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TIR/SWIR EXPERIMENTS FROM THE LPMAA

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Abstract

The Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique (LPMAA) with support from CNES (Centre National d'Études Spatiales) and CNRS (Centre National de la Recherche Scientifique) has developed the IASI-balloon (Infrared Atmospheric Sounding Interferometer) and the SWIR-balloon (Short Wave InfraRed) experiments. Both instruments can be accommodated on a gondola under stratospheric balloon and are based on the same Fourier transform spectrometer (FTS) operating in the nadir looking geometry. In the first configuration the instrument collects the atmospheric upwelling thermal infrared (TIR) radiation with a spectral coverage similar to the instrument IASI onboard the MetOp satellite, a platform operated by EUMETSAT and launched on 10 October 2006. In the second configuration SWIR-balloon analyses the reflected or backscattered solar radiation during daytime to improve the sensitivity to the total column for trace species measurements. These two experiments have already flown several times: 6 flights from Kiruna (Sweden) and Teresina (Brazil) for IASI-balloon and 2 flights from Kiruna for SWIR-balloon. Recently the SWIR experiment has been configured to contribute to the spectral and radiometric calibration of the TANSO-FTS instrument onboard the Japanese GOSAT satellite, which uses the SWIR (and TIR) information to enhance the capability to derive vertical information on the profile of greenhouse gases like CO₂ and CH₄. The radiometric calibration procedure in the SWIR spectral region is described as well as the newly developed radiative transfer code 4A/OP-SWIR for simulations of SWIR-balloon spectra. The comparison between observation and calculation is presented and shows the importance of the surface spectral albedo that has to be characterized before any species abundance retrieval.

1 - The LPMAA balloon-borne experiments

1.a - Instrumental description

The LPMAA has developed a down-looking balloon-borne spectrometer named IASI-balloon (Infrared Atmospheric Sounding Interferometer). The main part of this instrument is based on a Bomem DA2.01 Fourier transform interferometer. This interferometer is associated with two infrared detectors, one HgCdTe (Mercury Cadmium Telluride) and one InSb (indium antimonide) to cover the full thermal infrared (TIR) spectral region from 3.3 μm to 16 μm. Two onboard reference blackbodies, one warmed (WBB at 303 K) and one cooled (CBB at 253 K) are used to determine the instrument contributions (self emission and response function). Two onboard imagers, one visible CCD and one infrared camera, provide information to characterize precisely the atmospheric layers sounded by IASI-balloon: clouds, ground, water, forest, snow, ... A detailed description of this instrument has been made in Té *et al.* 2002^[1], 2005^[2] and 2007^[3].

Here we will focus more on the SWIR spectral domain with the new instrumental configuration SWIR-balloon, cf. Figure 1. SWIR-balloon is identical to IASI-balloon for the Fourier transform interferometer, the stratospheric gondola, nadir looking, ... But the optical elements inside the interferometer are different (entrance window, beamsplitter, optical filters, ...) to cover the SWIR spectral region from 1.4 μm to 2.5 μm. The instrument measures the reflected and/or scattered solar radiation. Different combinations of detectors and optical filters were tested, see the next section for flight details : for the SWIR01 flight, there were 2 identical InSb detectors to cover the TIR (2031-2257 cm⁻¹ & 2633-3291 cm⁻¹) and SWIR (4213-4476 cm⁻¹ & 4739-5529 cm⁻¹) spectral ranges at the same time; for the SWIR02 flight, one cold window InSb (3900-6000 cm⁻¹) and one InGaAs (6300-7300 cm⁻¹) were used to cover the SWIR domain.

For the radiometric calibration in the SWIR region, we have added to the onboard blackbodies a calibrated QTH lamp associated with a well-known diffuser type material named Spectralon (see section 2 for details on the radiometric calibration in the SWIR domain).

