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The Planetary Fourier Spectrometer (PFS) onboard the European Mars Express mission

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Abstract

The Planetary Fourier Spectrometer (PFS) for the Mars Express mission is an infrared spectrometer optimised for atmospheric studies. This instrument has a short wave (SW) channel that covers the spectral range from 1700 to 8200.0 cm^{-1} (1.2–5.5 μm) and a long-wave (LW) channel that covers 250–1700 cm^{-1} (5.5–45 μm). Both channels have a uniform spectral resolution of 1.3 cm^{-1}. The instrument field of view FOV is about 1.6° (FWHM) for the Short Wavelength channel (SW) and 2.8° (FWHM) for the Long Wavelength channel (LW) which corresponds to a spatial resolution of 7 and 12 km when Mars is observed from an height of 250 km. PFS can provide unique data necessary to improve our knowledge not only of the atmosphere properties but also about mineralogical composition of the surface and the surface-atmosphere interaction.

The SW channel uses a PbSe detector cooled to 200–220 K while the LW channel is based on a pyroelectric ($L_iT_aO_3$) detector working at room temperature. The intensity of the interferogram is measured every 150 nm of physical mirrors displacement, corresponding to 600 nm optical path difference, by using a laser diode monochromatic light interferogram (a sine wave), whose zero crossings control the double pendulum motion. PFS works primarily around the pericentre of the orbit, only occasionally observing Mars from large distances. Each measurements take 4 s, with a repetition time of 8.5 s. By working roughly 0.6 h around pericentre, a total of 330 measurements per orbit will be acquired 270 looking at Mars and 60 for calibrations. PFS is able to take measurements

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at all local times, facilitating the retrieval of surface temperatures and atmospheric vertical temperature profiles on both the day and the night side.

Keywords: Instrumentation; Atmosphere; Mars; Mars Express

1. Introduction and rationale

The Planetary Fourier Spectrometer (PFS) was built first for the Russian Mars 96 mission. It is a double pendulum Fourier Transform interferometer, with capabilities similar to the Mariner 9 IRIS experiment at thermal infrared wavelengths (250–1700 cm^{-1} or 5.5–45 μm), but it adds a Short Wavelength (SW) channel covering the spectral range form 1700 to 8200 cm^{-1} (1.2–5.7 μm). The spectral resolution is the same over the entire spectral range: 1.3 cm^{-1}.

The rational of this kind of experiment is multifold: we aim to solve the problem of the inversion of the 15 μm CO_2 band to obtain the vertical temperature profile without any assumptions about ground pressure and temperature, and to retrive the dust content of the atmosphere. Another very important objective is to get complete global coverage of the planet Mars in each season, to study seasonal variations in the global circulation. The high spectral resolution in the SW channel (we have more than 5500 as resolving power) is also very important to study the mixing ratio of trace gases in the Martian atmosphere. In addition, when the atmospheric transmissivity allows, we hope to study the mineralogic composition of the soil, specially stressing the importance of the spectral resolution to identify hydrated minerals, or, more important, the ice composition of the polar caps (see Orofino et al., 2000; Palomba et al., 1997a,b, 1998). This paper is devoted to instrument description and its operations in space, to the problems encountered, and to the kind of measurements we have been able to acquire (see Blecka and Colangeli, 1997; Blecka et al., 1997a,b; Colangeli et al., 1996; Esposito et al., 1997).

2. Instrument description

2.1. Introduction

PFS is a double pendulum interferometer working in two wavelength ranges (1.2–5.7 and 5.5–45 μm). Mars radiation is divided in 2 beams by a dichroic mirror. The two ranges also correspond to 2 planes, one on top of the other, in which the two interferometers are placed, so that the same motor can simultaneously move the 2 pendulums and the two channels are sampled simultaneously and independently. The pendulum motion is accurately controlled by means of a laser diode reference channel employing the same optics used for Martian radiation. The same laser diode also generates the sampling signal for the A/D converter, measuring optical path differences of 608.4 nm. The measurements obtained are double sided interferograms, so that an FFT on board can be computed when needed, without caring much about the zero optical path difference location. Some important parameters characterising the experiment are given in Table 1 (see also Formisano et al., 1993, 1996, 1997, 2004).

2.2. Instrument heritage

PFS is a Fourier transform spectrometer resulting from the effort of several groups from different countries: Italy, Russia, Poland, Germany, France and Spain. The flight hardware is produced in Italy (main digital electronics controlling the experiment, the Interferometer block with its controlling electronics and the

Table 1

Detailed PFS parameters	SW	LW
Spectral range μm	1.2–5.5	5.5–45
cm^{-1}	1700–8200	250–1700
Spectral resolution, cm^{-1}	1.3	1.3
FOV, deg	1.6	2.8
NEB, W $cm^{-2}sr^{-1}$	5×10^{-9}	4×10^{-8}
Detector type	Photoconductor	Pyroelectric
Material	PbSe	$LiTaO_3$
Temperature, K	210	290
Interferometer type	Double pendulum	
Reflecting elements	Cubic corner reflectors	
Beamsplitter	CaF_2	CsI
Max. optic. path differ., mm	$+-5$	$+-5$
Time for motion, s	5	5
Reference source		Laser diode at 1216 nm
SW/LW separation		KRS-5 with a multilayer coating reflecting SW radiation
Interferogram	Two-sided	
Samplings number	16384	4096
Sampling step, nm	608	608 (over sampled)
Dynamical range	2^{15}	2^{15}
Spectral points	8192	2048

GSE with the spacecraft simulator), in Poland (the Power supply, the pointing system). Russia and Germany produced some special flight parts and subassemblies. The flight software was produced in Italy. The experiment for Mars Express ESA mission inherited the concept and the basic design from the previous Mars 96 Russian mission. Needless to say, however, that a strong revision of many details was implemented so that the total mass decreased from the original 42 kg to the 30.9 kg of MEX.

