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Atmospheric Chemistry and Physics

Technical note: First spectral measurement of the Earth's upwelling emission using an uncooled wideband Fourier transform spectrometer

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Abstract. The first spectral measurement of Earth's emitted radiation to space in the wideband range from 100 to 1400 cm^{-1} with 0.5 cm^{-1} spectral resolution is presented. The measurement was performed from a stratospheric balloon in tropical region using a Fourier transform spectrometer, during a field campaign held in Brazil in June 2005. The instrument, which has uncooled components including the detector module, is a prototype developed as part of the study for the REFIR (Radiation Explorer in the Far InfraRed) space mission. This paper shows the results of the field campaign with particular attention to the measurement capabilities of the prototype. The results are compared with measurements taken by IASI-balloon (Infrared Atmospheric Sounding Interferometer – Balloon version), aboard the same platform, and with forward model estimations. The infrared signature of clouds is observed in the measurements.

1 Introduction

The observation of the upwelling emission in the full relevant spectral range, from the mid infrared (MIR) to the far infrared (FIR) region is one important missing measurement for the characterisation of the atmospheric Earth radiation budget.

Up to now instruments operating in the MIR region cover the range above 600 cm^{-1}. The spectral observation of the FIR region, below 600 cm^{-1}, was usually missing or covered only in narrow bands, because of technical limitations pertaining to space-borne spectrometers operating at long wavelengths. No space mission that exploits the FIR for Earth's observation has been made or selected for future operations.

Despite that, the FIR region is very important because most of the radiative cooling of the upper troposphere and lower stratosphere occurs there (Clough et al., 1992, 1995). In clear sky conditions, from one third to one quarter of the total greenhouse forcing is calculated to occur in the FIR (Sinha and Harries, 1995; Brindley and Harries, 1998), and larger effects are expected to be present in cloudy conditions.

The identification and characterisation of the atmospheric properties which modulate the Earth's emission in this spectral region is a mandatory task for global climate change estimations. For instance, several aspects related to water vapour have been debated recently. The absorption continuum must be evaluated with particular attention to its precise characterisation within the rotational band. The extent of direct or feedback processes (Stoker et al., 2001; Philipona et al., 2005), and the radiative forcing due to ice clouds (Rizzi and Maestri, 2003) must be quantified. Wideband spectral measurements covering the FIR region are expected to address the above issues and water vapour profile measurements with more accuracy (Rizzi et al., 2002a).

Atmospheric emission measurements from space in the FIR require high efficiency spectrometers that could be obtained with cooled detectors (Mlynczak et al., 2003), however, cooling systems are difficult and expensive to maintain for long-duration space operations. Recently the development of high-efficiency uncooled pyroelectric detectors has allowed the design of high performance Fourier transform

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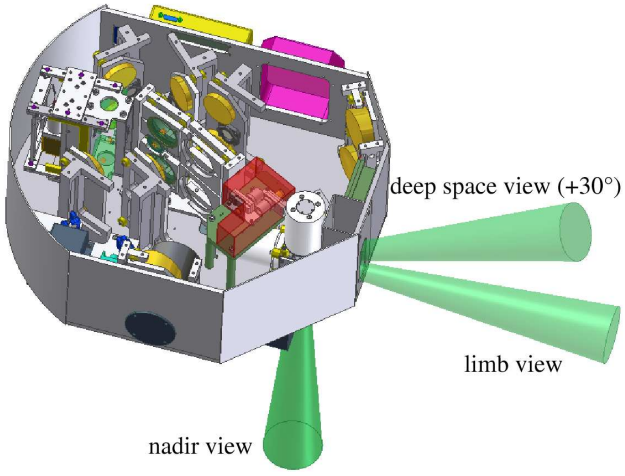

Fig. 1. REFIR-PAD illustration with three different viewing directions.

spectrometers (FTS) (Carli et al., 1999; Formisano et al., 2005), which do not require cooling systems.

The first project addressing these issues for the Earth's atmosphere was the Radiation Explorer in the Far InfraRed (REFIR) project supported by the European Union in 1998–2000 (Rizzi et al., 2002b). The FTS turned out to be the most challenging unit of the mission since it required high technological effort to manufacture and test the new components, most of which were not commercially available. A new FTS was designed with an optical layout that maximises the reliability of the spectrometer for long lifetime space applications and optimises its performances for uncooled operations (Carli et al., 1999; Palchetti et al., 1999).

