Characterization of the stray light in a space borne atmospheric AOTF spectrometer

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Abstract: Acousto-optic tunable filter (AOTF) spectrometers are being criticized for spectral leakage, distant side lobes of their spectral response (SRF) function, or the stray light. SPICAM-IR is the AOTF spectrometer in the range 1000-1700 nm with a resolving power of 1800-2200 operating on the Mars Express interplanetary probe. It is primarily dedicated to measurements of water vapor in the Martian atmosphere. SPICAM H_2O retrievals are generally lower than simultaneous measurements with other instruments, the stray light suggested as a likely explanation. We report the results of laboratory measurements of water vapor in quantity characteristic for the Mars atmosphere with the Flight Spare model of SPICAM-IR. The level of the stray light is below $1.3\cdot10^{-4}$, and the accuracy to measure water vapor is ~0.2 pr. μm, mostly determined by measurement uncertainties and the accuracy of the synthetic modeling. We demonstrate that the AOTF spectrometer dependably measures the water abundance and can be employed as an atmospheric spectrometer.

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1. Introduction

The stray light or spectral leakage of a spectrometer can be determined as a departure of a non-ideal spectral response function (SRF) from zero beyond its narrow peak corresponding to the spectrometer's spectral resolution. The spectral leakage hampers the possibility of the instrument to measure weak features in absorption, diffuse, or reflectance spectra. A practical spectrum frequently looks like a continuum close to the unity with weak absorption features, below a few percent. The detector measures light at all wavelengths, and the integration of the light from the non-ideal SRF over the entire spectral range results in the increase of the measured continuum. The depth of the measured absorption features remains the same, and the apparent equivalent optical depth (EOD) decreases. For example, let us assume the homogeneous or "grey" spectral leakage of 10^{-4}, characteristic of a relatively high-quality spectrometer measuring the EOD=10% in the spectral range of 700-1700 nm at a spectral resolving power of $\lambda/\Delta\lambda$=300. At 1000 nm the contribution of the stray light to the measured continuum will be about 3%, and the apparent EOD will be 9.97%. With the spectral leakage of $3\cdot10^{-4}$, and $\lambda/\Delta\lambda$=1000 the apparent EOD becomes 9.7%. Such an error in the equivalent depth is generally multiplied when translating to the measured quantity (concentration, partial pressure, etc.) resulting in significant, tens of percent, errors. It is difficult to characterize the SRF usually measured with line sources (lasers, Pen-Ray® lamps, etc.) below 10^{-3}. The appropriate approach to estimate the stray light is to simulate a real absorption spectrum and to measure the EOD.

Acousto-optic tunable filter (AOTF) spectrometers are largely used in a variety of applications, from medicine to astronomy [1, 2]. They gain popularity in space borne applications, for remote sensing [3] and for deep space [4-6]. AOTF works on a principle of Bragg's diffraction of light on the ultrasonic acoustic wave excited within a birefringent crystal. A variable radio frequency (RF) signal activates a piezoelectric transducer attached to the crystal. The AOTF spectrometer measures light sequentially, and when the RF is turned off, the filter serves as an electronic shutter, allowing accurate subtraction of the background signal, measured after every measurement or after every few measurements. The synchronous modulation cancels out all the stray light, which is not the result of the acousto-optic interaction. However, the scattering or multiple reflections of the acoustic wave field inside the crystal, the result of imperfect coupling of the transducer to the crystal, or imperfect absorber, and the optical diffraction at this erratic field, generates a synchronous parasitic signal. The SRF of an AOTF is theoretically described by $\sin^2 x/x^2$ function, its side lobes rapidly decreasing. The acoustic problems may result in amplification of the distant lobes, distortion of the SRF, or a continuous stray light.

Spectral properties of the AOTF are being extensively studied, however little attention is paid to the effects of the stray light. In the meanwhile the AOTF spectrometers have aroused some doubts about the measurement accuracy. In their recent papers Farina et al. [7, 8] report the deficiencies of the AOTF in time-resolved diffuse spectroscopy. Pilorget and Bibring [9, 10] experienced difficulties to reproduce the reflectance spectrum of a Spectralon Labsphere® wavelength calibration standard with an AOTF intended for monochromatic illumination of samples in a space borne microscope. Spectralon is the highly-reflective etalon with absorption features simulating the spectrum of a natural object. The stray light/distant side lobes effects are the most likely explanation for the observed difference.