2.3. Optical scheme of PFS-O

The optical schematic of PFS is shown in Fig. 1. The incident IR beam (coming from a pointing mirror) falls onto the entrance filter that separates the radiation into the SW channel and the Longwave length (LW) channel and directs each into the appropriate interferometer channel. The scanner in front of the interferometer allows the FOV to be pointed along or lateral to the projection of the flight path on the Martian surface. It also directs the FOV at internal black body sources and to the open space for in-flight calibration.

Each PFS channel is equipped with a pair of retroreflectors attached by brackets to an axle that is rotated by a torque motor, forming a double pendulum. The same axle and the drive mechanism are used for both channels, which are stacked on top of each other. The optical path difference is generated by the angular movement of the retroreflectors (Hirsch and Arnold, 1993). The torque motor controller uses the outputs of two reference channels, which are equipped with laser diodes. This interferometer design is very robust against slight misalignments in harsh environments compared with the classical Michelson-type interferometer (Hirsch, 1997; Arnold et al., 1993, 1994; Hirsch et al., 1992, 1994, 1996). Furthermore, as we shall see later, mechanical vibrations that may be present, affect the main radiation beam and the reference channel in the same way, so that meaningful measurements can still be taken.

The detectors are placed in the center of the parabolic mirrors. The optical path is changed by rotating the shaft of the double pendulum along its axis. In this way, the optical path difference will be four times greater than a single cube corner displacement since two mirrors move at the same time. The dichroic mirror acts as a fork which divides the two spectral ranges. It reflects all the wavelengths lower than 5.5 μm and transmits higher wavelengths. The band stop for wavelengths lower than 1.2 μm is provided by the silicon window, having a cutoff at 1.24 μm that is placed in the optical inlet of the SW channel; this filter is tilted by 1.5° to prevent radiation going back to the source from being partially reflected to the detector.

The double pendulum axis rotates by means of a brushless motor (two for redundancy) that have no mechanical friction. Thus, the shaft of the double pendulum is sustained just by two preloaded ball bearings at very low friction. An additional mechanical friction is added to stabilitize the pendulum speed.

If we place the zero optical path difference in the center of the mirror displacement, we can acquire double sided interferograms. A double sided interferogram has several advantages, among which a relative insensitivity to phase errors that otherwise must be corrected. A bilateral operation is adopted to reduce the time cycle of each measurement, but a separated calibration for each direction is recommended in order to maintain the predetermined radiometric accuracy.

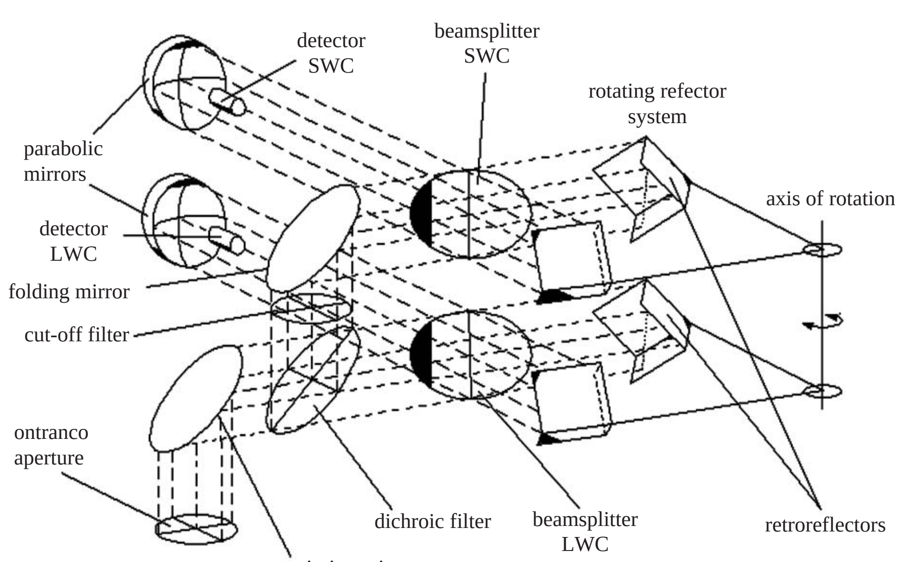

Fig. 1. PFS optical scheme.

A laser diode (InGaAsP at 1.216 μm) acts as the spectral reference and its detector is an infrared photodiode with maximum responsivity at about 1.2 μm. The beam of the reference channel is processed like the input signal so that the optical path of the reference is exactly coincident with the optical path of the signal to be studied. Moreover each channel has its own reference beam and a different length of the double pendulum arms is fully compensated. The reference channel beam path is just outside of the Martian radiation beam. Because the beam splitter of the long wavelength channel is not transparent at the wavelength of the corresponding laser diode used as the reference, a special small window was included during the manufacturing of it in order to produce negligible attenuation of the laser beams through the beam splitter itself. The unused output beams of the two reference channels terminate into optical traps (see Piccioni et al., 1997).

