated by the spectrum of the reference laser, which becomes visible in the main signal spectrum due to straylight effects. Being the laser line on the Nyquist border, its right ghost will be generated out of the instrument measurement range thus it will appear in the signal spectrum through the aliasing (Fig. 3.2). One must also notice that aliasing changes the phase of feature into opposite value, i.e. $\varphi_{\text{aliased feature}} = -\varphi_{\text{feature}}$.

![Figure 3.2. Aliasing of the laser line ghost](image)

Another peculiarity of the laser line modulation refers to the anti-aliasing filter that noticeably distorts data in the high wavenumber region. For more precise information about those distortions the Transfer Function of the filter has to be discussed (Fig. 3.3).

It has to be noticed that the filter will affect directly the spectrum of laser line and ghosts due to misalignment as they have physical nature; the ghosts generated by sampling error due to their numerical nature will be not affected by filter directly. However those ghosts are built from already filtered laser line shape thus an indirect filtering effect will still be present.

The anti-aliasing filter implemented in PFS is the 6th order Bessel filter with cut frequency at Nyquist. Its transfer function plots are shown in Fig. 3.3.
Figure 3.3. 6th order Bessel filter Transfer Function: magnitude and phase; a – semi log plot, b – zoom around cut-off wavenumber ($\sigma_{\text{cut-off}} = 8356 \text{ cm}^{-1}$).

Original signal spectrum at the Nyquist border will be distorted in amplitude and phase:

$$Y(\omega) = H(\omega) \cdot X(\omega),$$  \hspace{1cm} (3.15.1)

$$H(\omega) = |H(\omega)| \exp[i \varphi_H(\omega)],$$  \hspace{1cm} (3.15.2)

where $Y(\omega)$ and $X(\omega)$ are filtered and original signal correspondingly, and $H(\omega)$ is the filter transfer function described by its magnitude and phase.

In other words:

$$|Y(\omega)| = |H(\omega)| \cdot |X(\omega)|,$$  \hspace{1cm} (3.16.1)

$$\varphi_Y(\omega) = \varphi_H(\omega) + \varphi_X(\omega).$$  \hspace{1cm} (3.16.2)

Remembering that the pulsation can be obtained from the wavenumber by the relationship $\omega = 2\pi \sigma v_m$, the filter transfer function can be written as a function of the wavenumber. Generally $H(\omega)$ is varying “slowly” and can be considered constant throughout the spectral width of the laser line and its ghosts as they are narrow features in the spectrum. E. g. throughout the laser spectral band $|H(\sigma)| = 0.9553 \pm 0.02\%$ and $\varphi_H(\sigma) = -1 \text{ rad} \pm 0.04\%$.

Note: in the following we will use $H(\sigma)$ instead of $|H(\sigma)|$ to simplify the notation.

Now we rewrite Eq. (3.11) under direct and indirect filter effects, described by Eq. (3.15-3.16):

$$l_{\text{laser}}(\sigma) = A_{\text{laser}} \exp\{i [\varphi_{\sigma_1} + \varphi_H(\sigma_1)]\} H(\sigma_1) \delta(\sigma - \sigma_1)$$
$$+ A_{\text{laser}} A_1 \sigma_1 \exp\{i [\varphi_{\sigma_1} + \varphi^u d + \varphi_H(\sigma_1 + \sigma_d)]\} H(\sigma_1 + \sigma_d) \delta(\sigma - (\sigma_1 + \sigma_d))$$
$$+ A_{\text{laser}} A_2 \sigma_1 \exp\{i [\varphi_{\sigma_1} + \varphi^x d + \pi 2 + \varphi_H(\sigma_1)]\} H(\sigma_1) \delta(\sigma - (\sigma_1 + \sigma_d))$$
$$+ A_{\text{laser}} A_1 \sigma_1 \exp\{i [\varphi_{\sigma_1} - \varphi^u d + \varphi_H(\sigma_1 + \sigma_d)]\} H(\sigma_1 - \sigma_d) \delta(\sigma - (\sigma_1 - \sigma_d))$$
where $\sigma_l$ is the wavenumber of the reference laser line (with nominal value of 8330 cm$^{-1}$).

From the Eq. (3.17) we can obtain right and left ghost components in analytical form:

$$I_{\text{LEFT GHOST}}(\sigma) = A_{\text{laser}} A_1 \sigma_1 \exp \{ i [\varphi_{\sigma_l} - \varphi^u_d + \varphi_H(\sigma_l)] \} \times H(\sigma_l) \delta[\sigma - (\sigma_l - \sigma_d)]$$

$$+ A_{\text{laser}} A_2 \sigma_1 \exp \{ i \left[ \varphi_{\sigma_l} - \varphi^x_d + \frac{\pi}{2} + \varphi_H(\sigma_l) \right] \} \times H(\sigma_l) \delta[\sigma - (\sigma_l - \sigma_d)],$$

(3.18.1)

$$I_{\text{RIGHT GHOST}}(\sigma) = A_{\text{laser}} A_1 \sigma_1 \exp \{ i [\varphi_{\sigma_l} + \varphi^u_d + \varphi_H(\sigma_l + \sigma_d)] \} \times H(\sigma_l + \sigma_d) \delta[\sigma - (\sigma_l + \sigma_d)]$$

$$+ A_{\text{laser}} A_2 \sigma_1 \exp \{ i \left[ \varphi_{\sigma_l} + \varphi^x_d + \frac{\pi}{2} + \varphi_H(\sigma_l) \right] \} \times H(\sigma_l) \delta[\sigma - (\sigma_l + \sigma_d)],$$

(3.18.2)

$$I_{\text{RIGHT GHOST ALIASED}}(\sigma) = A_{\text{laser}} A_1 \sigma_1 \exp \{ -i [\varphi_{\sigma_l} + \varphi^u_d + \varphi_H(\sigma_l + \sigma_d + 2c)] \} \times H(\sigma_l + \sigma_d) \delta[\sigma - (\sigma_l + \sigma_d)]$$

$$+ A_{\text{laser}} A_2 \sigma_1 \exp \{ -i \left[ \varphi_{\sigma_l} + \varphi^x_d + \frac{\pi}{2} + \varphi_H(\sigma_l) \right] \} \times H(\sigma_l) \delta[\sigma - (\sigma_l + \sigma_d + 2c)],$$

(3.18.3)

where $c$ is the distance from the laser peak to the Nyquist limit (Fig. 3.2): in fact, due to divergence of the laser straylight they do not perfectly coincide.

Finally both ghosts superimpose and generate the distorted spectrum:

$$I_{\text{LM}}(\sigma) = I_{\text{LF}}(\sigma) + I_{\text{LG}}(\sigma) + I_{\text{RGA}}(\sigma),$$

(3.19)

where are $I_{\text{LG}}(\sigma)$ and $I_{\text{RGA}}(\sigma)$ the left and aliased right ghosts correspondingly, $I_{\text{LF}}(\sigma)$ is the filtered original laser line and $I_{\text{LM}}(\sigma)$ is the resulting modulated laser line spectrum.

Up to now we considered the laser line as the monochromatic feature (that is not physically true). However the obtained solution can be easily extended to the physically meaningful case through two additional statements: specifying the laser line spectral shape by its modulus $A_{\text{laser}}(\sigma)$ and phase $\varphi_L(\sigma)$ as functions of wavenumber $\sigma$ (as it is shown in the Eq. (3.20)):

$$I_{\text{LM}}(\sigma) = H(\sigma_l)(A_{\text{laser}}(\sigma) \exp [i [\varphi_L(\sigma_l) + \varphi_H(\sigma_l)]]) \ast \delta(\sigma - \sigma_l),$$

(3.20)
3.1.3. Direct model: testing and validation.

In the previous sections an analytical formulation for the ghost features was provided, developing the analytical base. In the following we will test this vibration model on actual spaceborne data from the Short Wavelength Channel (SWC) of the PFS instrument.

The typical SWC spectrum with reference laser switched on (Fig. 3.4) can be divided into two domains: the main signal continuum with its ghosts on the left side (up to 5000 cm\(^{-1}\)) and the modulated reference laser line on the right (region between 5000 cm\(^{-1}\) and 8330 cm\(^{-1}\)). The reason for this division is that the analytical expression of the ghosts will be different in those regions according to the scheme in the previous sections. However being referred to the same interferogram, they are modulated by the same vibration kernel; i.e. once the kernel is determined for the laser line domain, its formulation will be valid as well for the main signal one.

![MARTIAN spectra #106 (symmetrized)](image)

**Figure 3.4. Typical SWC spectrum of Martian atmosphere (data from Symmetrized spectrum #106, ORBIT0032).**

Ghost formation in the main signal continuum is characterized by the convolution with vibration kernel, as it is presented in Eq. (3.13). The complete demonstration of the direct vibration model thus would be the convolution of the “true” signal and the predicted vibration kernel, along with further comparison with the actually acquired data. The problem encountered is that there is no precise information available neither about the signal, nor about the kernel. As the first approximation of the model, the estimates of the signal and kernel are to be used.

The estimate of the vibration kernel can be obtained from the modulated laser line domain, owing to its near monochromatic properties.

The example of the laser line shape and its ghosts in the acquired PFS spectrum is shown on the Fig. 3.5.
Generally the laser line modulation is not a simple convolution problem and it is not invertible linearly (Eq. (3.17-3.20)).

Anyway it has been demonstrated in Eq. (3.18.1), (3.18.3) that the position between Laser Left Ghost and Laser Right Ghost Aliased is shifted by $2c$, where value of $c$ can be taken from the actual spectrum (Fig. 3.5) as about 1 cm$^{-1}$. This permits retrieving from the laser ghosts the approximate vibration kernel, which is not valid for the absolute values of modulations, but provides a fair estimation of $\sigma_d$ (Fig.3.6).

For the signal estimate the measured distorted spectrum (Fig. 3.4) can be used. In the range 2000 to 3500 cm$^{-1}$ the content of the signal is mostly described by the real Martian spectrum with the slighter ghost impact. So this spectral region was taken as the signal estimate for the direct vibration model. The results of convolution with kernel components are presented on the Fig. 3.7.
As it is seen on the previous image, some spectral features well-agree with the direct vibration model results, while others show less correspondence. This inconsistency can be explained by the fact, that the kernel estimates, used in the direct vibration model, do not recover neither actual phase nor modulus of the actual kernel.

To check the correspondence of the estimated ghost with the actual spectral feature, the correlation analysis was performed (Fig. 3.8). The characteristic feature to be analyzed was taken as the CO$_2$ absorption band (2200..2300 cm$^{-1}$), being the one with the highest contrast in signal intensity. The resulting correlation peaks for the ghosts in the no-signal region (up to 1500 cm$^{-1}$) are summarized in the Table 3.1. The ghosts that demonstrate better correlation are the ones where “phase guess” was closer to the real situation. For the vibration component II, the large shift value is explained by the smooth variation of the signal, disabling the possibility of precise shift determination. For vibrations II and IV, the correlation is high, showing that this methodology is correct at first order.
**Figure 3.8. Direct vibration model results: correlation check.**

<table>
<thead>
<tr>
<th>Vibration component number</th>
<th>Correlation peak number</th>
<th>approximate $\sigma_d$, [cm$^{-1}$]</th>
<th>shift from zero, [cm$^{-1}$]</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td></td>
<td>1010</td>
<td>-18</td>
<td>0.79</td>
</tr>
<tr>
<td>III</td>
<td></td>
<td>1750</td>
<td>3</td>
<td>0.81</td>
</tr>
<tr>
<td>IV</td>
<td></td>
<td>2070</td>
<td>1</td>
<td>0.66</td>
</tr>
</tbody>
</table>

**Table 3.1. Correlation analysis result: value and position of the peak.**
3.2. Numerical correction technique.

Basing on the analytical model described above, a numerical correction algorithm was elaborated for the PFS data treatment, as the representative FTS family instrument.