In our application the near-infrared AOTF spectrometer SPICAM-IR is dedicated for measurements of the Mars atmosphere [4], with the emphasis on water vapor in the 1380-nm band. The absorption due H_2O in the atmosphere of Mars is low, and a good measurement precision is required. SPICAM-IR is operated in orbit around Mars since 2004, and it continuously delivers atmospheric information. This high-resolution and broad-range instrument is especially susceptible to the stray light as explained in beginning of this section. To quantify its potential influence we measured the absorption by H_2O vapor in the laboratory with the flight spare model of SPICAM-IR. In this paper we report the results of these measurements, demonstrating high fidelity of the AOTF spectra, and a low level of the stray light and distortions.

2. SPICAM IR AOTF spectrometer at Mars Express ESA mission

SPICAM-IR is the first AOTF spectrometer operating onboard of a deep space mission. The instrument, the science investigation and operations are described in detail in [4]. We recall the scientific context, main features and parameters, related to the stray light.

The experiment measures water vapor and other species in nadir, and in solar occultation using a dedicated solar port. A non-collinear wide aperture [11] custom-built AOTF conserving two orthogonal polarizations is employed. Diffracted light is registered with two single-pixel detectors. The instrument covers the spectral range of 1000-1700 nm with spectral resolution of 0.5-1.2 nm (or of ~3.5 cm^{-1} throughout the spectral range). The resolving power $\lambda/\Delta\lambda$ is ~2000 in the range of the water vapor band. Wavelengths are registered sequentially with the increment of ~$0.1\Delta\lambda$; windowing or loose sampling allows reducing the duration of measurements. The field of view (FOV) in nadir is 1°. The instrument employs synchronous modulation (the AOTF is on during 50% of the measurement cycle) however a slightly variable temperature-dependent background, or dark current, originates from RF electrical interference.

SPICAM-IR on the Mars Express mission measures water vapor along with two other experiments of the mission, mapping spectrometer OMEGA, and Fourier-spectrometer PFS. Comparing to them and to earlier TES/Mars Global Surveyor measurements [12], SPICAM-IR delivered the lowest results [13]. The SPICAM-IR water vapor amounts were lower by a factor of 1.8 than those of TES, lower than PFS at 2.56 μm, and close to but still below those of OMEGA and those of PFS at 20 μm [14]. The stray light in SPICAM-IR was suggested as a likely explanation of the apparent bias.

Possible reasons for the stray light in the AOTF spectrometer were analyzed in [4]. The diffraction at higher harmonics of the RF was excluded, however the distant side lobes of the SRF, or the quasi-continuous “grey” spectral leakage remain a possibility. The achieved accuracy in characterization of the SRF is ~10^{-3} (see below), insufficient to rule out biases due to the stray light (see Section 1). Different characterization approach is therefore necessary.

3. Laboratory H_2O cell measurements

In order to characterize the stray light in the AOTF spectrometer, the Flight Spare Model of SPICAM-IR was used to measure the absorption in a cell filled with water vapor. The measurement principle is illustrated in Fig. 1. A halogen lamp illuminates a flat screen, which is observed by SPICAM-IR through a 59.75-cm metallic cell. The cell can be pumped out with a vacuum pump, or a precise amount of pure water vapor can be injected. The lamp formed a homogeneous spot on the screen encompassing the FOV of SPICAM, unobscured by the cell. The whole set up was placed into a sealed box filled with dry nitrogen to minimize the absorption by atmospheric water vapor. The nitrogen purge lasted 4 days, to reach the humidity of 1-1.5%. It corresponds to absorption of ~0.6%, small but detectable by SPICAM-IR, and taken into account. The water vapor pressure in the cell was measured with a pressure gauge.

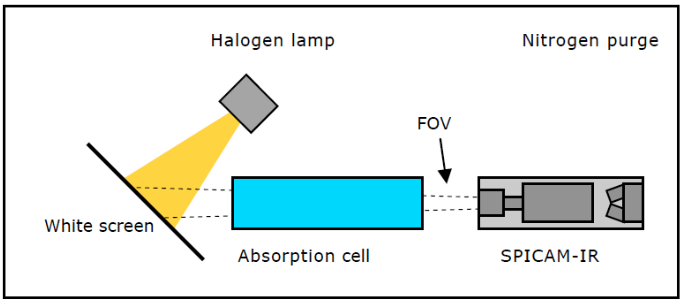

Fig. 1. A simplified diagram of the test set-up.

