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Toward a numerical deshaker for PFS

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ABSTRACT

The Planetary Fourier Spectrometer (PFS) onboard Mars Express (MEx) is the instrument with the highest spectral resolution observing Mars from orbit since January 2004. It permits studying the atmospheric structure, major and minor compounds. The present time version of the calibration is limited by the effects of mechanical vibration, currently not corrected. We proposed here a new approach to correct for the vibrations based on semi-blind deconvolution of the measurements. This new approach shows that a correction can be done efficiently with 85% reduction of the artifacts in a equivalent manner to the stacking of 10 spectra. Our strategy is not fully automatic due to the dependence on some regularization parameters. It may be applied on the complete PFS dataset, correcting the large-scale perturbation due to microvibrations for each spectrum independently. This approach is validated on actual PFS data of Short Wavelength Channel (SWC), perturbed by microvibrations. A coherence check can be performed and also validate our approach. Unfortunately, the coherence check can be done only on the first 310 orbits of MEx only, until the laser line has been switch off. More generally, this work may apply to numerically "deshake" Fourier Transform Spectrometer (FTS), widely used in space experiments or in the laboratory.

1. Introduction

The Planetary Fourier Spectrometer (PFS) is a double pendulum Fourier transform infrared spectrometer instrument onboard MEx, operating in the 1.2–5.5 μm for the Short Wavelength Channel (SWC), and 5–45 μ in the Long Wavelength Channel (LWC) (Formisano et al., 2005). It is based on a modified Michelson's scheme using a double pendulum with cubic reflectors. The optical path difference is defined by the zero crossing of a laser tacking the same optical path as the signal. The spectra presented in this article are the numerical Fourier transform of the recorded interferograms.

An experimental study of mechanical vibration impact on Fourier-transform spectrometer has been proposed based on PFS example (Comolli and Saggin, 2005). Analytical expression of all distortion effects have been formulated separately (Saggin et al., 2007): offset of the reference laser signal, mirrors speed variation, periodic misalignments, detector nonlinearity and internal reflections. More recently, a numerical simulation model has been proposed to explore all effects combined in order to understand the PFS signal (Comolli and Saggin, 2010). Perturbations are creating artificial features, called "ghosts", present in some spectra of the SWC but not in the LWC, thanks to the optimization of the pendulum velocity (Giuranna et al., 2005a, 2005b). Since the amplitude of ghosts is small (few % of the original signal) and its phase has a stochastic behavior, the worst cases correspond to only few significant ghosts (Shatalina et al., submitted for publication).

Quantitatively, the ghosts are affecting few % of the total spectrum energy (3% typically; 5% maximum). When single spectra are used, the absolute radiometric calibration is degraded, and spurious spectral features may appear in the spectrum, preventing any surface-related analysis, and introducing possible large uncertainties in the quantitative retrievals of abundances of minor species in the atmosphere. When discussing the calibration procedure for the SWC (Giuranna et al., 2005b) and the LWC (Giuranna et al., 2005a), the authors suggest to stack the data to correct for the effects of the mechanical vibrations. The position of ghosts depends on the frequencies of the external vibrations, which have been found to be quite stable. Since the phase of ghosts is random and the external frequencies are stable, only the signal should be coherent during the stack. This idea has been confirmed by numerical modeling of the perturbations (Comolli and Saggin, 2010). Practically, averaging a few spectra (ten or so) is enough to average out the ghosts. However, this will degrade the spatial and temporal resolution of PFS measurements, limiting the interpretation of small-scale features and hampering some scientific studies (e.g., the composition of ices; detection of minerals at the surface).

Typical PFS raw measurements are shown in Fig. 1. One can identify the major signals from Mars: thermal emission and

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reflection of solar energy, and the laser line stray-light. Also the contribution due to mechanical vibrations is shown on the signal, leading to additional energy shifted on left and right almost symmetrically. The ghost of the laser line is only one sided due to aliasing.

Our aim is to provide a new approach to process the PFS instrument with following constraint:

1. Correct the effect of mechanical vibrations due to both misalignment and optical path difference errors.
2. Perform the correction on each spectrum separately.
3. Validate the approach by using actual PFS observations.

In order to avoid unphysical solution, the algorithm is initialized with an a priori guess of the large scale structure of the spectra, adapted to each measurement, reproducing the Martian thermal emission and the reflected solar light (see Section 2.2.2).

A check of the correction can be done but requires the SWC laser diode switched on to estimate the vibration kernel independently (see Section 2.3).

2. Method

This section describes the direct model of the Martian spectra affected by vibrations. Then, an iterative procedure is exposed in order to invert it as well as some criteria to measure the quality of our estimation.

2.1. *Analytical formulation in the signal domain (0–5000 cm^{-1})*

As it can be seen from Fig. 1, it is possible to separate the whole spectrum into two wavenumber domains to deal the effects of the mechanical vibrations apart in each of them. From 0 to 5000 points (5000$*$1.02 cm^{-1}), we define the signal domain, where the thermal energy from Mars and the most of the reflected Martian energy are recorded, without significant laser line artefacts. The laser line domain is defined from 5000 cm^{-1} to 8330 cm^{-1}. It contains also the Martian signal but affected by laser line artefacts. Below 1700 cm^{-1} there is no meaningful signal due to the low detector responsivity (see Fig. 15 in Giuranna et al., 2005b), and this region is characterized only by ghosts of the continuum.