3.2.1. Inversion of the problem.

The whole PFS spectrum was subdivided into two parts to be treated separately:

- signal domain in the wavenumber range of 0 to 5000 cm\(^{-1}\);
- laser line domain in the wavenumber range above 5000 cm\(^{-1}\).

The actual energy is present in the signal domain, above the 1700 cm\(^{-1}\), due to the used detector responsivity curve (Fig. 3.9). Below 1700 cm\(^{-1}\) there are only ghosts of the continuum present in the spectrum and no meaningful signal. In the region above 5000 cm\(^{-1}\) the Signal-to-Noise Ratio becomes low due to the strong decrease of the detector responsivity [8], and thus the laser line domain is dominated by the laser line shape and its ghosts.

![Figure 3.9. SWC channel responsivity curve for forward (FWD) and reverse (REV) pendulum movement.](image)

In the current research the signal domain was treated only. After 5000 cm\(^{-1}\) in the laser line domain, the signal to noise ratio is too low to expect any signal from Mars due to the instrument low responsivity. This is dominated by the laser line shape and its ghosts, directly and in aliasing, and it will be used to test the coherence of the results. Since the laser has been switched off after orbit 662, leaving the spectrum region above 5000 cm\(^{-1}\) free from laser ghosts, such approach could not be used for most of PFS archive.

Calling back the Eq. (3.13-3.14), we rewrite the above expression for the measured raw PFS spectrum \(I_{PFS}(\sigma)\), having the input spectrum \(I_{Mars}(\sigma)\) and considering the wavenumber in the second term to be constant, \(\sigma \approx \sigma_k = 2500\) cm\(^{-1}\). Such an approximation is possible due to the fact that the most part of significant signal is actually concentrated in the 2000..3000 cm\(^{-1}\) wavenumber region (Fig. 3.4). We also include the error term \(\xi\), accounting for used approximation in convolution kernel modeling and for other distortions of spectrum, besides the modulation by mechanical vibrations.
\[ I_{\text{PFS}}(\sigma) = I_{\text{Mars}}(\sigma) \ast \left( \delta(\sigma) + \frac{K(\sigma)}{\sigma_k} \right) + \xi \]  
\[ I_{\text{PFS}}(\sigma) = I_{\text{Mars}}(\sigma) \ast K_{\text{PFS}}(\sigma) + \xi \]  
\[ K_{\text{PFS}}(\sigma) = \delta(\sigma) + B(\sigma) \exp[i\phi_B(\sigma)] + C(\sigma) \exp[i\phi_C(\sigma)] \]

where \( \delta(\sigma) \) is the Dirac function, \( I_{\text{PFS}}(\sigma) \) is the measured raw spectrum, \( I_{\text{Mars}} \) is the contribution of the raw spectrum from Mars, \( K_{\text{PFS}} \) the kernel due to mechanical vibration effects, \( \sigma \) is the wavenumber, and \( K(\sigma) \) is the un-normalized complex kernel. The quantities \( B, C, \phi_B, \phi_C \) are unknown and cannot be evaluated quantitatively due to the lack of knowledge about vibration amplitude and phase. In practice, the functions \( B, C, \phi_B, \phi_C \) are sparse over \( \sigma \) because the frequencies of vibrations are sparse. Please note that \( B, C, \phi_B, \phi_C \) are not symmetric around \( \sigma = 0 \) due to the relative phase. We propose to estimate those functions using an inversion procedure described below.

The adopted technique was based on the semi-blind deconvolution method [9]. For that purpose we introduce a Loss Function \( LF \), whose minimum would provide the estimates of Martian spectrum \( \hat{I}_{\text{Mars}} \) and vibration kernel \( \hat{K}_{\text{PFS}} \). This function not only quantifies the fitting of the estimated data to the original model, but also includes additional terms characterizing the available information about the physical data, such as the sparsity of vibration kernel and smoothness of the Martian spectrum.

\[
\hat{I}_{\text{Mars}}(\sigma), \hat{K}_{\text{PFS}}(\sigma) = \arg \min_{I_{\text{Mars}}, K_{\text{PFS}}} LF(I_{\text{Mars}}, K_{\text{PFS}}) 
\]

\[
LF = \frac{1}{2} \| I_{\text{PFS}} - K_{\text{PFS}} \ast I_{\text{Mars}} \|_2^2 + \lambda_K \| K_{\text{PFS}} \|_1 + \frac{\lambda_{\text{Mars}}}{2} \| D \ast I_{\text{Mars}} \|_2^2
\]

Three terms appear in \( LF \):

- A data fit term \( \frac{1}{2} \| I_{\text{PFS}} - K_{\text{PFS}} \ast I_{\text{Mars}} \|_2^2 \) that quantifies how well the estimated sources match the measured data. This term takes into account the characteristics of the noise supposed to be white and Gaussian. This data match term is sensitive to high frequency noise and must be balanced with regularization term which corresponds to a mathematical prior on the expected solution.
- A sparsity regularization term \( \| K_{\text{PFS}} \|_1 \) is chosen for the kernel, i.e.: sum absolute value of the kernel must be low. Indeed, the PFS kernel is supposed to be composed with few Diracs at mechanical vibration frequencies.
- A smooth regularization term is chosen for the Mars spectra: \( \| D \ast I_{\text{Mars}} \|_2^2 \), where \( D \) is a discrete first-order derivation operator. This prior promotes smooth solution in order to avoid noise improvement.

All these terms are balanced with two hyperparameters \( \lambda_K \) and \( \lambda_{\text{Mars}} \), both positive. The functional is convex for each variables - convex in \( I_{\text{Mars}} \) when \( K_{\text{PFS}} \) is fixed and vice versa - but not from the couple \( (I_{\text{Mars}}, K_{\text{PFS}}) \). The strategy we choose here is a classical alternative procedure: from initial guesses \( \hat{I}_{\text{Mars}}^0 \) and \( \hat{K}_{\text{PFS}}^0 \), an iterative procedure updates successively to the new estimates \( \hat{R}_{\text{PFS}}^n \) and \( \hat{I}_{\text{Mars}}^n \). The notation \( \hat{X} \) means the estimation of quantity \( X \).
3.2.2. Iterative procedure for the inverse problem solution.

At each iteration \( n \) we estimate successively the kernel \( \hat{R}^{n+1}_{\text{PFS}} \) and the signal \( \hat{I}^{n+1}_{\text{Mars}} \) until iteration \( N \) using the following steps:

- First estimation of the kernel \( \hat{R}^1_{\text{PFS}} \) from filtered \( \hat{I}^0_{\text{Mars}} \) and \( I_{\text{PFS}} \) with L1 regularization
- Iterative loop:
  - estimation of the Mars spectra \( \hat{I}^{n+1}_{\text{Mars}} \) from unfiltered \( I_{\text{PFS}} \) and \( \hat{R}^n_{\text{PFS}} \) with smooth regularization
  - estimation of the kernel \( \hat{R}^{n+1}_{\text{PFS}} \) from unfiltered \( \hat{I}^{n+1}_{\text{Mars}} \) and \( I_{\text{PFS}} \) with L1 regularization
- Last estimation of the Mars spectra \( \hat{I}^{\text{final}}_{\text{Mars}} \) from unfiltered \( \hat{R}^{\text{final}}_{\text{PFS}} \) and \( I_{\text{PFS}} \).

For both estimations, a convex optimization algorithm converges to the solution defined by the minimum of a criteria made of a data match and a regularizations terms. This means that the solution is unique and can be estimated either analytically or iteratively.

The scheme of described iterative process is shown on Fig. 3.10.

![Diagram](image.png)

**Figure 3.10.** Iterative procedure for the inverse problem solution.
Since the first step of the iterative procedure is the estimation of the kernel $\hat{R}_{\text{PFS}}^1$, the only a priori information of this iterative procedure is $\hat{I}_{\text{Mars}}^0$, estimated at initio. It can only be estimated at large scale (all absorption lines may differ from spectra to spectra due to non-homogeneity of chemical compounds in the atmosphere/surface of Mars), and thus the first iteration is done in a low-pass filtered space, as described in the section below.

### 3.2.3. Estimation of the PFS kernel and Martian Spectrum.

The estimation of the PFS kernel reduces to the following $l_1$ regularized convex (non smooth) problem:

$$
\hat{R}_{\text{PFS}}^{n+1} = \arg\min_{K_{\text{PFS}}} \frac{1}{2} \| I_{\text{PFS}} - K_{\text{PFS}} * \hat{I}_{\text{Mars}}^n \|_2^2 + \lambda_{\text{K}} \| K_{\text{PFS}} \|_1
$$

(3.22)

where $\hat{I}_{\text{Mars}}^n$ is the estimation of the Mars spectra at the $n$-th iteration. This problem is the well-known Lasso or Basis-Pursuit Denoising problem, and can be solved efficiently with the Fast Iterative Thresholding Algorithm (FISTA). Denoting by $\tilde{X}$ the adjoint of the $X$ and by $S_{\lambda}$ the so-called soft-thresholding operator ($S_{\lambda}(x) = \frac{x}{|x|} \max(|x| - \lambda, 0)$), the algorithm reads:

1. Let $i = 0$; $\tau^0 = 1$; $k = 1$; $Z^0 = K_{\text{PFS}}^n$ and $L = \| I_{\text{Mars}} \|^2$
2. $K_{\text{PFS}}^i = S_{\lambda_{\text{K}}/L}(Z^i + \frac{1}{L}(I_{\text{PFS}} - Z^i * \hat{I}_{\text{Mars}}^n) * \hat{I}_{\text{Mars}}^n)$
3. $\tau^{i+1} = \frac{1 + \sqrt{1 + 4\tau^i \lambda_{\text{K}}}}{2}
4. Z^{i+1} = K_{\text{PFS}}^i + \frac{\tau^{i-1}}{\tau^i + 1}(K_{\text{PFS}}^i - K_{\text{PFS}}^{i-1})$
5. $i = i + 1$
6. Go to 2 until $i = i_{\text{max}}$
7. $K_{\text{PFS}}^{n+1} = K_{\text{PFS}}^{i_{\text{max}}}$

From theoretical consideration, the kernel $K_{\text{PFS}}$ must be Dirac-shaped at zero, so we concentrate the energy around zero into a Dirac to create the kernel estimation $\hat{R}_{\text{PFS}}^{n+1}$. We would like to emphasize that there is no analytical solution of Eq. 3.2, so we solve this equation with an iterative procedure, initialized with the previous step $\hat{R}_{\text{PFS}}^n$. For the first initialization $\hat{R}_{\text{PFS}}^0$, we may use $\hat{R}_{\text{PFS}}^{\text{approx}}$, but any other guess (such zero) may be applied for the spectra with the reference laser switched off. Nevertheless, closer initialization leads to faster convergence.