Some prototyping activity was required in order to study the trade-off among all instrument parameters, to test the optical layout, and to optimise the data acquisition strategy. In 2001, a first prototype named REFIR-BreadBoard (REFIR-BB) (Palchetti et al., 2005) was developed for ground-based measurements and was successfully tested in 2004 from the South of Italy (Esposito et al., 2006). A second prototype named REFIR-Prototype for Applications and Development (REFIR-PAD) was optimised for stratospheric measurements from balloon-borne platforms.

REFIR-PAD was recently flown for the first time on board the Laboratoire de Physique Moléculaire pour l'Atmosphère et l'Astrophysique (LPMAA) gondola hosting the Infrared Atmospheric Sounding Interferometer (IASI) – balloon (Té et al., 2002) during the Equatorial Large Balloons Campaign (ELBC) performed in Brazil in June 2005.

This paper describes the results obtained during the first launch of REFIR-PAD with particular attention to the measurement capability of this instrument. In Sect. 2 the main specifications of the instrument and the laboratory characterisation are summarised. Section 3 is devoted to the results of the field campaign after the level 1 (from raw data to calibrated spectra) analysis. Comparisons are presented with both the IASI-balloon instrument in the MIR region and forward model calculations over the full spectral range.

Table 1. Configuration of the REFIR-PAD instrument for Earth's emission measurements.

Spectrometer specifications	
Interferometer ports	double-input/double-output
Spectral coverage	100–1400 cm^{-1}
Spectral resolution	0.5 cm^{-1}
Optical throughput	0.01 cm^2 sr
Field of view	0.133 rad
Line of sight	nadir, limb, deep space at +30°
Acquisition time	30 s
Absolute calibration error	0.5 K
Beam splitters	Ge-coated Mylar film
Detectors	DLATGS pyroelectric detectors
Size	62 cm diam., 26 cm heigth
Weight	55 kg

2 REFIR-PAD instrument

REFIR-PAD is a compact FTS with double-input/double-output port configuration, designed for being integrated on board different stratospheric platforms for field observations. The instrument has simple mechanical and electrical interfaces for an easy integration on the hosting platforms and it is not temperature stabilised. No telemetry is required, the acquired data are stored on board using pressurised hard disks. Figure 1 shows a diagram of the instrument with the identification of the possible viewing directions: nadir, limb and deep space view at +30° elevation angle.

REFIR-PAD makes use of two uncooled deuterated L-alanine-doped triglycene sulfate (DLATGS) pyroelectric detectors, stabilised at 25°C, which allow to reach the required noise performances. With these detectors photon noise is not a concern: broadband measurements and relatively hot sources can be observed without an increase of the measurement noise. The spectrometer does not require either cooling or temperature stabilisation since the double input/double output configuration allows to control all the input sources. Only the detector unit must be stabilised but the temperature involved is in the range of 25–30°C and the implementation of the control system is very easy. The interferometer can be operated with either polarising or amplitude beam splitters (BS) in order to maximise the performance in different spectral regions.

A summary of the main parameters that characterise REFIR-PAD in the configuration used for the measurements here reported is shown in Table 1.

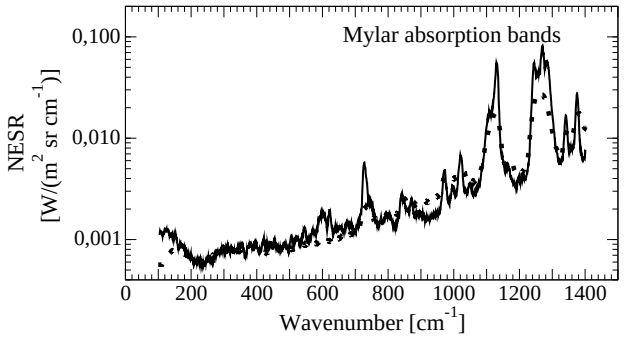

Fig. 2. Comparison between NESR measured during the 30 June 2005 flight (solid line) and lab vacuum tests (dots). The peaks of NESR are due to absorption bands of the Mylar substrate of the beam splitters.