Several precautions allowed maintaining stability of all parameters, such as lamp intensity, pressure and temperature in the cell, to make long, 30-min, measurements, improving the signal to noise ratio. The lamp and the instrument were powered ~20 min prior to measurements. We made sure in particular that the dark current was stable from the beginning to the end of a measurement. Similar duration was allowed for stabilization of the H_2O pressure in the cell after the injection. Special attention was paid to the purity of water, which may contain CO_2, reducing the partial pressure of H_2O. During the measurements the vacuum pumps have been stopped to cancel out vibrations and electrical interference.

The measurement sequence included the records of the lamp with an empty cell (reference signal), with the filled cell, and the dark current (lamp is off). The overall duration of this sequence for one H_2O pressure value was ~3 hours; about the same time needed for the evacuation of the cell.

We report the measurements of four H_2O pressures performed in June 2007 (see Table 1). During the tests SPICAM-IR was working in one of flight operation modes [4] recording 996 spectral points at the best sampling in the vicinity of the H_2O band at 1380 nm. The integration time for each spectral point was 5.6 ms.

Table 1. The water vapor pressure and temperature in the cell and the results of the data processing. The EOD is integrated in the range of 6675-7635 cm^{-1} (see Fig. 2a). The retrieved H_2O pressure and is its errors are calculated using the synthetic model for two cases: no stray light beyond the instrument's SRF (see Fig. 2b), and "grey" stray light of $1.0 \cdot 10^{-4}$.

#	H_2O pressure (mbar)	T, K	H_2O EOD (measured)	Retrieved H_2O pressure (mbar) no stray light	Retrieved H_2O pressure (mbar) stray light $1.0 \cdot 10^{-4}$
1	33.13	300.93	17.3817	31.61±1.07	33.68±1.11
2	13.27	303.95	7.105	12.43±0.57	13.25±0.45
3	10.06	301.6	5.85	9.65±0.55	10.30±0.53
4	5.8027	301.51	3.566	5.34±0.36	5.72±0.49

One measurement cycle contained up to 300 spectra, averaged to increase the signal-to-noise ratio. The measured spectra of the empty cell and the cell filled with H_2O are shown in Fig. 2a. The transmittance spectrum is obtained as:

$$Tr = \frac{I_m - DC(T_m)}{I_{ref} - DC(T_{ref})},$$

where Tr is resulting transmittance, I_m is measured spectrum, I_{ref} is the measured reference spectrum (empty cell), $DC(T)$ is the dark current depending on temperature for the measured and the reference spectrum, respectively. The dark current was calibrated for different temperatures, and interpolated.

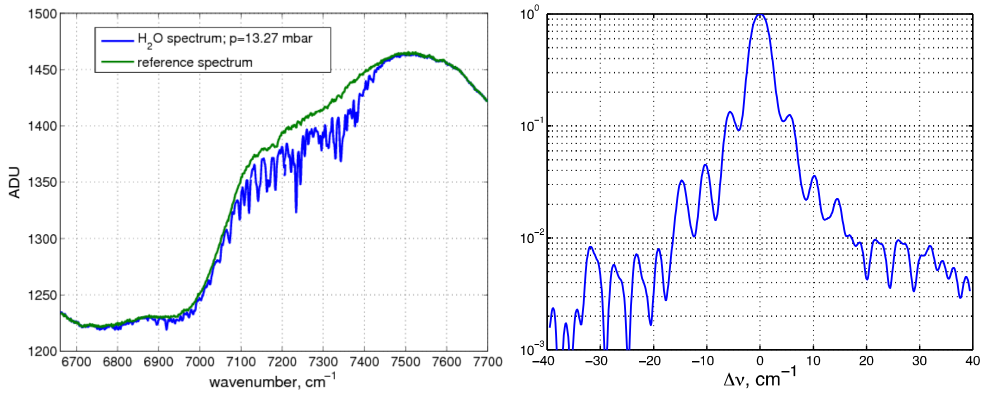

Fig. 2. (a) Spectra recorded with SPICAM-IR in the laboratory set-up. The reference spectrum with the empty cell (green line) and the H_2O absorption spectrum (blue line) measured at the pressure of 13.27 mbar. The dark current has been subtracted. (b) The spectral response function (SRF) of the Spare Model of SPICAM-IR measured with Xe Pen-Ray® lamp at 1529 nm.

4. Results

We constructed a synthetic model of the H_2O absorption using HITRAN2008 [15] database taking into account the self-broadening of water lines, the cell length and appropriate pressure and temperature. The synthetic spectra have been then convolved with the SPICAM-IR SRF (Fig. 2b). Beyond the range of the measured SRF we made several assumptions regarding the stray light: (i) no stray light: the SRF=0 beyond the range of Fig. 2b; (ii) different approximation of the far side lobes, described as log interpolation of both sides of SRF to from $3\cdot 10^{-3}$ to 10^{-5} at 100, 300, 700, 1000, etc. cm^{-1}; (iii) constant stray light of different levels from $5\cdot 10^{-5}$ to $3\cdot 10^{-4}$.