2.4. Electronics of PFS-O

The most important block in the electronics of PFS-O is the speed controller. The zero crossing of an interferogram of a monochromatic source with a very stable wavelength can be used for sampling the interferogram of the source to be studied. In the ideal case the interferogram of the monochromatic source must be a pure sine wave, but this is not possible because its interferogram is limited in time. The lower the wavelength of the reference source, the better the accuracy of the sampling.

In our case a 1.216 μm laser diode was used as a reference source due to the limited availability of laser diodes and to simplify the optical design. Because the wavelength of a laser diode depends on its temperature and power, much care must be taken in controlling them. The speed of the double pendulum is such that a frequency of 2 kHz is generated for the SW channel. Thus a train of pulses with frequency of 4 kHz comes out from the electronics of the SW reference channel. The thermal control is also very important for an infrared interferometer. Here, we use eight points for reading the temperatures and for heating the structure.

A ''locking system'' blocks the double pendulum during launch and during maneuvering for orbital insertion and correction. The procedure of locking and unlocking takes a minimum of 10 min but it can be repeated hundreds of times since it uses paraffin actuator. For safety reasons the launching vector was kept along the axis of the double pendulum corresponding to the maximum robustness of the interferometer.

The SW channel detector is a photo-conductor capable of working at temperatures down to 200 K. The SW detector is passively cooled through a radiator and its holder is partially insulated from the rest of the interferometer. For the LW channel we used a pyroelectric detector able to work without performance degradation even at ambient temperature.

2.5. Modes of operation

The PFS experiment has three operational modes. S*cience mode* is used during the observation sessions. In *sleep mode,* the interferometer and the pointing mirror are off, while the digital electronics are on to keep data, receive telecommands, and perform other activities. In *Autotest mode* a number of special measurements are made to control the stability of the motion, optical alignment, and other special functions.

3. The thermal environment

PFS must satisfy many contradictory requirements. In particular the SW channel detector needs to be cooled to 200–210 K, while the remainder of the experiment is operated at 285 K. The laser diode temperature needs to be stable to within a 0.1° to ensure that the motion is free from problems caused by the non monochromaticity of the laser. Also the LW channel detector needs to be stable, to measure a variable planetary surface temperature because PFS works as a differential instrument, All these conditions have been tested in space in the Near Earth Verification activity.

The Laser diode temperature is very well controlled and stable, so that a stable good motion of the double pendulum is guaranteed (Fig. 2). Similarly the LW channel temperature is well controlled (Fig. 3). Note the much expanded vertical scale. On the other hand, the temperature of the SW channel detector was well cooled by the spacecraft provided radiator (Fig. 4).

It should be noted that these thermal conditions, so important for a well behaved experiment, were not reached in the laboratory measurements, so all the ground calibrations are affected by unstable temperatures.

4. The mechanical environment

PFS has three mechanical devices whose performance is essential for the experiment to work. The first is the block-unblock system, a paraffin actuator that is used to lock the pendulum during spacecraft launching and other possible violent manoeuvres. This has always worked. A second important mechanism is the pointing mirror, which has eight different possible positions: five around Nadir ($0, +-12.5^\circ, +-25^\circ$), plus deep space ($+85^\circ$), internal calibration Black Body, and internal calibration lamp. The third mechanism is the double pendulum itself, which has only one motor for the two channels, plus a spare motor. The motor speed, which

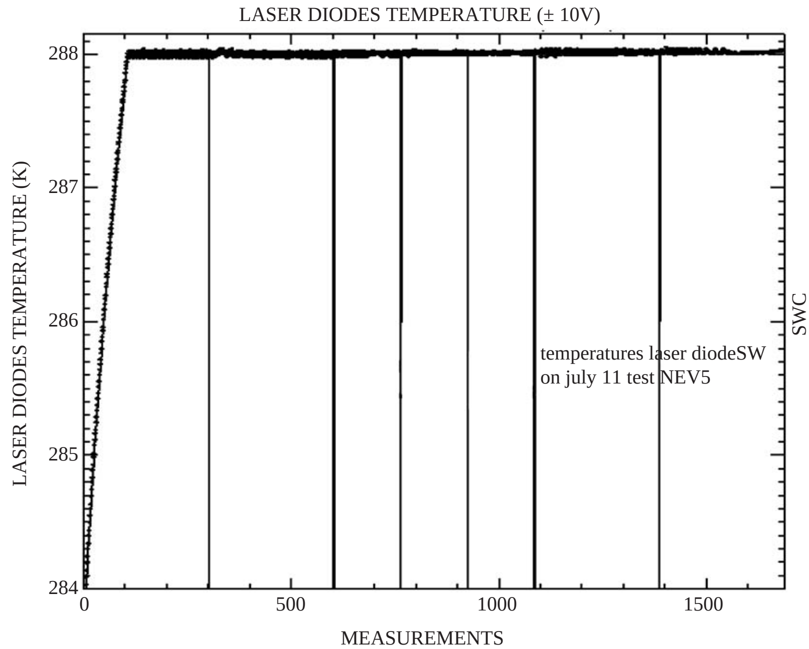

Fig. 2. Laser diode temperature in space.