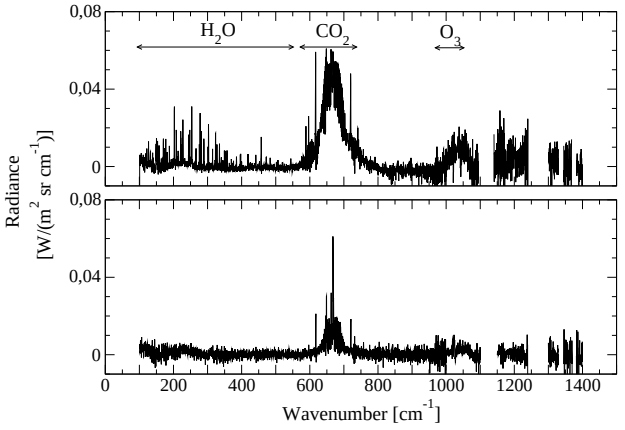

Fig. 3. Measurement of radiance emitted from the deep space (bottom panel) and the atmospheric limb (top panel).

The instrument was operated with Ge-coated Mylar BSs covering the 100–1400 cm^{-1} spectral range with 0.5 cm^{-1} unapodised resolution and 30 s acquisition time. A hot black-body (HBB) at about 80°C and a cold black-body (CBB) at about 20°C were used for calibration. The pointing mirror allows the spectrometer to look alternatively at these two sources during the in-flight calibration.

The instrument was characterised in the laboratory under vacuum conditions before the field campaign (Palchetti et al., 2005). The emission of the onboard BBs was known with a temperature error of about 0.5 K. HBB was used as the input source for the evaluation of the instrument performances. Different measurements of HBB at a pressure of 20 Pa were performed, and the noise equivalent spectral radiance (NESR) was calculated. The results, shown in Fig. 2 (dots), are in the range of 0.5–2 mW/(m^2 sr cm^{-1}), apart from a few narrow bands in which the NESR is larger due to a reduced instrument efficiency caused by the absorption of the Mylar substrates.

3 Results of stratospheric platform observations

REFIR-PAD was flown for the first time on the 30 June 2005 from the Timon airfield, near Teresina, located in the North-Eastern Brazil (in the region of Maranhao) at 5°5′ S, 42°52′ W. The ELBC campaign was led by the French Centre National d'Etudes Spatiales (CNES) in collaboration with the European Space Agency (ESA), within the framework of the Envisat (Environmental Satellite) validation campaigns, and with the Brazilian National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais - INPE).

The LPMAA gondola, that hosted REFIR-PAD, was launched at 3:36 local time and landed 10 h later at 270 km south-west of Timon. The flight reached the planned floating altitude of 34 km for about 8 h.

During the flight, 54 sequences (10 during the ascending leg and 44 at floating altitude) were acquired. Each sequence contained calibration spectra, deep space and limb view measurements, as well as nadir measurements. A total of 540 spectra per each output channel looking at the atmosphere at nadir were measured.

3.1 Instrument performances

The calibration accuracy can be verified using the deep space and the limb views. Since the BBs have temperature of about 290 K and 350 K while the nadir spectra correspond to brightness temperatures that may vary from 200 K to 300 K, the calibration implies an extrapolation. The correctness of this operation is verified by the absence of bias in the measurement of the deep space view where a nearly 0 K signal is expected. Figure 3, for instance, shows an example of the space view (bottom panel) and limb view (top panel) measurements. The measured radiance of the space view is nearly zero apart the contribution of the emission from the rotational water vapour band in the FIR region, the CO_2 at 667 cm^{-1}, and the O_3 at 1055 cm^{-1} that are even more visible in the limb spectrum. In these and in the following figures, the four high-frequency peaks of noise due to a reduced instrument efficiency caused by the absorption bands in the BS substrate (see Fig. 2) are masked with blanks.

The radiance in the 500–560 cm^{-1} spectral window, where no significant emission lines exist in either the space view or the limb view, can be used for an estimate of the absolute calibration error. In this narrow spectral region, the mean difference from zero has allowed to calculate the equivalent brightness temperature uncertainty, shown in Fig. 4 as a function of time, for a brightness temperature of 280 K. During the flight, the calibration error for a single measurement resulted to be less that ± 1 K peak-to-peak with values that oscillate around 0 K with a small bias (the average error is about -0.04 K). This result meets the requirement of an absolute calibration error of 0.1 K identified by Goody et al. (1998) for the identification of climatological fingerprints.