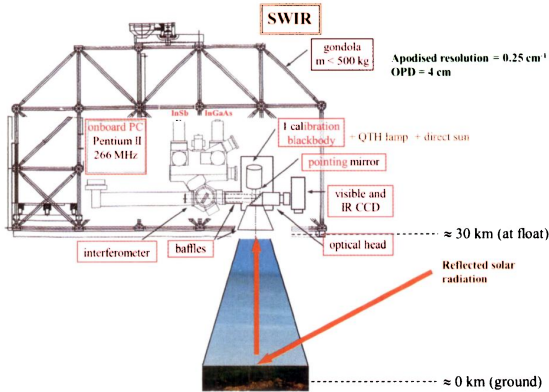


Figure 1. Schematic of the SWIR-balloon instrument and its gondola.

1.b - LPMAA balloon-borne flights

These two LPMAA experiments have flown already 8 times, cf. Table 1, in winter and summer from two different locations: Kiruna in the polar atmosphere (Sweden, 68°N, 21°E) and Teresina in the equatorial atmosphere (Brazil, 5°S, 42°50' W). The six flights of IASI-balloon were dedicated first to prepare the IASI mission and then to validate the IASI instrument onboard the MetOp satellite launched on 19 October 2006. The second flight IASI02 was performed for the SCIAMACHY validation (in nadir viewing)^[4]. Both SWIR-balloon flights have been performed more recently.

The first SWIR-balloon flight, combining TIR and SWIR spectral regions, was conducted during the 2009 summer campaign for the French

StraPolEte ANR project (<http://strapolete.cnrs-orleans.fr/>). This project was dedicated to the still incompletely explored polar stratosphere during the summer with balloon flights of different laboratories: SWIR-balloon and LPMA (Limb Profile Monitor of the Atmosphere) from LPMAA; SPIRALE, SALOMON, HELYSA and STAC from LPC2E (Laboratoire de Physique-Chimie de l'Environnement et de l'Espace); μ -RADIBAL from LOA (Laboratoire d'Optique Atmosphérique); DOAS (Differential Optical Absorption Spectroscopy) from Heidelberg University. The main goal of StraPolEte was to study the large scale transport and the mixing between air masses from higher and lower latitude that have a large impact on the trace gases and aerosol distribution at polar latitudes and thus on the stratospheric ozone budget. The ozone changes can affect the radiative budget and therefore the climate.

The second SWIR-balloon flight was a technological flight devoted to the SWIR spectral range. This flight was contributing to the spectral and radiometric calibration of the TANSO-FTS instrument onboard the Japanese GOSAT satellite. The GOSAT mission is the first space mission dedicated to the understanding of the greenhouse gases increasing impact, especially for CO₂ and CH₄. The TANSO-FTS^[5] purpose is to use the SWIR (and TIR) information to improve the precision and the capacity to retrieve the vertical distribution of CO₂ and CH₄. More precise measurements from space will allow a better coverage of the Earth to study the impact on the global climate of the increase of the greenhouse gases in the atmosphere. The following sections will focus on this second flight covering: radiometric calibration and comparison between observation and calculation.

Flight number	Date	Location	Time	Purpose
IASI01	March 13 th 2001	Kiruna (Sweden)	10:30 to 14:30 UT	TIR technological flight
IASI02	August 5 th 2002	Kiruna (Sweden)	18:30 to 22:10 UT	SCIAMACHY validation
IASI03	June 30 th 2005	Teresina (Brazil)	06:35 to 16:15 UT	Envisat validation
IASI04	March 1 st 2006	Kiruna (Sweden)	07:50 to 17:25 UT	Rehearsal of IASI validation
IASI05	February 22 nd 2007	Kiruna (Sweden)	15:05 to 20:05 UT	IASI-MetOp validation
IASI06	June 13 th 2008	Teresina (Brazil)	06:20 to 13:45 UT	IASI-MetOp validation
SWIR01	August 14 th 2009	Kiruna (Sweden)	09:25 to 15:10 UT	TIR/SWIR (StraPolEte)
SWIR02	April 25 th 2010	Kiruna (Sweden)	06:55 to 14:55 UT	SWIR technological flight

Table 1. Different flights of the LPMAA balloon experiments.