For the Mars spectra, the estimation reduces to a classical Thikonov regularization Idier:

$$
\hat{I}_{\text{Mars}}^{n+1} = \arg\min_{I_{\text{Mars}}} \| I_{\text{PFS}} - \hat{R}_{\text{PFS}}^{n+1} * I_{\text{Mars}} \|_2^2 + \lambda_{\text{Mars}} \| D * I_{\text{Mars}} \|_2^2
$$

(3.23)

Thanks to the fact that a convolution is diagonal in the Fourier domain, and the Parseval theorem, the solution reads:

$$
\mathcal{F}(\hat{I}_{\text{Mars}}^{n+1}) = \arg\min_{\mathcal{F}(I_{\text{Mars}})} \| \mathcal{F}(I_{\text{PFS}}) - \mathcal{F}(\hat{R}_{\text{PFS}}^{n+1}) \odot \mathcal{F}(I_{\text{Mars}}) \|_2^2 + \lambda_{\text{Mars}} \| \mathcal{F}(D) \odot \mathcal{F}(I_{\text{Mars}}) \|_2^2
$$

(3.24)

where $\odot$ is the Hadamard element-wise product and $\mathcal{F}$ the Fourier transform. Then, the estimation of the Mars spectra at iteration $n+1$ is given in closed form by:

$$
\hat{I}_{\text{Mars}}^{n+1} = \mathcal{F}^{-1} \left( \mathcal{F}(I_{\text{PFS}}) \odot \left( \mathcal{F}(\hat{R}_{\text{PFS}}^{n+1})^{-2} - \lambda_{\text{Mars}} \mathcal{F}(D)^{-2} \right) \right)
$$

(3.25)
where $\mathcal{F}\left(K_{\text{PFS}}^{n+1}\right)^{-2}$ (respectively $\mathcal{F}(D)^{-2}$) represents the vector containing the inverted squared elements of the vector $\mathcal{F}\left(K_{\text{PFS}}^{n+1}\right)$ (respectively $\mathcal{F}(D)$).

We would like to emphasize that Eq.3.25 is the analytical solution of Eq. 3.23 that does not require initialization.

### 3.2.4. Initial guesses of the Martian Spectrum and PFS kernel.

We estimate the Martian spectra large scale feature (noted $\hat{J}^{0}_{\text{Mars}}$) by two Planck functions and the major absorption features (Fig. 3.11), representing (i) the Martian thermal emission, (ii) the solar energy reflected back by Mars and (iii) the 2200-2400 cm$^{-1}$ gap, representing the CO$_2$ absorption band. The Martian temperature is estimated by fitting the 2500-3000 cm$^{-1}$ domain, where ghosts seem to be less pronounced. The Planck function of the sun is scaled to the 3800-4200 cm$^{-1}$ domain. We derive the raw spectra using the calibrations of detector responsivity and deep space measurements [8]. This initial guess is only valid at large scale because the absorption lines of major and minor gases may change, due to local pressure, atmospheric circulation, surface change and radioactive transfer effects.

The phase of the initial guess is taken similar to the signal in the domain, where ghosts are minor and a constant extrapolation is proposed to the ghosted region.

![Figure 3.11. Raw measurements $I_{\text{PFS}}$ (on left) and initial guess of the Martian Spectrum $\hat{J}^{0}_{\text{Mars}}$ (on right) for the PFS measurement ORBIT0032, #106.](image)

Because the iterative procedure is sensitive to initialization, both PFS spectra $I_{\text{PFS}}$ and mars initial guess $\hat{J}^{0}_{\text{Mars}}$ are filtered with a low-pass filter with a cut off frequency of $\frac{1}{20\Delta\sigma}$, where spectral resolution $\Delta\sigma$ is known to be 1.02 cm$^{-1}$. Such cut off was chosen in order to keep the realistic features.
The initial guess $\hat{I}^0_{\text{Mars}}$ will force the following initial step of the iterative procedure to find a local minimum around physical solution. Initializing the procedure with random or constant signal would lead to a non-physical solution.

Estimation of the PFS kernel $R_{\text{PPS}}^{\text{approx}}$ can be made from the laser line domain (see section 3.1.3). Neither amplitudes, nor phases are precise but the frequencies should be well described by this methodology. This kernel is used as initial guess $\hat{R}_{\text{PPS}}^0$ in order to reach the faster convergence of the first kernel estimation $\hat{R}_{\text{PPS}}^1$. Unfortunately, only Mars Express orbit below #634 are usable for this estimation, as afterwards the SWC reference laser was switched off. It represents 310 orbits out of 6255 orbits currently available i.e., less than 5% of the total orbits.

3.2.5. Parameters for result quality evaluation.

Distance between real and simulated PFS spectra. Because the only ground truth we could have is the measured PFS spectra $I_{\text{PFS}}$, it should be as close as possible to the final simulated PFS spectrum $I_{\text{PFS}}^{\text{final}} = \hat{I}_{\text{Mars}}^{\text{final}} + \hat{R}_{\text{PPS}}^{\text{final}}$. We use the Root Mean Square distance (RMS) of $I_{\text{PFS}}^{\text{final}} - I_{\text{PFS}}$. In this way, we evaluate at the same time the correctness of the estimated Mars spectrum $\hat{I}_{\text{Mars}}^{\text{final}}$ and of the instrument disturbance model characterized by $\hat{R}_{\text{PPS}}^{\text{final}}$.

Ghost removal in the signal domain (0 to 5000 cm$^{-1}$). In the 1 to 1530 cm$^{-1}$ wavenumber domain, no signal is expected due to the very low signal to noise ratio, with the only ghosts contribution in the raw spectra. Thus, one simple criterion to estimate the efficiency of the correction is to measure the energy of the estimated Mars spectrum $\hat{I}_{\text{Mars}}^{\text{final}}$ in this domain.

Ghosts in the laser line domain (5000 to 8330 cm$^{-1}$). The laser line modulated $I_{\text{LM}}^{\text{final}}$ through filter, aliasing and vibrations effects (see section 3.1.2) can be computed from the estimated kernel $\hat{R}_{\text{PPS}}^{\text{final}}$ using the exact formulation. To check the quality of the results, we evaluate the distance between the actually measured signal and the computed laser line modulated $I_{\text{LM}}^{\text{final}}$ with its ghosts.

Distance to the approximated kernel. The rough estimation of the kernel $R_{\text{PPS}}^{\text{approx}}$ can be done from the laser line domain. Neither amplitudes, nor phases are precise but the frequencies should well described by this methodology. The distance between $K_{\text{PPS}}^{\text{approx}}$ and $\hat{R}_{\text{PPS}}^{\text{final}}$ is also a criteria of good results.

Comparison with vibration frequencies from MEx telemetry and technical specification. Several sources of vibrations are present in the MEx platform, mainly reaction wheels, Inertia Measurement Unit (IMU) dithering. PFS eigen-modes can also be exited and are considered as “source” of vibrations. Since, these vibrations are not unique onboard MEx (crycooler, other instruments, ...) and the uncertainties on these vibrations frequencies are not known, it is not possible to have a supervised approach. One also have to note that all vibration frequencies may not be present in a PFS spectrum, depending the coupling with PFS. Nevertheless, a comparison between our blind estimation and the actual data will be a point of interest.

From each vibration frequency $f_d$ (in Hz), the perturbation is at wavenumber $\sigma_d = f_d / v_m$, with the pendulum speed $v_m$ can be calculated through the zero-crossing frequency $f_{zc}$ and zero-crossing length $d_{zc}$ (2500 Hz and 1.2 microns for typical PFS measurements at Mars): $v_m = d_{zc} \cdot f_{zc}$. 


**Reaction wheels.** Thanks to telemetry data from ESA, it is possible to estimate the frequencies of reaction wheels for ORBIT0032, spectrum #106 to be at 56.7 Hz, 40.6 Hz, 33.3 Hz and 30.3 Hz. Uncertainties are unknown.

**IMU.** Astrium technical specification of MEx (MEX.MMT.HO.2379) states that the IMU dithering onboard MEx are at 513.9 Hz, 564.3 Hz and 617.4 Hz. Uncertainties are unknown.

**PFS eigen-modes.** The PFS eigen-modes are around 135 Hz and 160 Hz. Uncertainties are unknown.

### 3.2.6. Semi-blind deconvolution technique results.

Due to the stochastic character of the ghosts and especially their phase, few % of the PFS spectra in the archive, randomly distributed, present significant level of perturbations. Typical spectra contain few of ghosts, while in some lucky cases they totally are absent. We propose to illustrate our algorithm on the ORBIT0032, spectrum #106 of PFS, that is characterized by a particularly high level of disturbances. This spectrum contains several obvious ghosts (as shown by the arrows in Fig. 3.4).

We find that the optimum inversion is reached with a loop of $N=2$, with special regularization parameter $\lambda_K=50$ for the first step due using the filtered initialization, and then usual parameters $\lambda_{\text{Mars}}=0.001$, $\lambda_K=1$ for other steps, while elaborating the unfiltered spectra.

For Mars spectra estimation, the final estimation $\hat{f}_{\text{Mars}}^{\text{final}}$ is presented on Figures 3.12 and 3.13. Those figures presents the raw spectrum and our corrected spectrum in comparison with a synthetic spectrum $\hat{f}_{\text{Mars}}^0$ (see section 3.2.4), as well as the stack of 20 spectra. Our correction clearly removes the ghosts in the region at 0-1530 cm$^{-1}$, around 2700 cm$^{-1}$, around 3450 cm$^{-1}$ and around 4150 cm$^{-1}$, similarly to the stacking method. The artifact at 2900 cm$^{-1}$ persists, due to pollution of hydrocarbons in the telescope. In the 4000-5000 cm$^{-1}$ domain our method improves the signal in comparison to the stacking method and partly corrects the artificial decrease of the signal. On another hand stacking clearly reduces the stochastic noise, that is not removed with our correction.

Figure 3.14 shows the evolution of the average spectra, when stacking 3, 5, 11 and 19 spectra. The plots clearly show that our method removes the ghosts contribution, already without stacking. In contrary, the stacking methods requires $\approx$10 spectra to remove this effect. The signal to noise ratio at the small scale, estimated by the standard deviation in the 0-1530 cm$^{-1}$, is not significantly changed between both methods.

The stack of $\approx$10 spectra corresponds to $\approx$10 spots of around 7 km each, so that the spatial resolution can be improved by one order of magnitude. In terms of temporal resolution improvement, it depends mainly on the location due to the very irregular observation density.
Figure 3.12. Final results of the spectrum ORBIT0032 #106; at the top: modulus of measured $I_{PFS}$ (blue), simulated $\hat{I}_{PFS}^{\text{final}} = \hat{I}_{Mars}^{\text{final}} \ast \hat{R}_{PFS}^{\text{final}}$ PFS spectrum (red) and the estimated Martian spectrum $\hat{I}_{Mars}^{\text{final}}$ (black); lack of fit between $I_{PFS}$ and $\hat{I}_{PFS}^{\text{final}}$ is $1.8 \times 10^{-5}$; in the middle: modulus (in log scale) and phase of the final estimated kernel $\hat{R}_{PFS}^{\text{final}}$; at the bottom: modulus and phase of the final estimated spectrum $\hat{I}_{Mars}^{\text{final}}$. 
Figure 3.13: Final results of the spectra ORBIT0032 #106 as compared with stacking and synthetic measurements, from top to bottom: (i) raw PFS measurements, all arrows represent ghosts artifacts; (ii) estimated spectra from our algorithm; (iii) synthetic measurement of PFS; (iv) stack of 11 PFS spectra; (v) stack of 11 estimated spectra from our algorithm. The arrow at 2900 cm$^{-1}$ represents the telescope contamination by hydrocarbons, the arrow at 4900 cm$^{-1}$ represents an artifact of abnormal small signal, probably due to ghosts.

Figure 3.14. Comparison of our correction versus the stacking method. Noise standard deviation from the 0-1530 cm$^{-1}$ are expressed for all spectra. Arrows at 2700 cm$^{-1}$ represent significant difference in the signal domain due to ghosts, that persists for stacking of at least 5 PFS spectra but well corrected by our method.

a – Stacking of corrected spectra from our method.  
b – Stacking of PFS spectra.
3.2.7. Quality of the results.

As illustrated in Fig. 3.12, the lack of fit between the real PFS spectra $I_{PFS}$ and the simulated one from our final guesses $f_{PFS}^{\text{final}} = f_{\text{Mars}}^{\text{final}} * R_{PFS}^{\text{final}}$ is very small ($\sim 10^{-5}$), showing that the solution is compatible with the observation.