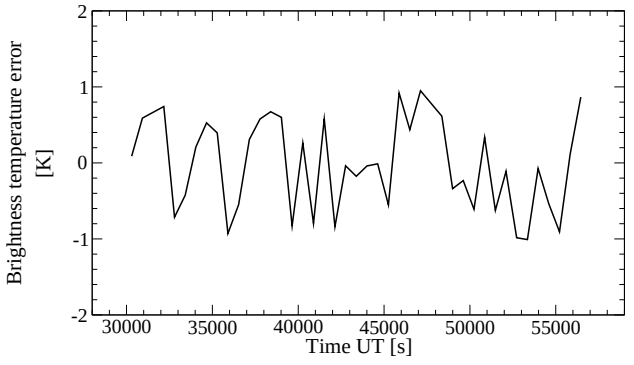

Fig. 4. Brightness temperature error during the flight, defined at 500–560 cm^{-1} for a brightness temperature of 280 K.

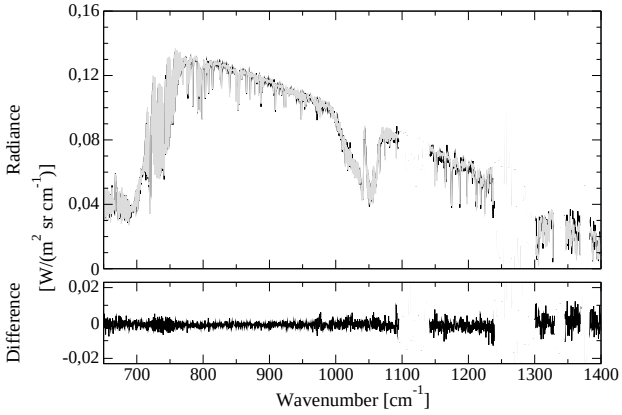

Fig. 5. Comparison of REFIR-PAD and IASI-balloon measurements (top panel – black and grey lines, respectively) and differences (bottom panel) in the common spectral region. Measurements were acquired near the end of flight at 14:49 UTC.

During the flight the instrument underwent a 10 K temperature variation which caused an interferometric misalignment and a corresponding loss of efficiency at high frequency. As a consequence the calibration function varied among measurements and could not be averaged in the data analysis.

We identified some components that can be optimised for future flights. Mainly they are the substrate type and planarity of the beam splitters, and the optical coupling of the detectors with the instrument. Further improvements of the radiometric performances of REFIR-PAD are, therefore, possible and the encouraging results of this first test flight are a good step in this direction.

In order to verify the measurement noise for nadir viewings, the NESR has been determined from the rms of a set of 10 measurements looking at a constant scene from a single sequence. The result, reported in Fig. 2 (continuous line), is comparable to the NESR measured in laboratory conditions (dots) and allows to conclude that the instrument correctly attained its radiometric performances during the flight. The corresponding SNR is about 150 in the region around the CO_2 band and meets the requirement of SNR>100 established in the space instrument feasibility study. This requirement was determined with sensitivity tests (Rizzi et al., 2002a,b) of the retrieval performances of a space instrument. A SNR>100 allows the retrieval of vertical profiles with 2 km resolution of temperature and H_2O with 1–2 K and 20% precision, respectively.

3.2 Comparison with IASI-balloon measurements

The accuracy of REFIR-PAD measurement has been checked against the results obtained with the IASI-balloon instrument sharing the same LPMAA gondola. IASI-balloon is a nadir looking Fourier transform MIR spectro-radiometer. Its spectral resolution is 0.1 cm^{-1}. The radiometric calibration is done by two blackbodies (HBB heated to +30°C and CBB cooled to −20°C).

The two instruments have different ground pixels and this difference must be taken into account in the comparison. The boresights of the two Fourier transform instruments were co-aligned along the nadir direction, on ground before launch, using an IR camera and a warm point-like target. The camera, mounted on board the gondola for temperature characterisation of the observed scene, works in the 7.5–13 μm spectral range and has a rectangular field of view of 0.416×0.312 rad (corresponding, at a float altitude of 34 km, to about 14×10 km on ground), which is sufficiently larger than both the IASI-balloon (0.016 rad) and the REFIR-PAD (0.133 rad) instantaneous fields of view (IFOV). In this way, the IR camera has allowed during the flight the identification of possible differences between the scenes seen by the two instruments.