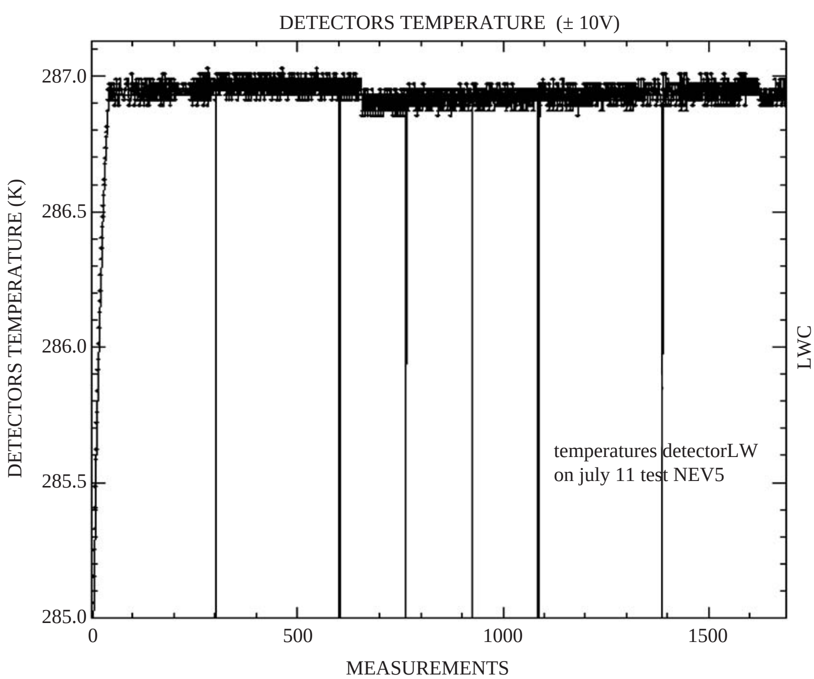

Fig. 3. LW channel detector temperature in space.

must be as constant as possible, is controlled by a system that uses the laser diodes interferogram signal to generate a feedback to keep it constant. The interferogram of the laser diode radiation is a sine wave whose zero crossings are used to sample the interferogram of the Martian radiation, and at the same time to control the pendulum speed. In a special mode of operation called Autotest, the time between successive zero crossings is measured as a test of the motion speed quality. Incorrect laser diode temperatures can occasionally generate a non-monochromatic signal, which generate a non uniform motion, can be revealed with the Autotest mode. Also external mechanical vibrations can generate a nonuniform motion, and they can be revealed in two parts of the Autotest procedure: in the pendulum speed measurements, and in the laser diode

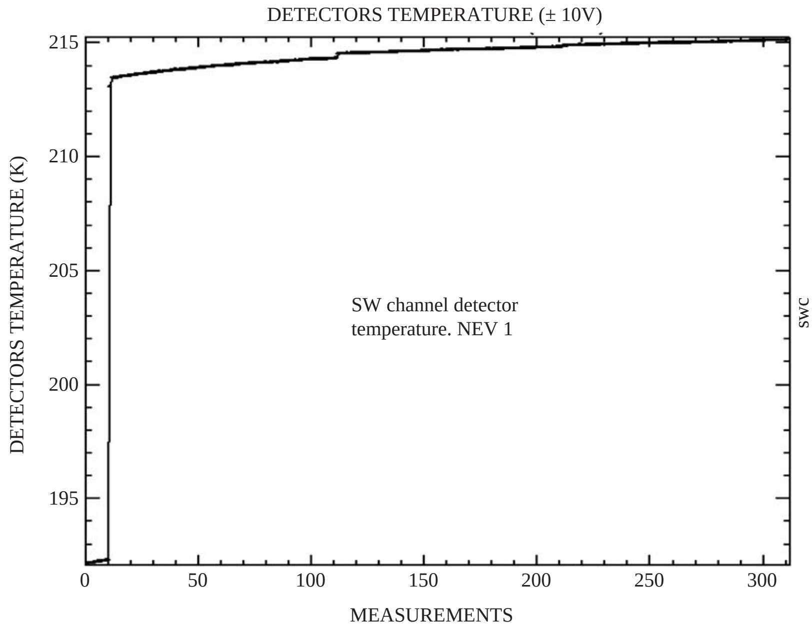

Fig. 4. Temperature of the SW channel detector in space.

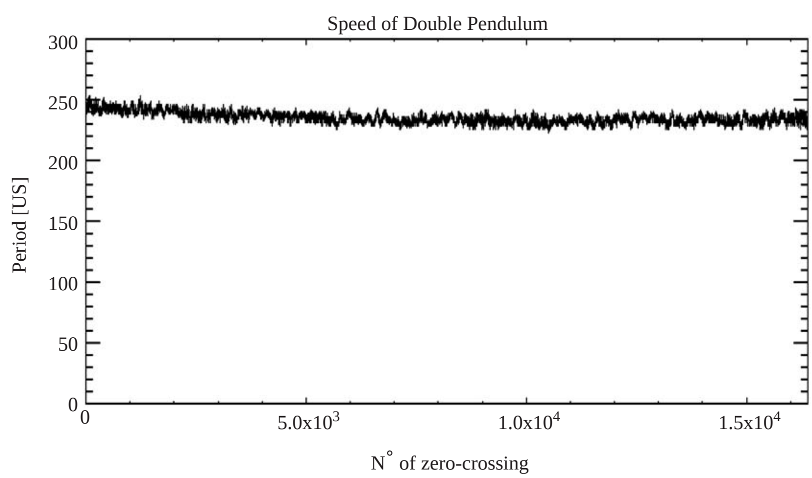

Fig. 5. Autotest measurements on ground.

interferogram sine wave shape sampling. Fig. 5 shows a typical Autotest speed measurements taken on ground.