The ghost removal in the 1 to 1530 cm$^{-1}$ domain is efficient to remove the norm by a factor of $\sim 2$ (the RMS is 0.0093 for the raw spectra and 0.0042 for the corrected spectra). The only signal left in $I_{\text{Mars}}^{\text{final}}$ seems to be random, as expected (Fig. 3.12). The theoretical value of noise standard deviation is about 0.1 using the estimated Signal to Noise ratio of about 100 in the 2000-2400 cm$^{-1}$. The estimated noise standard deviation of corrected spectra is in agreement with this value (Fig. 3.14).

The laser line modulations shape $I_{\text{LM}}^{\text{final}}$, evaluated through combined effects of filtering, aliasing and vibration kernel $R_{PFS}^{\text{final}}$, is compatible with the observation $I_{\text{LM}}$ (Fig. 3.15). The four main peaks are estimated, as well as some smaller peaks. The distance is relatively small $\sim 0.013$.

![Figure 3.15. Modulus of the simulated laser line modulation through combined effects of filtering, aliasing and vibration kernel (blue) and the observed $I_{\text{LM}}$ (red). The lack of fit is 0.027.](image)

The final kernel estimation $R_{PFS}^{\text{final}}$ is close to the initial kernel guess $R_{PFS}^{0} = R_{PFS}^{\text{approx}}$ with a distance $\sim 10^{-5}$. As it is illustrated in Fig. 3.16, the main vibration frequencies estimated in $R_{PFS}^{\text{approx}}$ are present in $R_{PFS}^{\text{final}}$. The estimation of $R_{PFS}^{\text{approx}}$ has been done under strong approximations, and the resulting differences might be explained by the unconstrained amplitudes of this estimation. Also $R_{PFS}^{\text{final}}$ represents a smooth signal due to the high frequencies filtering. Other methods without sparsity regularization don’t succeed to get such a sparse kernel, while we assume that the kernel is sparse due
to limited number of vibration components in the mechanical environment of PFS onboard MEx (eigen-mode of PFS, reaction wheels frequencies, inertia measurement unit dithering frequencies).

Figure 3.16. Modulus in log scale of the vibration kernel \( \hat{K}_{\text{PFS}}^{\text{final}} \) (blue line), the approximated kernel \( \hat{K}_{\text{PFS}}^{\text{approx}} \) (red line) and the reaction wheels vibration (dark grey line), and the combination of reaction wheels vibration components (light grey line). The lack of fit is \( 3.2 \times 10^{-4} \).

3.3. Conclusions.

In this chapter the analytical formulation of ghosts caused by mechanical disturbances has been derived. The adopted mathematical formulation is based on a linear convolution; this approach allows the inversion of the problem using supervised semi-blind deconvolution techniques for the signal domain. For the laser straylight, the derived non-linear mathematical formulation shows that inversion is not trivial. Leveraging on an approximated formulation of the laser line, it is possible however, to estimate the vibration kernel.

The direct vibration model has been tested using actual PFS data, by (i) estimating first the vibration kernel using the approximated formulation and then (ii) applying the convolution vibration model to the actual signal. It has been shown that, the results are in accordance with the observed spectral features in terms of wavenumber position though the amplitude estimation still need to be improved.

The described correction algorithm tested on the PFS dataset showed that it is possible to reduce significantly the ghosts from the observed signal using three coherent quantities: ghosts in the signal domain, laser line ghosts, distance to approximated kernel. The global shape of PFS spectra can be corrected with such algorithm, allowing the better estimation of temperature and of the thermal profile on each PFS measurement, improving the few % of spectra with high \( \chi^2 \) that could not be processed with currently applied calibration technique. Also such correction permits to avoid the continuum
removal step in the minor species retrieval. When the signal to noise ratio is high enough, our correction will also reduce the stacking procedure.

The only limitation of the proposed semi-blind deconvolution method application is the reduced wavenumber domain of meaningful signal, thus the technique is useful for the PFS data treatment, but might be irrelevant for the other FTS instrument.

The next step would be an algorithm able to correct large datasets (such as the complete PFS archive) that would require an efficient algorithm, timesaving implementations and the procedure being fully automatic.
References CHAPTER 3.


Annex 3.1.

Concerning the Eq. (3.11):

\[ I(\sigma) = A_s \exp(i\varphi_{s_d})\delta(\sigma - \sigma_s) + A_s \left\{ \begin{array}{l} A_1 \sigma_s \exp[i(\varphi_{s_d} + \varphi_{d_u})] + A_2 \sigma_s \exp\left[i(\varphi_{s_d} + \varphi_{d_d} + \frac{\pi}{2}\right)] \delta[\sigma - (\sigma_s + \sigma_d)] \\ + A_2 \left\{ A_1 \sigma_s \exp[i(\varphi_{s_d} - \varphi_{d_u})] + A_2 \sigma_s \exp\left[i(\varphi_{s_d} - \varphi_{d_d} + \frac{\pi}{2}\right)] \delta[\sigma - (\sigma_s - \sigma_d)] \right\} 
\]

For the simplification reasons the following notation can be used:

\[ B_{\exp}(i \varphi_{s_d}) = A_1 \exp(i \varphi_{d_u}) + A_2 \exp\left(i \left(\varphi_{d_d} + \frac{\pi}{2}\right)\right), \]

\[ C_{\exp}(i \varphi_{s_d}) = A_1 \exp(-i \varphi_{d_u}) + A_2 \exp\left(i \left(-\varphi_{d_d} + \frac{\pi}{2}\right)\right). \]

Annex 3.2.

Extension of the Eq. (3.12) can be performed in two steps.

**Step 1. Extension for the non-monochromatic input spectra.**

To go to the general source case, it has to be remembered that the non-monochromatic spectrum \( I_{\text{continuum}}(\sigma) \) can be expressed through its monochromatic components \( I_{\text{signal}_k}(\sigma) \) as following:

\[ I_{\text{continuum}}(\sigma) = \sum_k I_{\text{signal}_k}(\sigma) = \sum_k A_{s_k} \exp(i \varphi_{s_k}) \delta(\sigma - \sigma_{s_k}) \]

Modulated by single vibration component \( \sigma_d \), spectrum \( I_{\sigma_d}(\sigma) \) in its turn can be represented as the sum of the modulated monochromatic components \( I_k(\sigma) \):

\[ I_{\sigma_d}(\sigma) = \sum_k I_k(\sigma) \]

where \( I_k(\sigma) \) is defined in accordance with the Eq. (3.12):

\[ I_k(\sigma) = I_{\text{signal}_k}(\sigma) + \sigma_{s_k} I_{\text{signal}_k}(\sigma) \ast K_{\sigma_d}(\sigma) = A_{s_k} \exp\left(i \varphi_{s_k}\right) \delta(\sigma - \sigma_{s_k}) + \sigma_{s_k} A_{s_k} \exp\left(i \varphi_{s_k}\right) \delta(\sigma - \sigma_{s_k}) \ast K_{\sigma_d}(\sigma) = A_{s_k} \exp\left(i \varphi_{s_k}\right) \delta(\sigma - \sigma_{s_k}) + A_{s_k} \exp\left(i \varphi_{s_k}\right) [\sigma \delta(\sigma - \sigma_{s_k})] \ast K_{\sigma_d}(\sigma) \]
Note:
\[ \sigma_{sk} \delta(\sigma - \sigma_{sk}) = \sigma \delta(\sigma - \sigma_{sk}) = \begin{cases} \sigma_{sk} \delta(0), & \sigma = \sigma_{sk} \\ 0, & \sigma \neq \sigma_{sk} \end{cases} \]

Thus we obtain:
\[
I_{\sigma_d}(\sigma) = \sum_k \left\{ A_{sk} \exp \left( i \varphi_{\sigma_{sk}} \right) \delta(\sigma - \sigma_{sk}) + A_{sk} \exp \left( i \varphi_{\sigma_{sk}} \right) \left[ \sigma \delta(\sigma - \sigma_{sk}) \right] \ast K_{\sigma_d}(\sigma) \right\} = \\
\sum_k \left\{ A_{sk} \exp \left( i \varphi_{\sigma_{sk}} \right) \delta(\sigma - \sigma_{sk}) \right\} + \sum_k \left\{ A_{sk} \exp \left( i \varphi_{\sigma_{sk}} \right) \left[ \sigma \delta(\sigma - \sigma_{sk}) \right] \ast K_{\sigma_d}(\sigma) \right\} = \\
\sum_k I_{\text{signal}_k}(\sigma) + \left[ \sum_k \sigma I_{\text{signal}_k}(\sigma) \right] \ast K_{\sigma_d}(\sigma) = \\
\sum_k I_{\text{signal}_k}(\sigma) + \left[ \sigma \sum_k I_{\text{signal}_k}(\sigma) \right] \ast K_{\sigma_d}(\sigma) = \\
I_{\text{continuum}}(\sigma) + [\sigma I_{\text{continuum}}(\sigma)] \ast K_{\sigma_d}(\sigma)
\]

**Step 2. Extension for the arbitrary vibration component shape**

Having the vibration kernel \( K(\sigma) \) consisting of more than one harmonic, we obtain the final modulated spectrum as the combination of the modulations by each harmonic component \( \sigma_{d_j} \):

\[
I(\sigma) = I_{\text{continuum}}(\sigma) + \sum_j \left\{ [\sigma I_{\text{continuum}}(\sigma)] \ast K_{\sigma_d j}(\sigma) \right\} = \\
I_{\text{continuum}}(\sigma) + [\sigma I_{\text{continuum}}(\sigma)] \ast \sum_j K_{\sigma_d j}(\sigma) = \\
I_{\text{continuum}}(\sigma) + [\sigma I_{\text{continuum}}(\sigma)] \ast K(\sigma)
\]

where \( K(\sigma) = \sum_j K_{\sigma_d j}(\sigma) \), or in other words:

\[
K(\sigma) = \sum_j \left\{ B_j \exp \left[ i \varphi_{\sigma B_j}(\sigma) \right] \delta \left[ \sigma - (+\sigma_{d_j}) \right] + C_j \exp \left[ i \varphi_{\sigma C_j}(\sigma) \right] \delta \left[ \sigma - (-\sigma_{d_j}) \right] \right\}
\]
4. MECHANICAL DESIGN

This chapter is devoted to micro-MIMA mechanical design and thermoelastic analysis predicting instrument response to the mechanical and thermal loading conditions. Instrument behavior under static and dynamic loads (during takeoff from Earth and landing on Mars surface) has been investigated by means of FEM simulations performed on a simplified model. Thermoelastic analysis was performed in order to find temperature distribution on the structure during a simulated scenario of Martian environment and evaluate optical misalignment that it creates. In addition a tuning of the vibration isolation system parameters was performed, in order to reduce the effect of the random vibration excitation levels on the instrument structure.

4.1 Mechanical model

Following the optimized optical layout parameters the dimensions and position of optical elements (Fig. 2.7) were taken as a constraint for the mechanical design of MicroMIMA, plus the specified spectral resolution defining the OPD, provides the minimum required stroke of the double-pendulum.

Distance between beam splitter and cubic mirror has to ensure the possible movement of the last one.

For the enhanced spectral resolution option, $\Delta \sigma$ is 1 cm$^{-1}$, and maximum OPD required can be computed as following:

$$OPD_{\text{max}} = \frac{1}{\Delta \sigma} = 10 \, \mu\text{m} \quad (4.1)$$

In that case mirror displacement $MD$, needed to provide the maximum OPD, is:

$$MD = \frac{OPD}{4} = 2.5 \, \mu\text{m} \, (\pm 1.25 \, \mu\text{m}). \quad (4.2)$$

The gap between cubic mirrors and beam splitter to be kept above 1.25 $\mu$m in order to ensure calculated mirror displacement value:

Rough preliminary beamsplitter dimensioning resulted in following values: minimum major (minor) semiaxis 17 (12) mm (with min thickness ratio 0.1 of max dimension).

