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

Oleg Korablev,[1,*] Anna Fedorova,[1] Eric Villard,[2,3] Lilian Joly,[4] Alexander Kiselev,[1] Denis Belyaev,[1] and Jean-Loup Bertaux[2]

[1]*Space Research Institute (IKI), 84/32 Profsoyuznaya, 117997 Moscow, Russia; Moscow Institute of Physics and Technology, Institutsky dr. 9, 141700 Dolgoprudnyi, Russia*
[2]*LATMOS/CNRS, 78280 Guyancourt, France.*
[3]*ALMA/European Southern Observatory, Santiago, Chile*
[4]*GSMA/CNRS Univ. de Reims, Moulin de la Housse, BP 1039, 51687 Reims, France.*
**korab@iki.rssi.ru*

Abstract: Acousto-optic tunable filter (AOTF) spectrometers are being criticized for spectral leakage, distant side lobes of their spectral response function (SRF), or the stray light. SPICAM-IR is the AOTF spectrometer in the range of 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 (2-15 precipitable microns) with the Flight Spare model of SPICAM-IR. We simulated the measured spectra with HITRAN-based synthetic model, varying the water abundance, and the level of the stray light, and compared the results to the known amount of water in the cell. The retrieved level of the stray light, assumed uniformly spread over the spectral range, is below $1\text{-}1.3\cdot10^{-4}$. The stray may be responsible for the underestimation of water abundance of up to 8%, or 0.6 pr. μm. The account for the stray light removes the bias completely; the overall accuracy to measure water vapor is ~0.2 pr. μm. We demonstrate that the AOTF spectrometer dependably measures the water abundance and can be employed as an atmospheric spectrometer.

OCIS codes: (010.0280) Remote sensing and sensors; (010.1280) Atmospheric composition; (230.1040) Acousto-optical devices; (300.1030) Absorption; (300.6340) Spectroscopy, infrared.

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1. Introduction

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 spectral response function (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 distant lobes, or a continuous spectral leakage in the broad spectral range, a sort of stray light specific for the AOTF.

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 paper Farina et al. [7] report the deficiencies of the AOTF in time-resolved diffuse spectroscopy. The effect of stray light on reflectance spectra has been observed in [8] using a Spectralon Labsphere® Wavelength

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Calibration Standard with an AOTF intended for monochromatic illumination of samples in a space borne microscope. Spectralon is the highly-reflective etalon doped with rare earth elements with absorption features simulating the spectrum of a natural object. The stray light/distant side lobes effects are the most likely explanation for the difference observed between the AOTF and the reference FTS spectra.

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 spectral leakage. To quantify its potential influence we measured the absorption by H_2O vapor in the laboratory with the flight Spare Model (SM) 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 spectral leakage.

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 instrument measures water vapor and other species in nadir, and in solar occultation using a dedicated solar port. A non-collinear wide-aperture [9] custom-built AOTF conserving two orthogonal polarizations is employed. Diffracted light is registered with two photodiodes. 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). In the range of the water vapor band the resolving power $\lambda/\Delta\lambda$ is ~2000. Wavelengths are registered sequentially with the increment of $\sim 0.1\Delta\lambda$; 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. Possible reasons for the stray light in SPICAM 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.

SPICAM-IR on Mars Express measures water vapor along with two other experiments of the mission, mapping spectrometer OMEGA [10], and Fourier-spectrometer PFS [11, 12]. Comparing to them and to earlier TES/Mars Global Surveyor measurements [13], SPICAM-IR delivered the lowest results [14]. The SPICAM-IR water vapor amounts were lower by a factor of 1.8 than those of TES, lower than PFS measured in the 2.56-μm H_2O band, and close to but still below those of OMEGA and those of PFS measured in the thermal IR (above 20 μm). The spectral leakage in SPICAM-IR was suggested as one of possible explanations of the apparent bias [15].