2 - SWIR domain radiometric calibration

Before deriving the contribution from the sounded atmospheric layers (from TIR or SWIR atmospheric spectra), we have to characterize the

instrument contribution (offset and gain). Depending on the studied spectral domain, we use different reference sources to perform the radiometric calibration process. For the TIR configuration (IASI-balloon), we use two reference

blackbodies stabilized at two different temperatures (one warm and one cold)^{[1], [6]}. For the SWIR configuration (SWIR-balloon), we have replaced the cod blackbody by a reference QTH lamp (Quartz Tungsten Halogen) associated with a Spectralon diffuser, cf. Figure 2. Table 2 shows the hemispherical spectral reflectance factor of the Spectralon CSTM-SRT-99-100^[7]. The QTH lamp^[8] is radiometrically calibrated at the intensity of 6.6 A between 0.25 μm and 1.1 μm , over our SWIR region of interest (1.4 μm to 2.5 μm), cf. Table 3.

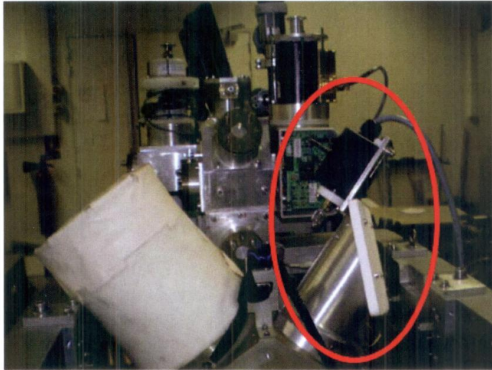


Figure 2. The QTH lamp with the Spectralon on the SWIR-balloon instrument.

Before using this information, we have to fit and extrapolate the reference curve into the SWIR region. But in order to have a signal of the same order as the atmospheric signal, the QTH lamp had to be used only at 1.5 A. Then a post-flight calibration of this QTH source was needed before performing the radiometric calibration of the

atmospheric spectra. But we have encountered different experimental problems. The QTH lamp voltage had large fluctuations during the SWIR02 flight and we have noticed that the QTH lamp signal is different in flight and on the ground. To resolve these experimental difficulties, we have determined the QTH lamp intensity to provide the same signal in flight and on the ground. Figure 3 shows the QTH lamp with the Spectralon spectra recorded in flight (in black) and on the ground (in red): (a) for the InSb detector and (b) for the InGaAs one. The spectra are identical except for the H₂O absorption band which is stronger on the ground than in flight (less H₂O in the dry stratosphere along the optical path between the QTH lamp and the entrance window of the interferometer). In order to characterize precisely this combination of the Spectralon and QTH lamp at 1.5 A, another reference source^[9], called *calibreur Fluke 4181*, is employed. It is a well characterized flat blackbody of 150 mm diameter which can be heated between 50 °C and 500 °C with a temperature precision between 0.5°C and 5°C. The average emissivity is about 0.95 from the TIR to SWIR. Figure 4 presents the radiometrically calibrated spectra of the QTH lamp at 1.5 A with the Spectralon in the InSb and InGaAs detectors. This reference source can be modelled in the SWIR region by a Planck function of 1123.15 K combined with an effective emissivity of 1.5×10^{-4} , which fits well both detectors. Using this model, atmospheric spectra are calibrated by a two reference sources radiometric calibration process which can be summarized by equation Eq.1.