The speed is determined from the measured time difference between zero crossings. The interval between zero crossings should be close to 250 μs (2000 Hz) for nominal speed. On board MEX in space the speed measured with the Autotest procedure gave a clear indication that mechanical vibrations were present (see Fig. 6). We studied these vibrations in several different ways, and under several different conditions. We concluded that there were three fundamental frequencies at 10–20, 105–110 and at 595–600 Hz modulating each other. In particular, the frequencies evident in Fig. 6 were identified in the spectrum of the laser diode radiation interferogram, shown in Fig. 7, as a central peak at 595 Hz, with the 2 satellites at 545 and at 655 Hz. The PFS measurements were strongly affected by these mechanical vibrations, but the instrument can still work, thanks to the design adopted for the interferometer and the reference channel. The effect of these disturbances is to increase the measurement noise in special narrow bands of wavenumbers, equivalent in frequencies to the ones of the mechanical vibrations.

These frequencies depend also on the speed used for the pendulum, and the narrow bands with increased noise can be moved to different parts of the spectrum of the incoming Martian radiation by changing the speed. After a long study, the pendulum speed was increased by 25% (we call this speed 2500 Hz) to yield the best

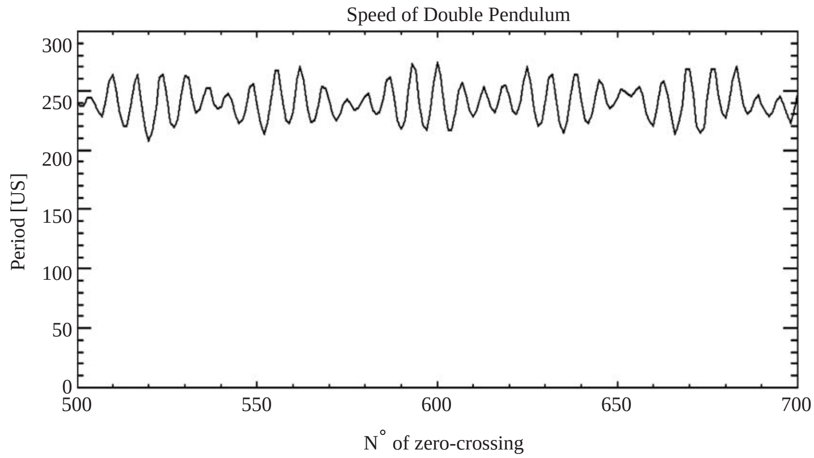

Fig. 6. Autotest measurements in space on board MEX.

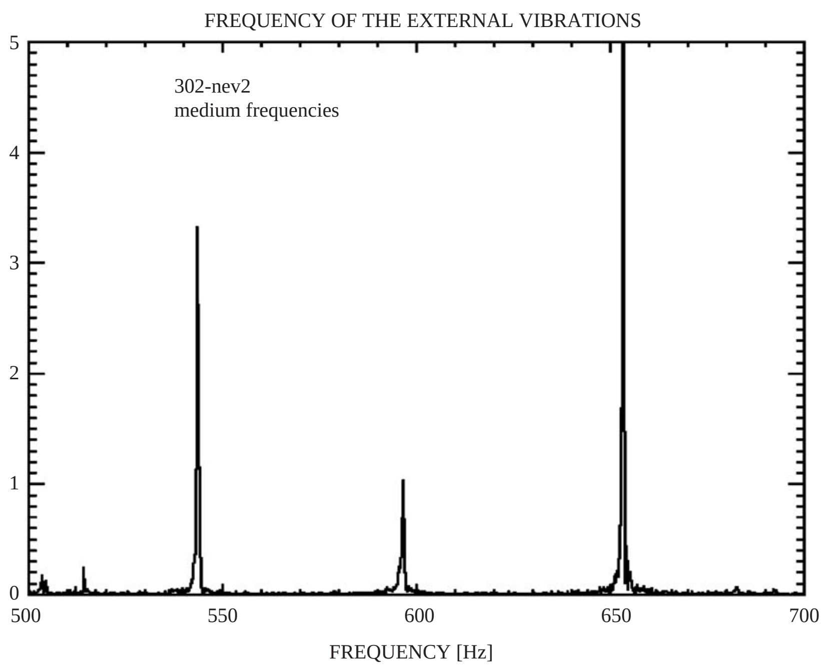

Fig. 7. Portion of the spectrum of the mechanical vibrations on board MEX : 595 Hz modulated by 110 Hz are evident.

compromise between the disturbances in the LW and SW channels. Essentially the compromise moves the disturbances to a range of wavenumbers of lower scientific importance. In any case in taking measurements at Mars, we shall have the possibility to repeat measurements with different speeds, to also cover the narrow ranges contaminated by the mechanical vibrations with good SNR. More details on the effects of the mechanical vibrations can be found in subsequent papers on the Calibrations of the LW and SW channels. In conclusion we stress the fact that, contrary to most other interferometers, the PFS capability to take good measurements has not been destroyed by the presence of the reported mechanical vibrations thanks to the design solutions adopted.