The transmission spectrum measured by SPICAM in the range of the water vapor band looks like a continuum with weak gaseous absorption features, below a few percent. The spectral leakage results in the increase of the measured continuum, while the depth of the measured absorption features remains nearly the same. Then the apparent equivalent optical depth (EOD, the optical depth integrated over the spectral interval of interest) decreases. For example, let us assume a relatively high-quality spectrometer measuring the EOD = 0.1 in the spectral range of 700-1700 nm at a spectral resolving power of $\lambda/\Delta\lambda$ = 300, affected by spectral leakage of 10^{-4} in the entire range. At 1000 nm the contribution of the stray light to the measured continuum will be about 3%, and the apparent EOD will be 0.0997 (0.3% error). With $\lambda/\Delta\lambda$ = 2000, and the spectral leakage of $3\cdot10^{-4}$ (which might be the case of SPICAM) the apparent EOD becomes 0.094 (6% error). Such uncertainty in the equivalent

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depth is multiplied when translated to the measured water concentration, and could result in significant, tens of percent, errors.

It is difficult to characterize the SRF with line sources (lasers, Pen-Ray® lamps, etc.) below 10^{-3}. This accuracy is insufficient to rule out biases due to the straylight. The appropriate characterization approach to estimate the stray light is to simulate a real absorption spectrum and to measure the EOD.

3. Laboratory H_2O cell measurements

In order to characterize the stray light in the AOTF spectrometer, the flight Spare Model (SM) of SPICAM-IR was used to measure the absorption in a cell filled with water vapor. The SM was fully calibrated following the same procedures as the one in flight [4], and the two instruments are nearly identical in terms of SRF width and its spectral behavior. Slight differences found only in sensitivities, and in the wavelength assignment. The SRF side lobes of the Flight model are lower than that of the SM, though characterized in narrower range (see below). We assume that the two AOTFs, produced in a same batch, and the two instruments are nearly identical, and the SM is representative to characterize, or to constrain the spectral leakage of SPICAM-IR operational in orbit around Mars.

The measurement principle is illustrated in Fig. 1. A halogen lamp illuminates a flat Lambertian screen, which is observed by SPICAM-IR through a 59.75-cm long metallic cell. The cell can be pumped out with a vacuum pump, or a precise amount of pure water vapor can be injected. SPICAM observed the illuminated screen trough the cell, its 1° FOV passing inside the cell (diameter of 35 mm) and falling within the homogeneous illuminated spot (diameter of ~65 mm). 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 on the optical path out of the cell of ~0.6%, small but detectable by SPICAM-IR.

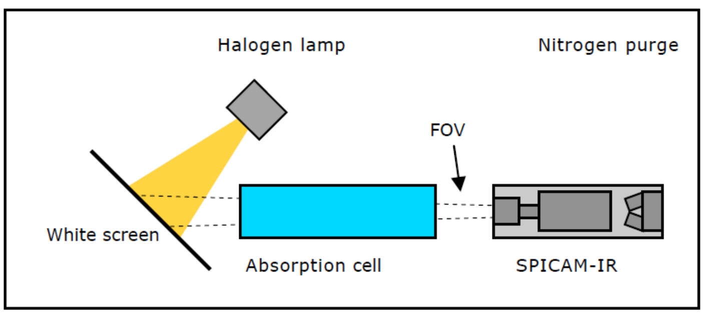

Fig. 1. A simplified diagram of the test set-up.

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. In particular the drift of the instrument temperature, which determines the dark current was minimized. Similar duration was allowed for stabilization of the H_2O pressure in the cell after the injection. The water vapor pressure in the cell was measured with a pressure gauge; the accuracy and the drift was typically < 0.8%. The temperature in the cell during a measurement sequence drifted by ~1 K. Special attention was paid to the purity of water vapor in the cell, which may be contaminated by 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 cell filled with H_2O vapor, and the dark current (the lamp is off). The overall

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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 with 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. 2(a). The H_2O pressure is retrieved comparing the measured spectrum to the HITRAN-based synthetic model for two cases: no stray light beyond the instrument's SRF, see Fig. 2(b), and "grey" stray light of $1.0 \cdot 10^{-4}$. The and is its errors reflect the uncertainties of the fit.