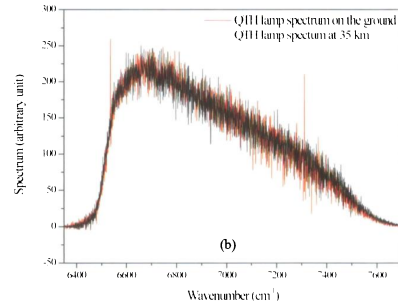
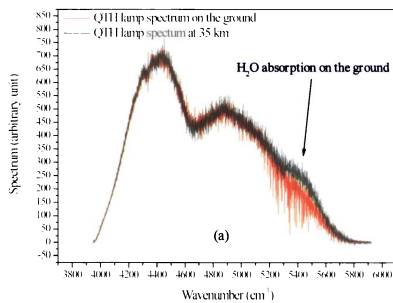


Figure 3. The two SWIR regions spectra of the QTH lamp with the Spectralon on the SWIR-balloon instrument.

Wavelength (μm)	0.250	0.500	0.750	1.000	1.250	1.500	1.750	2.000	2.250	2.500
Reflectance factor	0.979	0.995	0.993	0.993	0.992	0.991	0.998	0.973	0.969	0.943

Table 2. Hemispherical spectral reflectance factor for the diffuser CSTM-SRT-99-100.

Wavelength (nm)	250	300	400	500	600	700	800	900	1000	1100
Irradiance	2.34×10^{-5}	1.86×10^{-4}	1.96×10^{-3}	6.20×10^{-3}	1.13×10^{-2}	1.54×10^{-2}	1.75×10^{-2}	1.81×10^{-2}	1.72×10^{-2}	1.53×10^{-2}

Table 3. Absolute spectral irradiance ($\text{W} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}$) of the QTH lamp at 6.6 A.

$$S_{\text{scene}}^{\text{calib}} = \frac{B_{\text{QTH}}(S_{\text{scene}}^{\text{meas}} - S_{\text{BB}}^{\text{meas}}) - \epsilon_{\text{BB}} B_{\text{BB}}(S_{\text{scene}}^{\text{meas}} - S_{\text{QTH}}^{\text{meas}})}{S_{\text{QTH}}^{\text{meas}} - S_{\text{BB}}^{\text{meas}}} \quad (1)$$

In Eq. (1) $S_{\text{scene}}^{\text{calib}}$ is the atmospheric scene spectrum; B_{QTH} is the radiance calculated as discussed above for the QTH lamp at 1.5 A with the Spectralon diffuser; ϵ_{BB} and B_{BB} are respectively the emissivity and the Planck function of the blackbody (BB); $S_{\text{view}}^{\text{meas}}$ is the measured spectrum of the corresponding view (QTH lamp, blackbody or atmospheric scene).

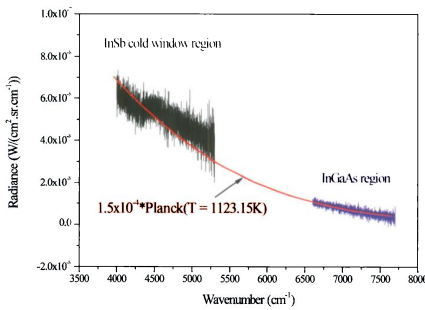


Figure 4. The QTH lamp with the Spectralon calibrated spectra for both detectors.

Selected series of atmospheric spectra have been radiometrically calibrated for the scenes with very stable meteorological conditions during their recordings (clear sky and same ground surface). Figure 5 presents an example of infrared and visible images which demonstrate that the sounding is reaching the ground surface. A radiometrically calibrated atmospheric spectrum is shown in Figure 6 recorded at the same time as the previous images. The spectrum background can be fitted by a Planck function at 433 K. This effective brightness temperature does not have the same meaning as in the TIR (usually a real surface or cloud top temperature weighted by the emissivity). Even if the atmospheric spectrum is quite noisy, we can notice distinctly the absorption lines of different atmospheric species: the absorption lines of CH_4 and H_2O in the interval 4500 cm^{-1} - 4600 cm^{-1} and the strong absorption bands of CO_2 between 4800 cm^{-1} and 5000 cm^{-1} . The relevance and the quality of this atmospheric spectrum can be verified and tested by comparison with a theoretical spectrum calculated by the 4A/OP-SWIR radiative transfer model which is described in the following section.