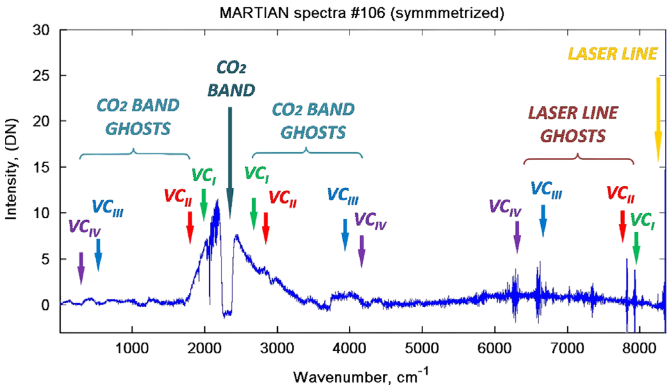

Fig. 1. Typical symmetrized PFS measurement in SWC. Signal and major CO$_2$ band and laser lines are noted. The four main ghosts are identified as "Vibration Component" (VC) affecting both signal and laser line.

At larger wavenumber than 5000 cm^{-1}, the signal is affected by the laser line shape and its ghosts, directly and in aliasing. This domain will be used to test the coherence of the results. Since the laser has been switched off after orbit 634, it could not be used for the complete PFS archive (see Section 2.3).

Using some mathematical reorganization and simplification, the analytical expression of mechanical vibration due to periodic misalignment and optical path errors can be written as a convolution products in complex form, see Eq. (13) in Shatalina et al. (submitted for publication). Assuming that the domain of wavenumber with significant signal I_{Mars} around $\sigma \sim 2000–3000$ cm^{-1} is constant ($\sigma_k \sim 2500$), the following equation

$$I_{PFS}(\sigma) = I_{Mars}(\sigma) + [\sigma . I_{Mars}(\sigma)] \star K(\sigma), \tag{1}$$

simplifies to

$$I_{PFS}(\sigma) = I_{Mars}(\sigma) \star \left[\delta(\sigma) + K(\sigma).\sigma_k\right]. \tag{2}$$

with $\delta()$, the Dirac function.

By rewriting

$$I_{PFS}(\sigma) = I_{Mars}(\sigma) \star K_{PFS}(\sigma), \tag{3}$$

with $I_{PFS}(\sigma)$ the measured raw spectra, I_{Mars} the contribution of the raw spectra from Mars, K_{PFS} the kernel representing the mechanical vibration effects, σ the wavenumber, and $K(\sigma)$ the non-normalized complex kernel (Shatalina et al., submitted for publication).

From Shatalina et al. (submitted for publication), the kernel of all frequency of vibrations is

$$K_{PFS}(\sigma) = \delta(\sigma) + A(\sigma) e^{i\varphi_A(\sigma)} + B(\sigma) e^{i\varphi_B(\sigma)}. \tag{4}$$

The quantities A, B, φ_A, φ_B are unknown and cannot be evaluated quantitatively due to the lack of knowledge about vibration amplitude and phase. In practice, the functions A, B, φ_A, φ_B are sparse over σ because the frequencies of vibrations are sparse. Note that A, B, φ_A, φ_B are not symmetric around $\sigma = 0$ due to the relative phase. We propose to estimate those functions using an inversion procedure described in the next section.

The assumption of a reduced wavenumber domain is valid in first approximation due to the sensitivity of the detector and the typical Martian signal, leading to a misfit factor of 0.8 × to 1.2 × that is reasonable for this case. In addition, our strategy is to use semi-blind deconvolution algorithm in order to ensure the best fit any kind of spectra. This way, the wavenumber domain of significant signal has not to be defined explicitly.

Including to our model an additive noise ε which stands for the others sources of acquisition noise besides the mechanical vibrations and the error due to our PFS modeling by a convolution kernel K_{PFS}, PFS spectra in signal domain as illustrated in Fig. 2 are

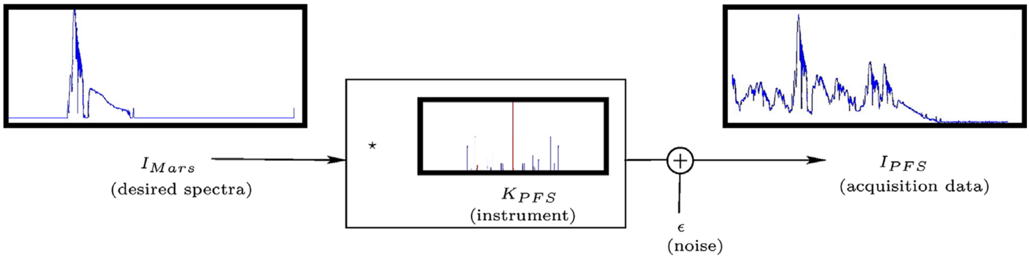

Fig. 2. Model of acquisition by the PFS instrument.