To streamline the FE calculations the model (Fig. 4.1) has been split in a list of separately analyzed subassemblies:

- instrument frame (IF);
- double pendulum group (DPG);
- piezo-bender actuator assembly (PBA);
- beamsplitter assembly (BSA).
Instrument frame (IF) (Fig. 4.2) is an aluminum alloy structure optimized in order to prove its sufficient stiffness characteristics for the expected excitation frequency range. For each IF analysis other elements, optical and mechanical, were modeled as concentrated masses:

- optical system of four ZnSe lenses of approximate masses (including about 30% increase for the mounting means) 1.4 g, 0.1 g, 1.2 g, 2.1 g and folding mirror of 1 g;
- beamsplitter assembly: 5 g;
- piezo-actuator subassembly: 6 g;
- double pendulum group: 13.2 g.

As Locking Mechanism (LM) and Reference Laser Group (RLG) are not pointed for calculations in this work so they were included in the IF system as a schematic elements of varying masses (to guarantee the total mass constraint).

Double Pendulum Group (DPG) is represented as two hollow aluminum brackets on the c-flex bearing supports (material: stainless steel) (Fig 4.3, a). The mounting of the cubic corner mirrors is performed through the intermediate spherical elements to allow instrument alignment (Fig 4.3, b). With regards to the geometric symmetry of the structure, the analysis of the pendulum group behavior was reduces to the single the pendulum arm analysis (Fig 4.3, c).
Beamsplitter subassembly (BSA) (Fig. 4.4) is represented by beamsplitter and compensator plates, mounted on the holder compliant edges through the adapter ring of Vespel elements. Such a mounting system ensures the reduction of thermal stresses on the optical elements due to the difference in the thermal expansion coefficients of optical and metallic parts of the assembly.

Piezo Bender Actuator (PBA) subassembly (Fig. 4.5, a) consists of 2 piezo-bender actuators, clamped at their extremes on the mounting structure and joined to the pendulum arm through the metal foil. Those last ensure not only mechanical mounting of the actuators, but also insulation of the electrical contact areas. The number and positioning of the actuators was chosen to ensure their optimal operating conditions with the safety margin of 2 [1].
Finally all model components are brought together in the following Table 4.1.

<table>
<thead>
<tr>
<th>Subassembly</th>
<th>Element</th>
<th>Material</th>
<th>Mass, g</th>
<th>Total mass, g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lenses</td>
<td>Entrance optics + mounting</td>
<td>CaF₂</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gathering lens + mounting</td>
<td>CaF₂</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reference laser detector subgroup</td>
<td></td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.8</td>
</tr>
<tr>
<td>Beamsplitter subassembly</td>
<td>Beamsplitter + mounting</td>
<td>CaF₂</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compensator + mounting</td>
<td>CaF₂</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Cubic corner mirrors</td>
<td>Cubic corner mirror</td>
<td>SiO₂</td>
<td>2 x 1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Mirror holder</td>
<td>AL7075-T6</td>
<td>2 x 1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Folding mirror</td>
<td>Folding mirror + mounting</td>
<td>SiO₂</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Optical system total mass</strong></td>
<td></td>
<td><strong>16.6</strong></td>
<td></td>
</tr>
<tr>
<td>IF</td>
<td>Frame</td>
<td>AL7075-T6</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>DPG</td>
<td>Brackets</td>
<td>AL7075-T6</td>
<td>2 x 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sphere</td>
<td>AL7075-T6</td>
<td>2 x 0.55</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cylinder</td>
<td>AL7075-T6</td>
<td>2 x 0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C-flex bearings</td>
<td>Steel</td>
<td>2 x 0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DPG base</td>
<td>AL7075-T6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>9.2</strong></td>
</tr>
</tbody>
</table>
Table 4.1. MicroMIMA model components and their masses.

<table>
<thead>
<tr>
<th>PBA</th>
<th>Actuator</th>
<th>2 x 0,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezo-holder frame</td>
<td>AL7075-T6</td>
<td>4</td>
</tr>
<tr>
<td>Shaft</td>
<td>AL7075-T6</td>
<td>2 x 0,4</td>
</tr>
<tr>
<td>Holder</td>
<td>AL7075-T6</td>
<td>2 x 0,3</td>
</tr>
<tr>
<td>Insulator</td>
<td>Vespel-SPC50000</td>
<td>2 x 0,08</td>
</tr>
<tr>
<td>Piezo-connection elements</td>
<td>AL7075-T6</td>
<td>2 x 0,2</td>
</tr>
<tr>
<td>Metal foil</td>
<td>Steel</td>
<td>0,03</td>
</tr>
</tbody>
</table>

| Mechanical system total mass | 42,2 |

Table 4.1. MicroMIMA model components and their masses.

4.2 Structural analysis.

The described model has undergone the structural static and frequency analysis, in order to evaluate the structure with respect to the mission environment constrains: response to the expected acceleration loads of 10g acceleration and absence on natural modes below 150 Hz.

4.2.1. Finite Element Model for structural analysis

The list of materials and their mechanical properties used in micro-MIMA is presented in the following Table 4.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young modulus, [MPa]</th>
<th>Poisson ratio</th>
<th>Density, [kg/m3]</th>
<th>Tensile strength, [MPa]</th>
<th>Yield strength, [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al alloy 7075-T6</td>
<td>7-10^4</td>
<td>0,35</td>
<td>2710</td>
<td>530</td>
<td>475</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>19,3-10^4</td>
<td>0,27</td>
<td>7990</td>
<td>800</td>
<td>600</td>
</tr>
<tr>
<td>CaF₂</td>
<td>7,6-10^4</td>
<td>0,26</td>
<td>3180</td>
<td>36,5</td>
<td>n. a.</td>
</tr>
<tr>
<td>Float glass (SiO₂)</td>
<td>7,3-10^4</td>
<td>0,17</td>
<td>2200</td>
<td>n. a.</td>
<td>n. a.</td>
</tr>
<tr>
<td>Vespel SPC-5000</td>
<td>3,99-10^4</td>
<td>0,41</td>
<td>1460</td>
<td>163</td>
<td>n. a.</td>
</tr>
</tbody>
</table>

Table 4.2. Material properties.
Instrument Frame.

The instrument frame model for the structural analysis realizes all the MicroMIMA mechanical and optical elements schematically through the concentrated mass/stiffness elements, while the applied restrains represent the instrument mounting on the Demonstrator mast, as it is shown on Figure 4.6.

Figure 4.6. Instrument Frame model for structural analysis.

The DPG structure mounting through the C-Flex bearings was represented through the concentrated stiffness property in accordance with technical datasheet [2] for the chosen bearings [1]:

- radial stiffness – 350 N/mm;
- axial stiffness – 580 N/mm;
- rotational stiffness – 0.01 Nm/rad.

To achieve reliable results was created a parabolic tetrahedron elements mesh with element size of 0.5 mm, value identified as the minimum to have at least two elements per thickness, what is recognized as adequate mesh quality index in the used FEA software (CatiaV5).

Double Pendulum Group.

The structural analysis was performed on the free arm of the Double Pendulum group, as it is the representative trouble spot of the structure. The model for the analysis is shown on the Fig. 4.7, where restrains represent the arm mounting on the DPG base. Connection to the PBA through the metal foil was neglected in this analysis, due to its high compliance with respect to the whole structure.
Figure 4.7. Double Pendulum Group model for the analysis.

For mesh were also chosen parabolic tetrahedron elements of 0.5 mm size, found to be an acceptable tradeoff between results accuracy and computation time.

**Beamsplitter subassembly.**

The BSA analysis model (Fig. 4.8) restraints approximate the mounting of the assembly on the instrument frame. In particular: the Beamsplitter holder three-point mounting on the frame and the positioning of the compensator holder inside the frame orifice.

Figure 4.8. Beamsplitter assembly: model for the analysis.

The Beamsplitter and Compensator optical plates were represented physical elements (not schematically) in order to prove that designed mounting ensures absence of critical stresses on the optics under take-off/landing loads.

For mesh of the mechanical elements were taken parabolic tetrahedron elements of 0.25 mm size, to realize efficiently the fine structure of the compliant edges and adaptor ring; optical elements the chosen mesh was coarser (1 mm) following the two-elements per thickness meshing suggestion.
**Piezo-bender Actuator subassembly.**

Piezo-bender motors do not undergo specific analysis as specification technical data, provided by the producer, answers the mechanical requirements. The model for analysis of the whole structure (actuators are represented by their approximate mechanical properties) is given on Figure 4.9.

![Figure 4.9. Piezo-bender actuator assembly: model for the analysis.](image)

The applied to the model restraints simulate the mounting of the structure on the instrument frame and connection to the pendulum arm.

### 4.2.2. Static stress analysis

Static stress analyses were performed on the described structures for the equivalent acceleration of 1000 m/s² along X, Y, Z directions.

For each loading condition should be fulfilled the following Margin of Safety (MOS) inequality:

\[
MOS = \frac{\sigma_{\text{yield}}}{\sigma_{\text{max} \cdot \text{SC}}} > 1, \quad (4.3)
\]

where \( \sigma_{\text{yield}} \) is the material yield stress, \( \sigma_{\text{max}} \) is the max Von Mises stress in the structure and SC is the safety coefficient.

**Instrument Frame subassembly**

Results from the static stress analyses on the Instrument Frame structure are presented on the Figure 4.10.

Having the yield stress of AL alloy structure \( \sigma_{\text{yield}} = 475 \text{ MPa} \) and being the maximum Von Mises stresses along each direction:

- \( \sigma_{\max} X = 90 \text{ MPa} \),
- \( \sigma_{\max} Y = 98 \text{ MPa} \),
- \( \sigma_{\max} Z = 63 \text{ MPa} \),

with safety coefficients for stresses in-plane with optical layout \( \text{SC}_{X,Y} = 1.5 \) and the orthogonal one \( \text{SC}_Z = 2 \), safety margins are
- $\text{MOS}_X = 3.5,$
- $\text{MOS}_Y = 3.2,$
- $\text{MOS}_Z = 3.8.$

It has to be noticed the inequality (4.3) is accomplished for all three loading cases.

Figure 4.10. Instrument Frame stresses: 

- $a$ – load along Z axis;
- $b$ – load along X axis;
- $c$ – load along Y axis.
**Pendulum Arm subassembly**

Results from the static stress analysis on the Pendulum Arm structure are presented on Figure 4.11.

![Figure 4.11. DPG stresses: a – load along Z axis; b – load along X axis; c – load along Y axis.](image)

Having the yield stress of AL alloy structure $\sigma_{\text{yield}} = 475 \text{ MPa}$ and being the maximum Von Mises stresses along each direction:

- $\sigma_{\text{max}} X = 90 \text{ MPa},$
- $\sigma_{\text{max}} Y = 35 \text{ MPa},$
- $\sigma_{\text{max}} Z = 30 \text{ MPa},$

with same safety coefficients applied: $SC_{X,Y} = 1.5$ and $SC_{Z} = 2$, safety margins are

- MOS$_X = 3.5,$
- MOS$_Y = 9.0,$
- MOS$_Z = 7.9.$

It has to be noticed that the actual stresses on the optical elements will differ from the evaluated by these analyses ones, as the used model did not represent their mounting in details.
Finally, the inequality (4.3) is accomplished for all three loading cases.

**Piezo-Bender Actuators subassembly.**

Results from the static stress analysis on the Piezo-Bender Actuators assembly structure are presented on Figure 4.12.

![Figure 4.12. PBA stresses: a – load along Z axis; b – load along X axis; c – load along Y axis.](image)

As the elements of the analyzed assembly are manufactured from different materials (Al alloy and vespel), it is necessary to evaluate their Margins of Safety separately.