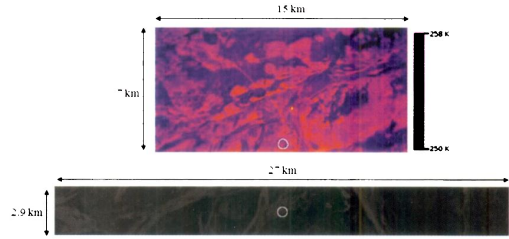


Figure 5. Infrared and visible images recorded at 14:25:17 UT.

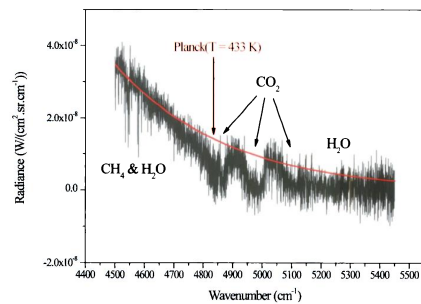


Figure 6. Radiometrically calibrated atmospheric spectrum recorded at 14:25:17 UT.

3 - 4A/OP-SWIR model

The 4A/OP-SWIR model is an extension of the 4A/OP model initially developed for the TIR and now extended to the SWIR domain. The 4A/OP model is a user-friendly software for various scientific applications. This model is co-developed by LMD (Laboratoire de Météorologie Dynamique) and NOVELTIS with support from CNES (Centre National d'Études Spatiales). NOVELTIS is in charge of the operational version^[10, 11] derived from the LMD 4A model (Automatized Atmospheric Absorption Atlas). The 4A/OP model is a fast and accurate line-by-line and layer-by-layer forward radiative transfer model for the computation of transmittances, radiances and Jacobians, particularly efficient in terms of accuracy and computation time. The 4A/OP model provides a fast computation of transmittances and radiances by using a comprehensive database of monochromatic optical thicknesses for up to 43 atmospheric molecular species. The model is based on the latest GEISA spectral line catalogue (other spectroscopy databases can be used). Each atmospheric modelled layer is described in terms of a spherical atmosphere and the observation can be in zenith,

nadir or limb looking geometries (including refraction). The user can define a wide variety of surface and earth atmospheric conditions, including the spectral emissivity or albedo functions. Theoretical spectra are computed at high spectral resolution (nominally at $5 \times 10^{-4} \text{ cm}^{-1}$) and can be convolved with various types of instrument line shapes. The model allows coupling with an inversion algorithm for the retrieval of atmospheric constituents. The model in the infrared region (4A/OP-TIR from 600 to 3000 cm^{-1}) has been largely validated^[12, 13, 14] and is the reference radiative transfer model for IASI-MetOp level 1 Cal/Val and level 1 operational processing. Since 2009, NOVELTIS has been working on the extension of the model to the SWIR domain with support from CNES in order to contribute to the preparation of new possible CO₂ satellite missions. Different physical effects have been added for this SWIR extension as Rayleigh scattering, the solar spectrum, the Doppler shift of solar lines, an updated line-mixing for CO₂, multiple scattering modules in order to take into account the contribution of aerosols and cirrus, ... The 4A/OP-SWIR model is being validated by comparison with other existing models and by testing its output versus real measurements from space with GOSAT data and with ground-based (TCCON) and balloon data.

4 - Observation versus calculation

The theoretical spectrum is modelled assuming a Planck function at 6000 K for the solar spectrum at the top of the atmosphere with a solar zenith angle of 72° around the observed location at 68.16° N and 25.69° E. The solar radiation is assumed to be reflected by a surface albedo of 0.1 constant between 4200 and 5500 cm^{-1} . The instrument line shape is considered as a sinc function with a Full Width at Half Maximum (FWHM) of 0.24 cm^{-1} (consistent with the experimental FWHM of 0.25 cm^{-1}). The ground altitude is 323 m with a surface pressure of 977.7 hPa (information from radio-sounding). The three largest contributors to the absorption are H₂O, CO₂ and CH₄. The vertical volume mixing ratio (vmr) profile of the species is provided by a standard climatology and CO₂ is assumed to have a constant vertical mixing ratio profile of 384 ppmv (parts per million by volume). With these assumptions, the theoretical spectrum is calculated and then compared in Figure 7 (in red) to the measured atmospheric spectrum (in black). We observe a general agreement between the two spectra. But the shape of each spectrum is different.