#	H_2O pressure (mbar)	T (K)	Measured H_2O EOD	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	0.1738	31.61 ± 1.07	33.68 ± 1.11
2	13.27	303.95	0.0711	12.43 ± 0.57	13.25 ± 0.45
3	10.06	301.6	0.0585	9.65 ± 0.55	10.30 ± 0.53
4	5.8027	301.51	0.0357	5.34 ± 0.36	5.72 ± 0.49

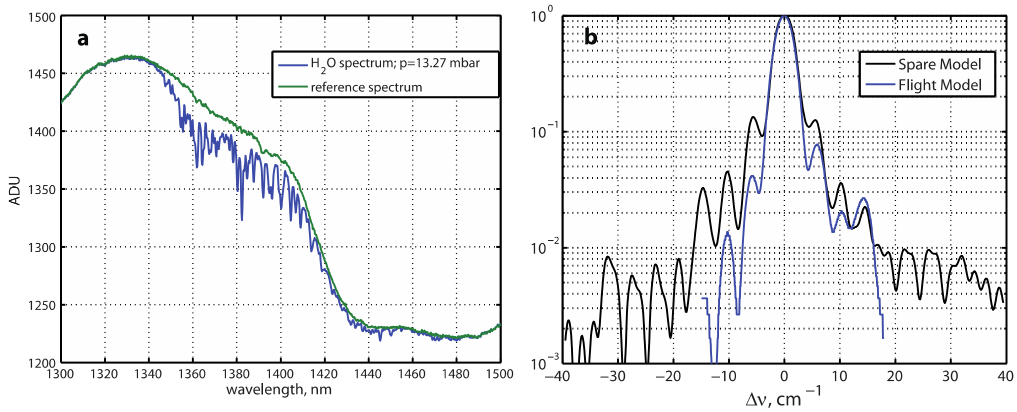

Fig. 2. (a) Spectra recorded with SPICAM-IR in the laboratory set-up. The reference spectrum with the empty cell (green curve) and the H_2O absorption spectrum (blue curve) measured at the pressure of 13.27 mbar. The dark current is subtracted. (b) The spectral response function (SRF) of the Spare Model of SPICAM-IR measured with Hg-Ar Oriel lamp at 1529 nm (black curve). The SRF of the Flight Model (blue curve) is shown for comparison.

One measurement cycle contained up to 200-250 valid 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. 2(a). The transmittance spectrum is obtained as:

$$Tr = \frac{I_m - DC(T_m)}{I_{ref} - DC(T_{ref})}, \qquad (1)$$

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 of the instrument for the measured and the reference spectrum, respectively. The dark current was calibrated for different temperatures, and interpolated. With the uncertainty of an individual spectrum of 6-7 ADU (this value accounts for the drift of the lamp; the noise of DC is ~4 ADU), the S/N of Tr is superior to 2500.

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4. Results and conclusions

We constructed a synthetic model of the H_2O absorption using HITRAN2008 [16] 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 retrieved through the spectral range a described in [4]. 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. 2(b); (ii) approximation of the far side lobes, described as log extrapolation of SRF at both sides from down to 10^{-5} at 100, 300, 1000, etc., cm^{-1}; (iii) constant stray light of different levels from $5 \cdot 10^{-5}$ to $3 \cdot 10^{-4}$.

The fitting is performed by minimizing the chi-squared difference between the measured and the synthetic transmission. We vary the quantity of water vapor in the cell and the model of the spectral leakage. The best agreement 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. Example spectra are presented in Fig. 3. The modeling ignoring the spectral leakage results in overestimation of the absorption in water features, and the residual is visibly biased. The account for the spectral leakage light allows much better match; the difference becomes symmetric and reflects imperfect synthetic modeling. The retrieved pressure values for all measurements are presented in Table 1.