The best agreement between measured and synthetic transmissions is achieved with the “grey” stray light of $(0.7\text{-}1.3)\cdot 10^{-4}$; the results are undistinguishable from the log extrapolation of the far side lobes to 300 cm^{-1} and wider. The spectra are presented in Fig. 3. The modeling ignoring the stray light results in overestimation of the absorption in water vapor lines, and the difference of the model and the measured spectra is visibly biased. The account for the stray light allows much better match; the difference becomes symmetric and reflects imperfect synthetic modeling. In both cases the difference curves are biased towards positive values below 7430 cm^{-1}, likely due to long-term trends in the dark current or other parameters of the set-up. In practical retrievals such bias can be readily removed using differential absorption (DOAS) technique. The χ^2 and the retrieved pressure values for all measurements are presented in in Table 1.

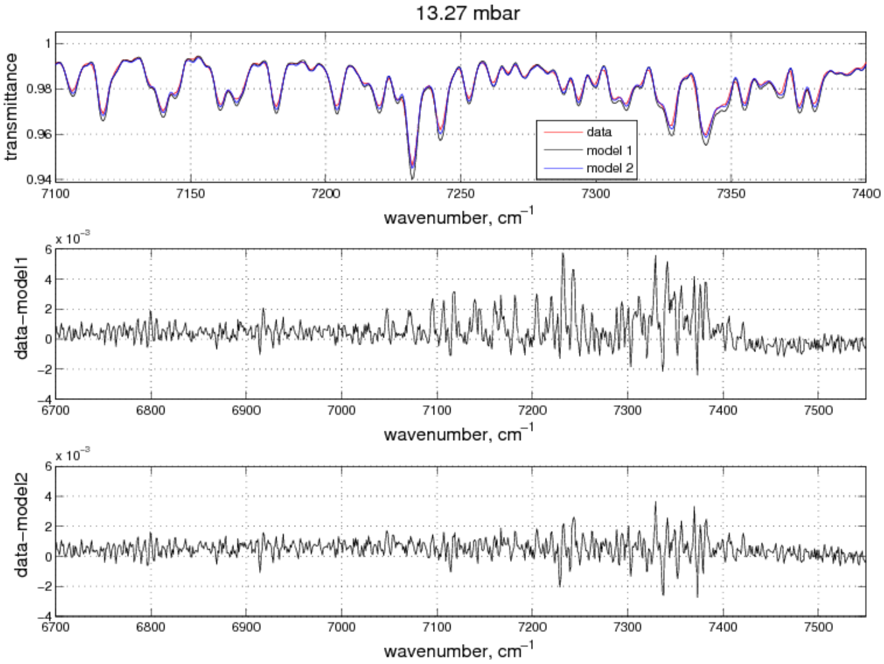

Fig. 3. (a) H_2O at 13.27 mbar spectrum recorded by SPICAM-IR (red curve) and compared with two synthetic models: one (black curve) takes into account the SRF (Fig 2b) only (case (i), see text). Best fit (blue curve) is computed for the "grey" stray light of 1.3 10^{-4}. The differences between the models and the measured spectrum are presented in panels (b) and (c).

5. Conclusions

The Flight Spare model of SPICAM-IR instrument equivalent to one flying on Mars Express was recalibrated in order to analyze the stray light in the AOTF spectrometer, and its influence on the H_2O vapor measurements. The contribution of the stray light and/or far side lobes of the AOTF is below $1.3 \cdot 10^{-4}$, assuming the "grey" stray light in the entire spectral range, the result is similar to a high-quality grating spectrometer. Nevertheless, the stray light should be accounted for when retrieving the H_2O abundance from the AOTF spectra. In our measurements we minimized the random noise, and achieved the accuracy to retrieve H_2O in the range of 2.5-14 pr. µm, typical for a dry Mars atmosphere, of 0.19-0.47 pr. µm. This accuracy is determined by trends of the laboratory set-up and deficiencies of the synthetic spectra modeling.

The comparisons of different Mars water vapor datasets resulted in revision of TES/MGS climatology, reducing the difference between SPICAM and TES: from a factor of 1.8 to 1.2. After reanalysis SPICAM results are close to OMEGA retrievals, and are in better agreement with other Mars Express experiments [16]. Still, the SPICAM measurements remain lower than other results, but this could not be explained by instrumental problems of SPICAM.

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