5. In flight activity

During one Observation session on the Martian orbit (one pericenter pass) PFS first performs calibrations, pointing the Scanner sequentially to deep space and to calibration sources. PFS then takes the pre computed number of measurements with the scanner pointing Nadir. Finally, the calibration sequence is repeated. The Autotest is performed before the first calibration sequence and after the second calibration sequence. Each measurement has a header containing all the necessary housekeeping information.

5.1. Data transmission modes

The data transmission mode defines the kind of scientific data PFS must select and store in the Mass Memory to be sent to Earth. The data transmission modes 1–14 are obtained with PFS operating in the science operating mode. Only data transmission mode 0 is obtained when the PFS is operating in the Autotest mode.

For any science data transmission mode, PFS acquires both LW and SW interferograms. If spectra are required, PFS performs a fast Fourier transform of the interferograms. Then, depending on the data transmission mode, PFS produces the required data. The entire interferograms can be selected or just the central part can be returned, giving reduced resolution. Modules (absolute values) of spectra can be selected in terms of spectral intervals (reduced range). There are 15 data transmission modes:

MODE 0—Autotest.
MODE 1—only LW channel interferograms.
MODE 2—Half resolution SW and LW interferograms.
MODE 3—Only half resolution LW interferograms.
MODE 4—Only half resolution SW interferograms.
MODE 5—Full LW interferogram and one sided (right) SW interferograms.
MODE 6—One sided LW and SW interferograms (right).
MODE 7—Full interferogram LW and SW.
MODE 8—Full interferogram SW.
MODE 9—Full LW interferogram and one sided (left) SW interferograms.
MODE 10—One sided LW and SW interferograms (left).
MODE 11—Full power spectrum LW and SW.
MODE 12—Full power spectrum LW.

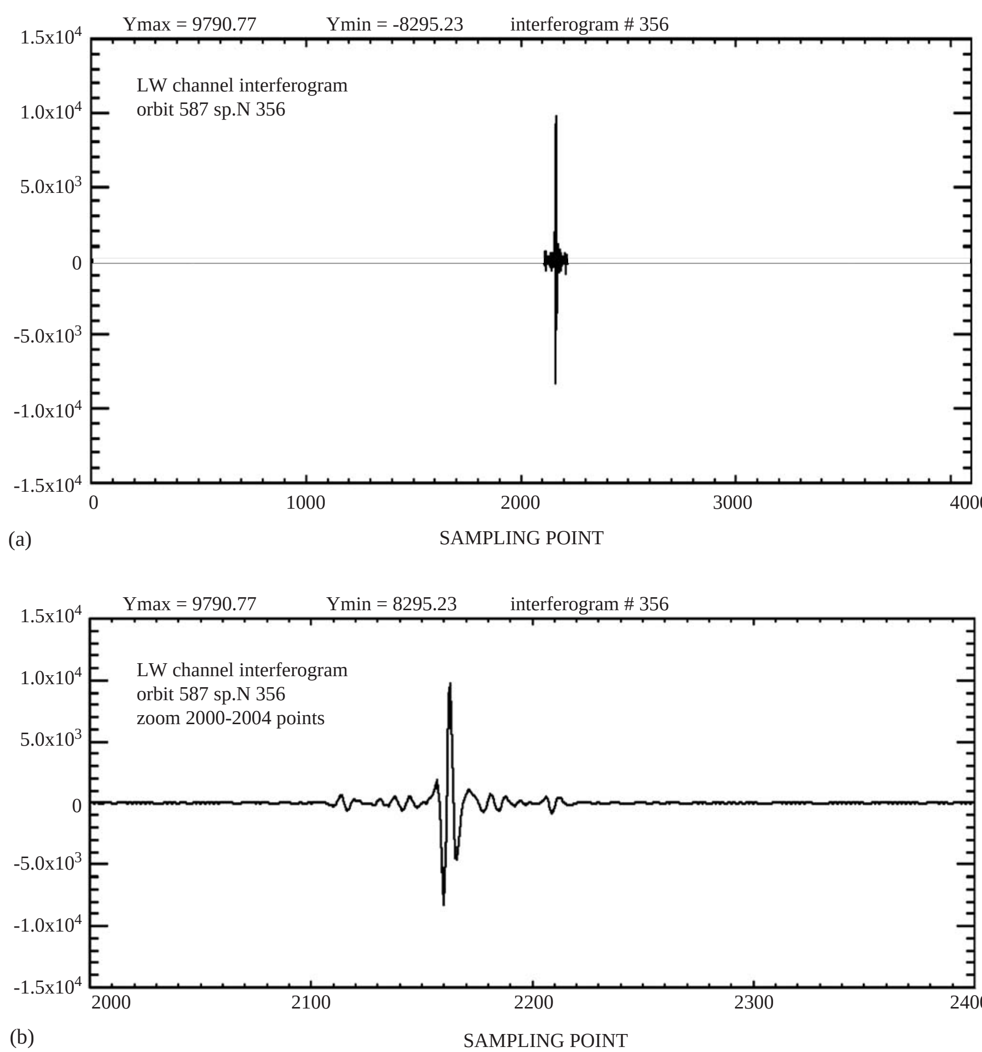

Fig. 8. (a) LW channel interferogram from orbit 587 (global measurement nonsymmetrised). (b) Zoom on the central part of the same measurement.