The choice of a constant surface albedo of 0.1 seems to be a too simplistic assumption as compared to the reality. In our case, the Scandinavian region is covered by forests and lakes which are still frozen at the end of April. Moreover the landscape is largely covered by snow. Bowker *et al.* (1985)^[15] have provided typical snow albedo data in the SWIR region, cf. Table 4. Similarly Yokota *et al.* (2003)^[16] have considered different kinds of forest albedo from the USGS database. Using this information, we have modelled the ground surface in the SWIR-balloon Instantaneous Field Of View (IFOV) as covered with the following fractions: $\frac{3}{4}$ by snow and $\frac{1}{4}$ by evergreen forest. Then a more realistic and more appropriate theoretical spectrum is shown in red in Figure 8. Both spectra (measured and calculated) are in good agreement: same shape and intensity. This good comparison demonstrates the necessity to characterize precisely before any retrieval the surface spectral albedo which affects strongly the atmospheric spectra baseline.

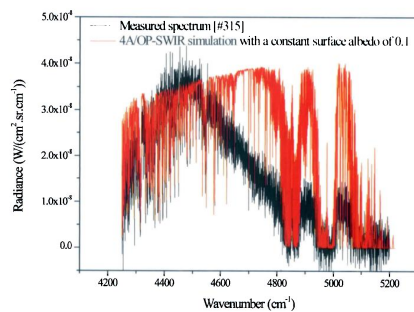


Figure 7. Comparison between the measured spectrum (in black) and the theoretical one (in red) using a constant surface albedo.

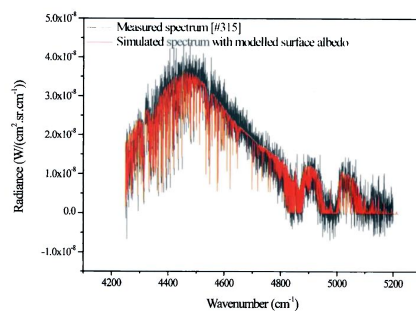


Figure 8. Influence of the spectral dependence of the surface albedo.

Wavelength (μm)	1.900	1.940	1.980	2.020	2.060	2.100	2.140	2.180	2.220	2.260	2.300
Surface albedo	0.029	0.009	0.007	0.007	0.007	0.012	0.025	0.048	0.072	0.074	0.045

Table 4. Typical spectral albedo of snow from Bowker et al. (1985).

5 - Conclusion

This paper has described the balloon-borne instrument SWIR-balloon which is derived from the IASI-balloon instrument (used in the TIR region). In the SWIR spectral range, SWIR-balloon measures the reflected and/or scattered solar radiation. We have performed a post-flight characterization of the QTH lamp associated with a Spectralon diffuser in order to achieve a proper radiometric calibration of the atmospheric spectra. Radiometrically calibrated atmospheric spectra have been derived from 4250 to 5200 cm^{-1} . The 4A/OP-SWIR model, developed by NOVELTIS with support from CNES, has been briefly described and was used to model the theoretical spectrum observed by SWIR-balloon. The comparison between the measured spectrum and the calculated one has demonstrated the strong influence of the surface spectral albedo. In order to improve the quality of the atmospheric spectra for the next balloon flight, we are developing a new acquisition electronic which will allow higher scanning speed (less variation in the IFOV). A new detector (InGaAs with Peltier cooling) will improve the signal to noise ratio and will provide a better coverage of the various GOSAT spectral intervals. We hope to acquire a SWIR imager to better characterize the radiance distribution within the IFOV of the balloon-borne Fourier transform spectrometer in the same spectral range.

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