The yield stress for the AL alloy structure is $\sigma_{\text{yield}} = 475$ MPa and maximum Von Mises stresses along each direction are:

- $\sigma_{\text{max}} X = 65$ MPa,
- $\sigma_{\text{max}} Y = 20$ MPa,
- $\sigma_{\text{max}} Z = 26$ MPa.

For the vespel elements the Margin of Safety should be calculated starting from the tensile strength $\sigma_{\text{TS vespel}} = 163$ MPa, while the max Von Mises stresses on the vespel elements are:

- $\sigma_{\text{max}} X = 0,5$ MPa,
- $\sigma_{\text{max}} Y = 0,2$ MPa,
\[ \sigma_{\text{max}} Z = 1 \text{ MPa}. \]

Using same safety coefficients \( SC_{X,Y} = 1.5 \) and \( SC_{Z} = 2 \), safety margins (taken the minor ones from the calculated for the aluminum and vespel elements) are

- \( \text{MOS}_X = 3.6, \)
- \( \text{MOS}_Y = 16, \)
- \( \text{MOS}_Z = 9. \)

Finally, the inequality (4.3) is accomplished for all three loading cases for the whole structure.

**Beamsplitter subassembly.**

Results from the static stress analysis on the Beamsplitter subassembly structure are presented on Figure 4.13.

![BSA stresses](image)

**Figure 4.13. BSA stresses: a – load along Z axis; b – load along X axis; c – load along Y axis.**

As the elements of the analyzed assembly are manufactured from different materials (Al alloy, vespel, CaF\(_2\)), it is necessary to evaluate their Margins of Safety separately.
The yield stress for the AL alloy structure is $\sigma_{\text{yield}} = 475$ MPa and maximum Von Mises stresses along each direction are:

- $\sigma_{\text{max}} X = 9$ MPa,
- $\sigma_{\text{max}} Y = 16$ MPa,
- $\sigma_{\text{max}} Z = 14$ MPa.

For the vespel and CaF$_2$ elements the Margin of Safety should be calculated starting from the tensile strength $\sigma_{\text{TS vespel}} = 163$ MPa and $\sigma_{\text{TS CaF}_2} = 36.5$ MPa.

Max Von Mises stresses on the vespel elements are:

- $\sigma_{\text{max}} X = 0.25$ MPa,
- $\sigma_{\text{max}} Y = 0.15$ MPa,
- $\sigma_{\text{max}} Z = 0.15$ MPa.

Max Von Mises stresses on the CaF$_2$ optical elements are:

- $\sigma_{\text{max}} X = 0.2$ MPa,
- $\sigma_{\text{max}} Y = 0.1$ MPa,
- $\sigma_{\text{max}} Z = 0.08$ MPa.

Using same safety coefficients $SC_{X,Y} = 1.5$ and $SC_Z = 2$, safety margins (taken the minor ones from the calculated for the aluminum and vespel elements) are

- $\text{MOS}_X = 35$,
- $\text{MOS}_Y = 20$,
- $\text{MOS}_Z = 17$.

Finally, the inequality (4.3) is accomplished for all three loading cases for the whole structure.

### 4.2.3. Frequency analysis

Modal analyses have been performed to assure that all the structure natural frequencies are above 150 Hz limit.

#### Instrument Frame subassembly.

The first five natural frequencies of the Instrument Frame structure are listed in the Table 4.3.

<table>
<thead>
<tr>
<th>Mode</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, Hz</td>
<td>410</td>
<td>520</td>
<td>655</td>
<td>780</td>
<td>785</td>
</tr>
</tbody>
</table>

Table 4.3. IF: natural frequencies.

The first natural mode (410 Hz) of the Instrument Frame structure is shown on the Figure 4.14. It consists in the bending of the base plane.
The first three natural frequencies of the Pendulum Arm structure are listed in the Table 4.4.

<table>
<thead>
<tr>
<th>Mode</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, Hz</td>
<td>550</td>
<td>2300</td>
<td>3800</td>
</tr>
</tbody>
</table>

**Table 4.4. Pendulum Arm natural frequencies.**

The first natural mode for the Pendulum Arm structure (550 Hz) is shown on the Figure 4.15. It consists in the bending of the arm from its mounting surface.

**Figure 4.15. Pendulum arm first natural mode (550 Hz).**
Piezo-Bender Actuators subassembly.

The first natural frequencies of the Piezo-Bender Actuators assembly are listed in the Table 4.5.

<table>
<thead>
<tr>
<th>Mode</th>
<th>I (piezo-actuator)</th>
<th>II (mounting structure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, Hz</td>
<td>380 ± 20%</td>
<td>2650</td>
</tr>
</tbody>
</table>

Table 4.5. Piezo-Bender Actuators assembly natural frequencies.

The first natural mode (2650 Hz) of the Piezo-Bender Actuators assembly structure is shown on the Figure 4.16. It consists in the rotation of the actuator mounting shaft with respect to the frame. The modes related to the piezo-actuators are not the subject of this research as they are provided by the producer [3].

Figure 4.16. Piezo-Bender Actuators assembly first natural mode (2650 Hz).

Beamsplitter subassembly.

The first five natural frequencies of the Beamsplitter assembly are listed in the Table 4.6.

<table>
<thead>
<tr>
<th>Mode</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, Hz</td>
<td>450</td>
<td>670</td>
<td>680</td>
<td>695</td>
<td>700</td>
</tr>
</tbody>
</table>

Table 4.6. Beamsplitter assembly natural frequencies.

The first vibration mode for the of the Beamsplitter assembly (450 Hz) is shown on the Figure 4.17. It consists in the punching shear of the circular surface for the optical elements mounting.

Figure 4.17. Beamsplitter assembly first natural mode (450 Hz).
4.3 Vibration isolation system parameterization.

This paragraph will be focused on the parameterization of the vibration isolation system in order to reduce the transmitted vibrations due to predicted levels of random excitation for the mission [4].

The isolation system is represented by three damping elements (Fig. 4.18), placed under the mounting surface of the instrument. Their radial and axial stiffness properties are to be tuned in order to achieve the minimum response of the optical layout to the random environment expected on the spacecraft. As the loss function to be minimized were taken acceleration levels of the Beamsplitter central point, keeping the first natural mode frequency constraint.

![Vibration isolation system and its simplified model](image)

**Figure 4.18. Vibration isolation system and its simplified model.**

In accordance with [4] the levels of random excitation are summarized in the Figure 4.19 and Table 4.7.

![Example of Random Qualification Levels](image)

**Figure 4.19. Random environment (Qualification load levels).**
<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>Level, g²/Hz</th>
<th>Mass, kg</th>
<th>Random OOP, g²/Hz</th>
<th>Random IP, g²/Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>+ 6 dB</td>
<td>0.5</td>
<td>0.96</td>
<td>0.41</td>
</tr>
<tr>
<td>100</td>
<td>According to table</td>
<td>1</td>
<td>0.74</td>
<td>0.32</td>
</tr>
<tr>
<td>400</td>
<td>According to table</td>
<td>2</td>
<td>0.51</td>
<td>0.22</td>
</tr>
<tr>
<td>2000</td>
<td>- 6 dB</td>
<td>3</td>
<td>0.40</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.34</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**Qualification levels**

**Table 4.7. Levels of random excitation.**

For the further calculations the out-of-plane vibration levels were taken as they represent the worst loading case. The two isolation element configurations were analyzed, when the radial stiffness equal or differs from the axial ones: $K_X = K_Y = K_Z$, $K_X = K_Y \neq K_Z$. The first modal shapes for the both cases are shown in the Figure 4.20.

![Figure 4.20. First modal shapes: a – $K_X = K_Y = K_Z$; b – $K_X = K_Y \neq K_Z$.](image)

The summary of the tuning procedure is reported in the Table 4.8.

<table>
<thead>
<tr>
<th>Ref. case #</th>
<th>Stiffness, ×10⁴ N/m</th>
<th>Acceleration level power, ×10³(m/s²)²</th>
<th>1st mode frequency, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$K_{X,Y,Z} = 4$</td>
<td>x: 67.1, y: 61.6, z: 263.5</td>
<td>155</td>
</tr>
<tr>
<td>2</td>
<td>$K_{X,Y,Z} = 5$</td>
<td>x: 68.9, y: 62.3, z: 276.3</td>
<td>170</td>
</tr>
<tr>
<td>3</td>
<td>$K_{X,Y,Z} = 6$</td>
<td>x: 70.4, y: 62.6, z: 285.9</td>
<td>185</td>
</tr>
<tr>
<td>4</td>
<td>$K_{X,Y,Z} = 7$</td>
<td>x: 85.8, y: 135.6, z: 313.1</td>
<td>195</td>
</tr>
<tr>
<td>5</td>
<td>$K_X = 3$, $K_Z = 10$</td>
<td>x: 81.4, y: 76.6, z: 272.0</td>
<td>175</td>
</tr>
<tr>
<td>6</td>
<td>$K_{X,Y} = 4$, $K_Z = 6$</td>
<td>x: 75.4, y: 68.6, z: 260.8</td>
<td>160</td>
</tr>
<tr>
<td>7</td>
<td>$K_{X,Y} = 4$, $K_Z = 8$</td>
<td>x: 79.9, y: 70.5, z: 269.7</td>
<td>180</td>
</tr>
</tbody>
</table>

**Table 4.8. Resulting acceleration levels of the studied point and the first natural frequencies of the structure as a function of isolation element stiffness properties.**
As it is seen from the above data, the case #1 results in the lower acceleration levels of the Beamsplitter central point, but its reduced first natural frequency makes the next convenient case (case #2) to be the optimal choice, with the proposed damper stiffness properties are the following ones:

\[ K_{X,Y,Z} = 5 \times 10^4 \text{ N/m}. \]

4.4 Thermal design.

There are different simulated scenarios of Martian environment which provide the temperature field on the instrument. Thermoelastic analysis was performed in order to find temperature distribution on the structure during the worst scenario [1] and evaluate the created optical misalignment.

4.4.1. Thermal model

For thermoelastic analysis main interest is related to those structural elements that hold optical subsystem. Thus in instrument thermal model only the main mechanical subassemblies are used, while other elements are represented as additional inertia properties (Fig. 4.21). The constraining was performed in the same way as for the Instrument Frame structural analyses (Fig. 4.6).

![Figure 4.21. Input for the thermal analysis: \(a\) – Mars environment scenario (dust storm); \(b\) – created thermal loads on the model.](image)

The thermal properties of the used materials are summarized in the Table 4.9.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal expansion, (\times 10^{-5}) m/m°C</th>
<th>Thermal Conductivity, N/s°C</th>
<th>Specific heat capacity, (m^2/s^2/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al alloy 7075-T6</td>
<td>2,36</td>
<td>172</td>
<td>960</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>1,17</td>
<td>16,2</td>
<td>500</td>
</tr>
<tr>
<td>Float glass (SiO(_2))</td>
<td>0,06</td>
<td>1,38</td>
<td>740</td>
</tr>
<tr>
<td>Vespel SPC-5000</td>
<td>4,5</td>
<td>33</td>
<td>9,2 (\times 10^5)</td>
</tr>
</tbody>
</table>

Table 4.9. Thermoelastic properties of the materials.
4.4.2. Thermoelastic analysis.

Using Pro-Engineer software a temperature distribution on the structure under predicted temperature load was calculated and the results are given on Figure 4.22.

![Figure 4.22. Temperature distribution.](image)

Another obtained result is the displacement field of elements (Fig. 4.23).

![Figure 4.23. Thermoelastic analysis: displacement field](image)

The evaluated stress field on the structure is not considered in this work, as due to the schematic representation of the elements, the artificial increase of stress levels was present in the contacting areas.
### 4.4.3. Optical elements misalignments calculation.

Optical elements misalignments must not exceed some levels in order to ensure instrument efficiency. Those levels provide limit values for optical element shifts:

- displacements max 0.5 μm;
- tilt max 1 arc sec.