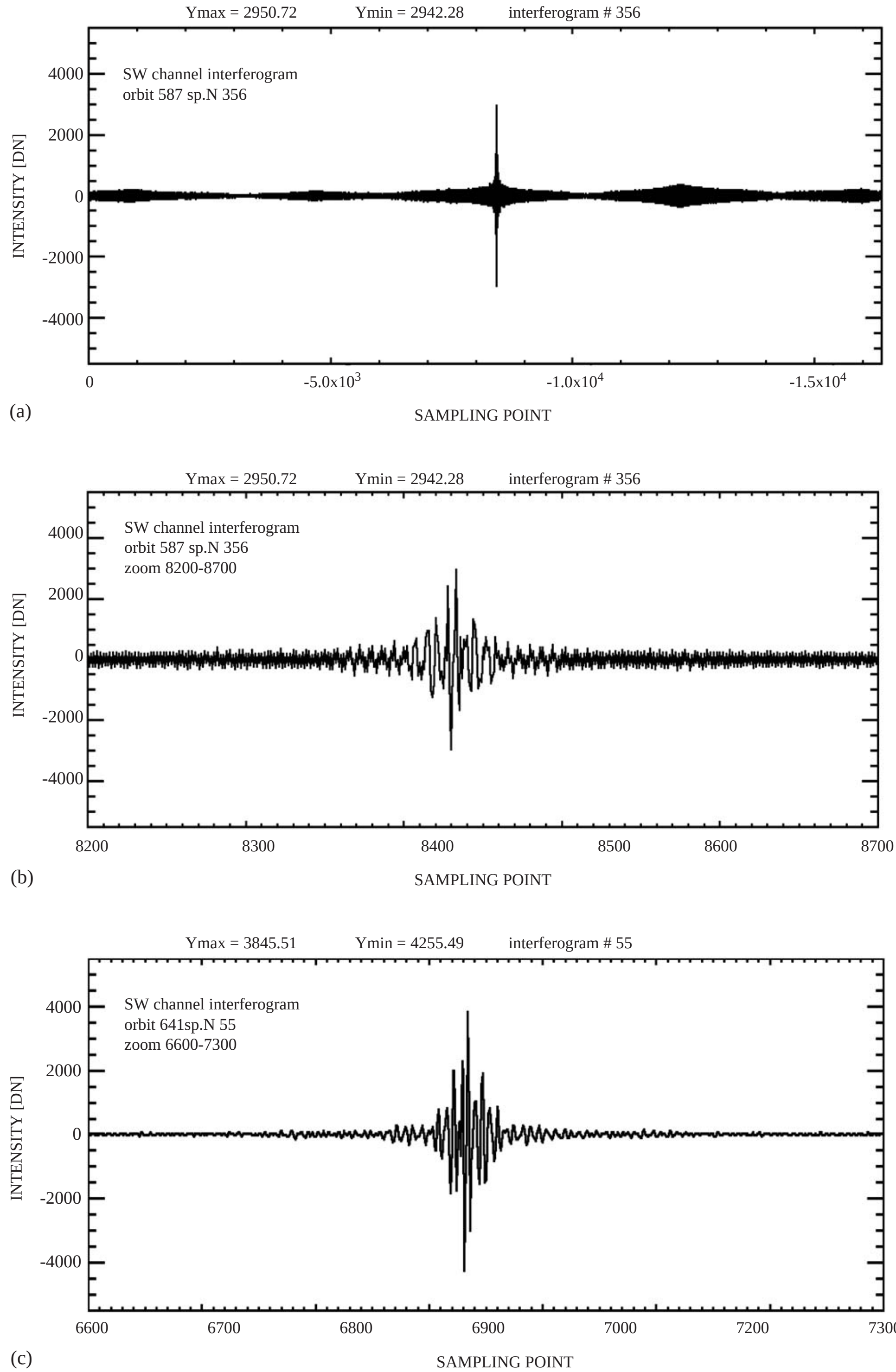

Fig. 9. (a) SW channel global interferogram. (b) zoom on the central part of the interferogram. Note the large modulations due to mechanical vibration effects on the laser diode radiation. (c) Zoom on the central part of the SW channel interferogram when the driving laser was from LW and the SW channel laser was switched off. Note the strong reduction of the apparent noise.

MODE 13—Spectral parts. (entire LW and thermal part of the SW)
MODE 14—Only SW power spectrum.

Of these 15 modes, the most used ones are mode 7, mode 6, and mode 2.