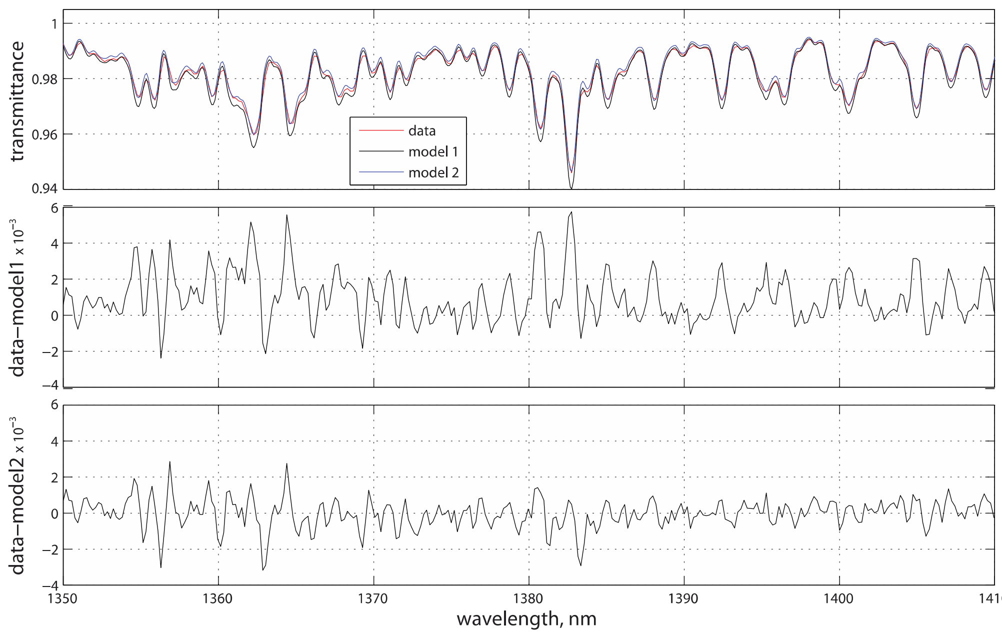

Fig. 3. Upper panel: H_2O at 13.27 mbar spectrum recorded by SPICAM-IR (red curve) and compared with two synthetic models: one (black curve) with no stray light (case (i), see text). The best fit (blue curve) is computed for the "grey" stray light of 1.3 10^{-4}. The differences between the measured spectrum and the models are presented in middle and lower panels.

Concluding, the Flight Spare model of SPICAM-IR instrument equivalent to one flying on Mars Express was recalibrated in the laboratory using the H_2O cell in order to analyze the stray light in the AOTF spectrometer, and its influence on the H_2O vapor measurements. We minimized the random noise, and concentrated on the effects of the stray light. 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, this stray light should be accounted for in the AOTF spectra retrievals. In the range of measured pressures, corresponding to H_2O contents of 2.5-14 precipitable microns, typical total water vapor in a dry Mars atmosphere, the underestimation due to the spectral leakage is about 0.2-0.6 pr. µm, or 4-8%. The underestimation is more evident for larger water contents, when relative accuracies are better. The account for spectral leakage of $\sim 10^{-4}$ in the entire spectral range removes the underestimation completely: the retrieved amounts of water coincide within ± 0.2 pr. µm or ~2%. In both cases the retrieval accuracy determined by trends of the laboratory set-up and deficiencies of the modeling is 0.19-0.47 pr. µm (2-6%).

The comparisons of different Mars water vapor data sets resulted in revision of TES/MGS climatology, reducing the difference between SPICAM and TES from a factor of 1.8 to 1.2. After the reanalysis, including the account for spectral leakage and a number of other updates, the SPICAM results become close to OMEGA [10] retrievals, and are in better agreement with other Mars Express experiments [17]. Still, SPICAM measurements, in particular those for larger H_2O contents, remain lower than other results, but this could not be explained by instrumental problems of SPICAM.

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