The displacement field on the structure provides data about optics mounting surfaces shifts. Those shifts describe 3-dimensional movement of optical elements and cause instrument misalignments. The relative data is provided in Table 4.10.

<table>
<thead>
<tr>
<th>Optical element</th>
<th>Displacement in vertical direction, μm</th>
<th>Displacement in horizontal direction, μm</th>
<th>Tilt, arcsec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Entrance optics</td>
<td>0.114</td>
<td>0.111</td>
<td>0.079</td>
</tr>
<tr>
<td>Lens 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lens 2</td>
<td>0.102</td>
<td>0.095</td>
<td>0.078</td>
</tr>
<tr>
<td>Lens 3</td>
<td>0.069</td>
<td>0.053</td>
<td>0.076</td>
</tr>
<tr>
<td>Gathering lens</td>
<td>0.031</td>
<td>0.042</td>
<td>0.064</td>
</tr>
<tr>
<td>Folding mirror</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Beamsplitter</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CCM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCM1</td>
<td>0.0970</td>
<td>0.064</td>
<td>-0.029</td>
</tr>
<tr>
<td>CCM2</td>
<td>0.0971</td>
<td>0.003</td>
<td>-0.010</td>
</tr>
<tr>
<td>CCM relative displacement</td>
<td>0.0001</td>
<td>0.0320</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 4.10. Optical system misalignments.**

As it is seen from the results there is no shift of any optical element which could provide some critical misalignment in optical system.

### 4.5. Conclusions.

The performed structural analysis proves the ability of the designed instrument configuration to resist the predicted mechanical loads, while the thermoelastic analysis ensures that also under the worst Martian environment scenario there will not be present any critical misalignments in the instrument optical structure that might considerably reduce the instrument overall efficiency. At the same time the tuning of the damper stiffness parameters can be used for the optimal vibration isolation system design and evaluation of the created displacements on the instrument elements.
References CHAPTER 4.


5. MOCK-UP DESIGN AND TESTING

This chapter is devoted to the design and preliminary verification experiments of the micro-MIMA laboratory mock-up in order to evaluate the instrument performance. Being generally simplified from the structural point of view this mock-up includes the detailed representation of the optimal optical layout, elaborated in the previous chapter, with the main elements mounting that keeps the possibility of their regulation and adjustment in order to achieve the maximum efficiency.

5.1 Mock-up model

The elaborated model of the laboratory mock-up (Fig. 5.1) follows the designed optimal layout in terms of optical elements materials, coatings and dimensions. The mechanical structure of the mock-up is simplified in order to reduce production costs and time. All the main elements present did not undergo neither static nor dynamic structural design. The mock-up is created only for optical performance evaluation, and not the mechanical behavior check. Another difference with the flight model of the instrument (Fig. 4.1) is that there was left the possibility of mounting of different entrance optical systems.

![Mock-up Model Diagram](image)

**Figure 5.1. Laboratory mock-up model:**
- **a** – without entrance optical system;
- **b** – with the pointing mechanism mounted as the entrance optics.

The optical layout of the mock-up includes the following elements:

- Beamsplitter (BS);
- cubic corner mirrors (CCM);
- entrance optics group (pointing mechanism, PM or fish-eye system, FES);
- gathering lens (GL);
- photodetector (PD);
- reference laser group (RLG).

Mechanical layout contains two main elements:

- double pendulum group (DPG);
- piezoactuator group (PAG).

5.1.1. Optical elements mounting.

The elaborated optical elements mounting allows their positioning and regulation in order to increase the overall instrument optical efficiency.

*Beamsplitter group.*

Beamsplitter is inserted and glued in the cylindrical part (Fig. 5.2) mounted on the beamsplitter frame element. To guarantee exact position of the beamsplitter group middle optical plane a compensator (element totally identical to beamsplitter) is inserted in beamsplitter frame from another side. Such solution provides good accuracy for the instrument performance check, while would be inconsistent for any kind of load tests, because glue connection is very delicate.

![Figure 5.2. Beamsplitter group mounting.](image)

*Cubic corner mirrors*

Cubic corner reflectors of required dimensions are chosen from the producer company catalog [1]. Their mounting on the double pendulum group brackets has to provide the possibility of regulation of axis direction for further alignment. Solution method is represented on the Fig.5.3, where regulation requirements are fulfilled by usage of a spherical joint.
For regulation bracket arm and CCM group are connected to two separate cylinders, with the outer cylinder rigidly connected to the bracket and the inner one to the CCM holder, as it is shown in the scheme on Fig. 5.4. Axis adjustment is performed by four radial screws. After regulation is done spherical joint is strengthened by tightening the fixing screw on the bracket arm.

Entrance optics system plus gathering lens

The entrance optics was designed in two variants:

- Pointing Mechanism;
- Fish-Eye System.

The pointing mechanism (Fig. 5.5) consists of two mirrors, rotating and fixed ones, which allow to direct the incoming sun-light beam inside the instrument pupil parallel to its optical axis [2].
The Fish-Eye System is presented on Fig. 5.6. The lens mounting followed basically same approach: lens is inserted in the frame (replicating its surface) and from another side is jammed be a threaded pin. All three lenses are mounted in separate modules (I and II) inserted into common threaded frame, in order to allow their relative displacement for the exact positioning.

Gathering lens is mounted following the same principle (Figure 5.7). Its position is fixed, as the photodetector mounting allows movement in order to be placed in the lens focal plane.
Photodetector.

Photodetector and its characteristics are taken from the producer company data sheet [3]. Its mounting is represented on the Fig. 5.8.

Reference laser group.

The reference laser is mounted in the laser tower (Fig. 5.9, b), where its emitted beam is collimated by means of short-focal-length lens; after passing the same optical path as the main incoming radiation, the beam is directed towards the reference channel detector by means of the folding mirror (Fig. 5.9, a). The mounting of all elements allows their relative movement in order to focus the laser beam exactly on the detector element.
Figure 5.9. Reference laser group: \(a\) – general scheme; \(b\) – laser mounting inside the laser tower; \(c\) – reference channel detector mounting in its frame.
5.1.2. Mechanical layout.

Mechanical elements of the laboratory mock-up fulfill the function of the double pendulum motion during the interferogram recording.

*Piezoactuator group.*

Piezoactuator group consists of two piezoactuators restrained in the common clamp element mounted on the instrument frame (Fig. 5.10). With bracket arm it is coupled by an additional support through a steel foil connection.

![Figure 5.10. Piezomotor scheme.](image)

Clamping elements ensure not only mechanical fixation, but also the electrical isolation of the piezoactuators.

*Double pendulum group.*

Double pendulum group represents base for the CCM subgroups (Fig. 5.11). It is mounted using flexural pivots (bearings) [4] and for accuracy reasons uses common base with beamsplitter group.
5.2 Instrument adjustment activities.

After the mock-up was produced and assembled (Fig. 5.12), a number of preliminary adjustment procedures was carried out before putting instrument into operation.
Those procedures included the cubic corner reflectors alignment, main detector placement in the gathering lens focal plane, alignment of the reference laser system and elaboration of the motion control signal for the piezo-actuators group.

5.2.1. Cubic Corner Mirrors alignment.

The goal of the alignment procedure was to improve the instrument efficiency by increasing the modulation factor due to optical misalignments $m_1(\sigma_u)$ (Eq. 2.4). The alignment set-up is shown on Figure 5.13a, where the aligned position of the cubic corner reflectors can be found through the interference fringes of the monochromatic diffused radiation. The adjustment of the reflector axis position was performed by means of the alignment tool described in section 5.1.1.

![Alignment tool](image)

**Figure 5.13.** Cubic corner reflectors alignment procedure: a – alignment set-up; b – interference fringes.

5.2.2. Main signal detector positioning in the gathering lens focal point.

The real focal plane of the lens might differ from the nominal one due to the tolerances of the mounting structure and lens itself. The determination of the actual focal plane requires some additional adjustment activities. The corresponding set-up for the detector positioning is shown on Figure 5.14.
Figure 5.14. Detector positioning set-up.

The radiation of the infrared lamp is collimated by means of parabolic mirror, and amplitude \( \Delta V \) of the step reading due to the lamp switch on/off, is measured for the different detector offset positions \( \Delta X \) from the nominal focal plane (Fig. 5.15). Such evaluation was performed for the offsets in the range of \( \pm 1 \) mm with the step of 0.1 mm.

Figure 5.15. An example of the acquired signal (+ 0.3 mm offset).

The obtained information about the \( \Delta V(\Delta X) \) dependence is summarized in the Figure 5.16.

Figure 5.16. Step signal amplitude as a function of the detector offset from the nominal focal plane.
As it is seen from the given graph, the actual focal plane position, corresponding to the maximum step amplitude readings, is shifted from the nominal one by the distance of 0.1 mm. During mock-up testing the detector was placed in accordance with this evaluation.

5.2.3. Reference laser system alignment.

The reference laser system alignment procedures consisted in direction of the outgoing laser beam on the corresponding reference channel detector. In order to have a clean reference signal, the accurate pointing is crucial, as the optical layout (beamsplitter in particular) is not efficient at the laser diode is emitting wavelength of 635 nm (Fig. 2.4). High values of the reference channel SNR ensures precise reading of its zero-crossings and thus correct sampling of the main interferogram.

The reference channel readings after the performed alignment procedures are shown of Figure 5.17. For the controlled pendulum motion the acquired signal is filtered around the frequency of the expected sine-shaped laser line interferogram (Fig. 5.17, b).

![Figure 5.17. Reference channel readings: a – free oscillations of the double pendulum; b – controlled motion of the double pendulum at constant velocity (filtered signal).](image)

5.2.4. Double-pendulum motion control signal.

The motion control signal, sent to the piezo-actuators group (Fig. 5.18, a), was built in a way to arrive to the maximum achievable span of the mirror motion, in order to obtain the highest possible spectral resolution. It consists of the constant component and of a set of harmonics, which are multiples of the main harmonic component frequency $f_1 = 255$ mHz. It can be easily noted that after the $3^{rd}$ harmonic, the components become of negligible magnitude (Fig. 5.18, b).
Figure 5.18. Control motion signal: $a$ – time history; $b$ - spectrum.

Such composition of a signal ensures absence of components that could possibly excite pendulum system resonant modes, as the first natural mode frequency of the structure $f_{nat}$ is 14 times higher than last meaningful harmonic component of the signal $f_{III} = f_1 \times 3 = 765$ mHz (Fig. 5.19).

Figure 5.19. Double pendulum resonances check (data from the vibrometer): $a$ – time history; $b$ – spectral analysis.

The corresponding measurement of the CCM displacement is shown on the Figure 5.20. As it is seen from the figure, the CCM motion is smooth with no oscillations present, thus the resonances of the structure are not excited.
The maximum span of the linear motion arrives to 2.2 mm what corresponds to the instrument spectral resolution of 1.14 cm⁻¹, while the nominal resolution is of 2 cm⁻¹ and the enhanced one is of 1 cm⁻¹. The reduction of the motion span with respect to the declared one is due to the additional stiffness of the roughly realized connection between piezo-acturator and pendulum bracket by the steel foil element.

5.3 Instrument first verification.

After all preliminary adjustments have been done, the instrument was ready to be put into the operation. The instrument first verification included following activities:

- measurement of the reference laser line spectrum in the frequency domain and the adoption of an appropriate filtering strategy;
- measurement of the calibration lamp spectrum;
- evaluation of mean lamp spectrum through the modulus averaging, rough interferogram symmetrization and following the Forman phase-correction algorithm.

5.3.1. Reference laser line spectrum.

As the instrument optical system is optimized for a particular wavenumber range, and the emitted laser radiation does not included in it, an appropriate filtering strategy is required in order to obtain a clear reference channel time history with easily recognizable zero-crossings. On the Figure 5.21 is shown an acquired reference channel time history and its spectrum.
Figure 5.21. Reference channel data: a – time history; b – spectrum.