5.2. Sample of measurements

In concluding this paper we would like to show some real data from Mars. We only show raw data here because separate papers will deal with the

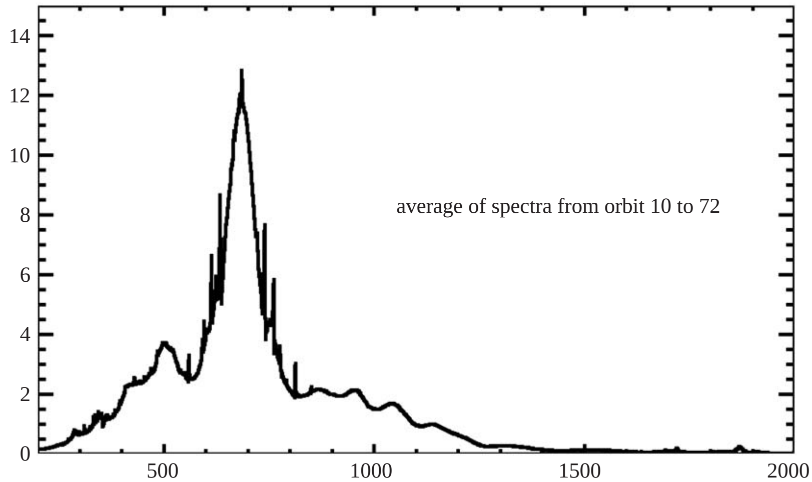

Fig. 10. Raw data from the LW channel. Note the intense 15 μm CO_2 band and all the q-branches there around. See text.

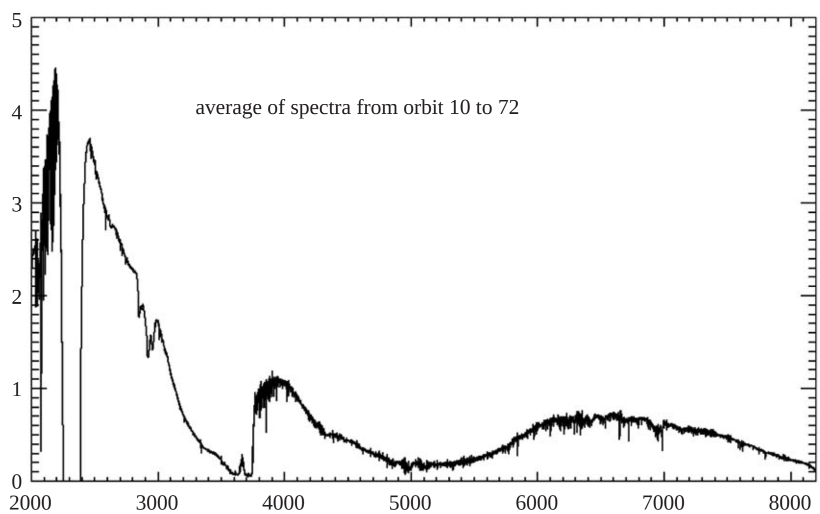

Fig. 11. Raw data from the SW channel. Note the intense 4.3, 2.7, 2.0 microns CO_2 bands. Many CO and H_2O lines are also visible.

calibration procedures. The scientific information present in these data is presented in the subsequent scientific papers.

Fig. 8a shows a measured LW channel interferogram while Fig. 8b shows a zoom in the central part (close to zero optical path difference). We note that, being here shown the nonsymmetrised interferogram, the central peak is obtained for a position (measurement 2165) somewhat asymmetric but anyhow very close to the center of the measurements. In the reverse measurement the asymmetry may be somewhat bigger. Fig. 9 shows similarly the interferogram for the SW channel from a single measurement. In Fig. 9a the entire interferogram is shown while in Fig. 9b the central part close to the zero optical path difference is enlarged. From both panels it is evident that there is a strong modulation away from the central peak. This modulation is the effect of the laser diode radiation modulated by the mechanical microvibrations. More discussion and details on the effects caused by them on the spectra will be given in the following papers on the calibrations of the two PFS channels. Here we note only that after an in depth study of the several effects caused by the micro vibrations we operated the experiment using the LW channel laser diode also for controlling the motion of the pendulum and the SW channel laser diode was switched off. In this way we were able to clean the measurements from most of the negative effects as it is shown by the central part of an interferogram measured in these conditions (see Fig. 9c). Finally we show some spectra resulting from FFT computation on ground from the measured interferograms.

Fig. 10 shows a LW channel spectrum averaged over 1680 measurements. PFS performs differential measurements. Therefore the colder the source (with respect to the detector and instrument temperature), the higher the signal. That is why the 15 μm CO_2 band appears as a very intense peak in the figure. Well over 1800 spectral points are shown in the figure. Small bumps on the right of the spectrum (above $1500\,cm^{-1}$) are due to spacecraft mechanical microvibrations, while the larger oscillations seen on both sides of the CO_2 band are due to the instrument transfer function.

In Fig. 11 we show a similar raw data spectrum for the SW channel. Again the spectrum is an average over 1680 measurements. Due to the high spectral resolution the spectrum seems to be noisy, while, on the contrary, it is extremely rich of information. Note that 6200 spectral points are shown in the figure.

For a discussion of the performance of the experiment and the signal-to-noise ratio of the measured spectra we send the reader to the following papers. Here we add only that the interferograms were sampled with a 16 bits ADC of which 2 bits were considered noise. From synthetic spectra computed with PFS spectral resolution in CGS units we expect to have SNR for the LW channel up to 200 at $600\,cm^{-1}$ while for the SW channel we expect an SNR from 10 (at $8000\,cm^{-1}$) to 100 (at $2700\,cm^{-1}$).

In conclusion it may be stated that PFS at Mars has been working nominally (see Persky, 1995).

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