As it is seen from the Figure 5.21, the reference channel signal is full of noise and the zero-crossings of the laser radiation interferogram are poorly detectable. Remembering Eq. 1.3, an approximate evaluation of the laser line position in the spectrum can be found the average velocity of the cubic corner reflector according the following formula:

\[ f_{\text{laser}} = \frac{4v_{\text{CCM}}}{\lambda_{\text{laser}}} \]  

(5.1)

The average CCM velocity in its turn can be evaluated in its turn from the vibrometer measurements (Fig. 5.22).

Figure 5.22. CCM position tracking: linear region.

The found average velocity \( v_{\text{CCM}} \) is equal to 1.07 mm/s. The above measurement does not represent the exact CCM velocity due to the possible inaccuracy in vibrometer pointing. Having laser radiation nominal wavelength of 635 nm, the approximate frequency of the laser line is 6700 Hz.

The zoomed spectral region around the above frequency is shown on the Figure 5.23a with the easily detectable laser line spectrum. It has to be noted that finally the laser line is not a single peak feature due to the non-constant velocity of the CCM motion, coming from the possible mechanical vibrations and the overall system non-linearity. The reference channel time history was restored from the highlighted spectral region belonging to the laser line by a simple truncation of the spectrum, keeping the signal in the range of 6700..7400 Hz (Fig. 5.23, b). Some ringing can present at the end of the
interferogram due to discontinuities in the used filtering function. In such case the ringing region is simply cut-off before the further zero-crossings determination. Such phenomenon leads in the reduction of the maximum optical path difference in the interferograms and thus in reduced spectral resolution. The accurate adequate filtering window has to be applied for each measurement.

Figure 5.23. Reference channel filtering: \( a \) – spectral data; \( b \) – restored interferogram time history.

An afterwards evaluation of the pendulum velocity is required in addition in order to check its smoothness, as any peaks in the velocity time history might be caused by the fake zero-crossing reading due to the noise still present in the reference channel (Fig. 5.24).
Figure 5.24. CCM velocity: data from the laser interferogram zero-crossings.

5.3.2. Calibration lamp spectrum.

The experimental set-up is shown on Figure 5.25.

![Experimental set-up](image)

Figure 5.25. Experimental set-up.

Main channel detector is constantly cooled, and its temperature is controlled by means of the embedded thermistor. All the data were acquired under cooling with the maximum allowed cooling power; the monitored thermistor resistance for each single interferogram lay in range of 9.1..9.2 kOhm and thus the detector temperature was of -27..-26°C, what corresponds to 1.2 % variations in detector detectivity [3].

The acquired interferogram is given on Figure 5.26. It has to be noted that the interferogram is not symmetric as the middle CCM position does not correspond to the zero OPD due to the poor initial instrument adjustment. For the averaging procedures a symmetrization algorithm has to be implemented.
Figure 5.26. Acquired interferogram: a – full time history; b – zoom around zero OPD.

The resampling of the interferogram is performed at the zero-crossings of the restored reference laser interferogram time history (the recovering of that interferogram was performed as described in Section 5.3.1 for each measurement). The resampled interferogram is shown on Figure 5.27.

Figure 5.27. Resampled interferogram: a – full time history; b – zoom around zero OPD.

Examples of single spectra coming from such interferograms are shown on Figure 5.28. All measured spectra were acquired with nominal spectral resolution of 2 cm$^{-1}$.
Figure 5.28. Single spectra acquired.

As the first averaging attempt, a simple averaging by modulus was performed on four interferograms (Fig. 5.29). Such an averaging reduces the noise but does not eliminate it completely, as in averaging by modulus the noise phase is brought to zero.

Figure 5.29. Averaged spectrum: first attempt, averaging by modulus.
The second attempt was performed by averaging the interferograms. For such reason the interferograms were approximately symmetrized: the interferogram peak was take to be the zero OPD, and the symmetry was achieved my mirroring the remaining tail on another side of interferogram (Fig. 5.30).

![Graph showing approximate interferogram symmetrization.](image)

**Figure 5.30. Approximate interferogram symmetrization.**

Such a symmetrization is not completely accurate, as the real zero OPD does not necessarily fall in the sampled point; it creates a phase shift for the signal, moreover such shift would be different from one interferogram to another (Fig. 5.31) creating the reduction in the spectrum of the averaged interferogram (Fig. 5.32).

![Graphs showing symmetrized interferograms with different zero OPD positions.](image)

**Figure 5.31. Symmetrized interferograms with different zero OPD positions: a – whole interferogram; b – zoom around zero OPD.**
The final implemented averaging approach was following the Forman algorithm. The created by approximate symmetrization signal phase shift was found for each interferogram from the low resolution spectrum, computed for the short interferogram cut around zero OPD, where signal-to-noise ratio is high. This phase shift was subtracted from the calculated phase for each full spectrum, leaving the signal phase around zero and noise phase random. Finally the symmetrized interferogram was restored from the obtained spectral data. The averaging was performed on the symmetrized interferograms. The resulting spectrum for same four measurements is presented on Figure 5.33.
The Forman symmetrization does not result in drops of the spectrum magnitude, and the noise level is reduced with respect to the averaged by modulus spectrum due to the conservation of randomness of the noise phase during the averaging.

5.3.3. Rough evaluation of instrument sensitivity.

Finally the approximate evaluations of instrument sensitivity were performed starting from the knowledge of the used calibration lamp SA727-5M reference spectrum.

Such spectrum represents a simple scaled Planck function (Fig. 5.34). The scaling coefficient is taken in accordance with the distance from the source to the detector (Fig. 5.35), which in the used set-up is represented by the total optical path and equals to 192 mm.

![Figure 5.34. Planck function of incident power.](image1)

![Figure 5.35. Calibration lamp flux density as a function of distance [5].](image2)
For the sensitivity definition the averaged smooth spectrum was taken, calculated from the narrow window interferograms around the zero OPD (averaging was performed by modulus, as signal-to-noise ratio around the zero OPD is quite high). Such spectrum was interpolated up to the nominal spectral resolution 2 cm\(^{-1}\) (Fig. 5.36).

![Smoothed acquired spectrum](image)

**Figure 5.36. Smoothed acquired spectrum.**

The instrument sensitivity \(IS\) as a function of wavenumber \(\sigma\) was evaluated from the following formula:

\[
IS(\sigma) = \frac{S(\sigma)}{P(\sigma)} \tag{5.2},
\]

where \(P(\sigma)\) is the incident power, W/cm\(^{-1}\); and \(S(\sigma)\) is the instrument spectral readings, V/cm\(^{-1}\).

The results of the sensitivity evaluation are given in Figure 5.37. The instrument sensitivity remains stable along the whole wavenumber range of interest of 2000..5000 cm\(^{-1}\).
The expected instrument sensitivity $I_{\text{TEORETICAL}}$ can be calculated through instrument overall efficiency $\xi$ (includes instrument optical efficiency and FOV/truncation modulation factors, Eq. 2.4) and the detector responsivity $R$, provided by the producer [3]:

$$I_{\text{TEORETICAL}} = \xi R \quad (5.3)$$

The declared peak responsivity $R$ for the modulation frequency of 1000 Hz and the detector temperature of 25°C equals to $8.42 \cdot 10^4$ V/W. For the tested mock-up optical layout the overall efficiency $\xi$ at the wavenumber, correspondent to the abovementioned modulation frequency, equals to 0.44, and thus the predicted instrument sensitivity equals to $3.7 \cdot 10^4$ V/W. The correspondence between

Figure 5.37. Roughly evaluated instrument sensitivity: $a$ – general data; $b$ – data in the wavenumber range of interest.
modulation frequency and wavenumber was calculated through the formulation given in Eq. 2.24, having the mean CCM velocity of 1.2 mm/s (Fig. 5.24). It has to be noted, that such correspondence is only approximate due to fluctuations of the actually measured velocity.

The measured peak instrument sensitivity $IS$ is at 2600 cm$^{-1}$ (what corresponds to modulation frequencies around 1000 Hz) and equals to $7.01 \cdot 10^3$ V/W, what is five times lower than the predicted value.

Such a disagreement in results can be explained by the fact of rough estimation of the signal power and the approximation of the actual instrument efficiency by the ideal one. For instance the poor instrument alignment reduces the efficiency with respect to the theoretical one, evaluated for the perfectly aligned configuration. Deviations of the actual signal power from the estimated one are caused by the partial obscuration of the instrument pupil with the reference laser tower, as the active area becomes reduced with respect to the nominal one used for the signal power evaluations. Also the fact that the calibration lamp position was not controlled might result in not complete filling of the instrument Field-of-View by the source radiation and thus in additional losses in the incoming power. An extended radiation source should be used for more precise evaluations of the instrument sensitivity.

5.4 Conclusions.

The mock-up preliminary verification proved the functionality of the designed instrument in the wavenumber range of interest with the specified nominal spectral resolution. However the rough and simplified design of the mechanical layout did not permit to arrive to the maximum declared performance characteristics. Their realization requires additional facilities for the finer optical alignment and the improved motion control system.
References CHAPTER 5.

6. CONCLUSIONS

The main result of this work is the design of a miniaturized Fourier Transform Spectrometer MIMA, micro Mars Infrared Mapper, and the development of its laboratory mock-up. The scientific scope of the instrument is the Martian atmosphere observation. Its nominal spectral resolution is of 2 cm$^{-1}$ (with the option enhanced resolution up to 1 cm$^{-1}$) that allows to recognize the spectral features of the main elements of interest in the atmosphere and in particular to assess methane abundance with ppb resolution. A set of strict constraints were applied to the design: a mass limit of less than 250 g and a power budget inside 5 W. For comparison the previous similar FTS instrument, MIMA, designed for the ESA mission "ExoMars Pasteur 2013", had a mass constraint of 1 kg. Another considered constraint was a resistance for the expected shock levels during landing, described as a quasistatic acceleration of 1000 m/s$^2$. The mechanical design was carried-out by means of finite element models simulating the static and dynamical loading conditions on the instrument and providing as a result the optimization of mass and size of the mechanical components. The included thermoelastic analysis ensured absence of instrument optical efficiency decreases also under the worst predicted Martian environment scenario.

The additional design activities were carried out in order to increase the instrument performance characteristics, i.e. Signal to Noise Ratio. Those activities included maximization of the theoretical SNR starting from the analytical expressions for Noise Equivalent Spectral Radiance, NESR reduction was achieved by means of the optical layout geometry optimization and by selection of optical elements that offer highest efficiencies for the instrument wavenumber range of interest. The optimization process was supported by the theoretical evaluation of the expected SNR levels for different application cases, such as laboratory observations by the instrument on the Earth and actual acquisition of Martian atmosphere spectrum during the mission, with the achieved SNR in range of $10^4$. Moreover, the instrument gas detection capability was evaluated showing that the instrument allows evaluating the presence of CH$_4$ in the Martian atmosphere with both nominal and enhanced spectral resolutions with the SNR in range of 100.

The analytical design was followed by the development and testing of the laboratory mock-up, which proved the instrument functionality in the wavenumber range of interest with the specified nominal spectral resolution.

Knowing that sensitivity to the mechanical vibrations is a well-known drawback of all the FTS family instruments, an innovative data treatment technique was created able to deal with undesired spectral distortions of unknown nature allowing the single spectrum correction. Such a technique increases the spatial resolution of the mapping process by avoiding the need of spectral averaging and becomes crucial when the desired information is linked to a particular mapping area associated to an individual spectrum. It was based on the extended analytical formulation of distortions formation. As a result was developed an iterative numerical algorithm. The elaborated technique was tested on the available dataset of the PFS (Planetary Fourier Spectrometer onboard MarsExpress 2003), and proved its consistency significantly reducing the distortions of the observed signal.