The comparison is performed in the spectral region from 650 to 1400 cm^{-1} common to the two instruments, with the IASI data resampled to the lower resolution of REFIR-PAD of 0.5 cm^{-1}. The measurements were chosen so that the observed scene was constant within the IFOV of REFIR-PAD (which is the largest of the two) also considering the displacement of about 1.5 km of the ground pixel due to the horizontal drift of the gondola during the comparison. The condition of an homogeneous scene was found only at the end of the flight at 14:49 UTC when clear sky and uniform land coverage occurred during the measurements. The comparison shown in Fig. 5 is good in terms of the absolute difference between the two measurements. In the earlier part of the flight, the comparison is still good in the CO_2 region (where the same atmosphere is observed) but in the atmospheric window the emitted radiance depends on the surface characteristics and on the scattered low-altitude clouds, and differences are observed between the measurements of the two instruments. The larger difference that appears in the 1300–1400 cm^{-1} range is a random effect and it is mainly due to the reduced

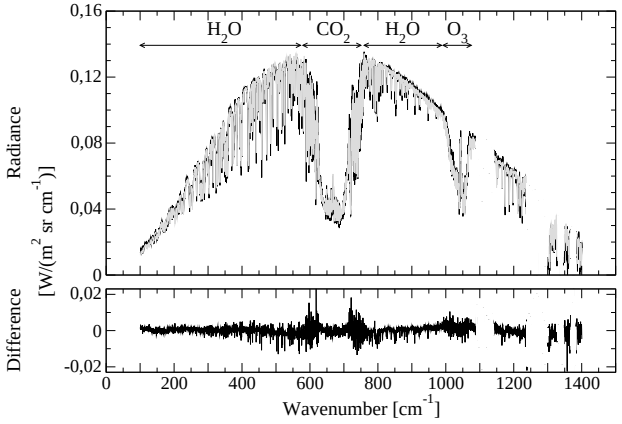

Fig. 6. Comparison of REFIR-PAD with ARTS forward model (top panel) and differences between the two curves (bottom panel).

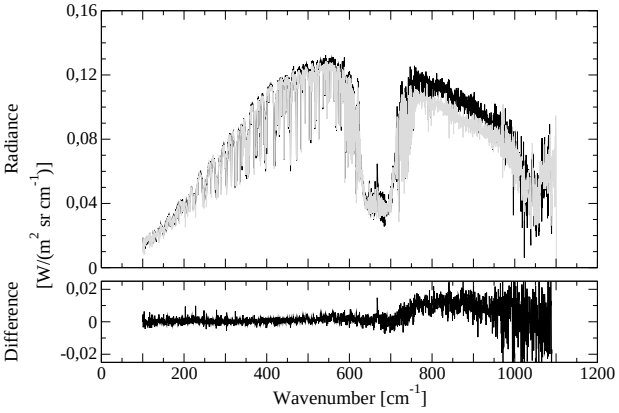

Fig. 7. Comparison between measurements in clear sky and in presence of clouds (top panel – black and grey lines, respectively) and differences (bottom panel).

performances of REFIR-PAD. Indeed, above 1250 cm^{-1} the beam splitter efficiency reduction, caused by both absorption bands of the Mylar substrate and the planarity error, reduced the instrument performances with an increase of the NESR.

3.3 Wideband radiance

Observations over the whole spectral region observed by REFIR-PAD are compared with a simulation obtained by the ARTS (Atmospheric Radiative Transfer Simulator) forward model (Buehler et al., 2005) as a reference. In the simulation we used pressure and temperature values obtained from a balloon sounding performed from the nearest meteorological station (Manaus, 03°08′ S, 59°58′ W) in the same time window of the IASI-balloon/REFIR-PAD flight. The CO_2 volume mixing ratio used was 375 ppm, while the water vapour profile was fitted with a non-linear least-squares routine by using the REFIR-PAD data because sounding measurements were found to have a too large error. The other atmospheric profiles were taken from the tropical scenario of the FASCOD (Fast Atmospheric Signature CODe) dataset (Anderson et al., 1986). The result of the comparison between measured data and forward model, shown in Fig. 6, gives a generally good agreement. The differences that exist are expected to be mostly due to a possible mismatch in the temperature profile.

Other significant new information could be extracted by the REFIR-PAD measurements after the completion of the retrieval analysis. Water vapour and temperature profiles in clear sky conditions can be retrieved by taking advantage of the wideband coverage and of the new water vapour measurements in the FIR rotational band (Lubrano et al., 2000; Rizzi et al., 2002a). The retrieval of vertical concentration profiles is beyond the aim of this work and it will be covered in a future paper.

The wideband emitted radiances can also be affected by clouds, which are detected by the IR camera co-aligned with IASI-balloon and REFIR-PAD. Figure 7 shows the difference in the spectral radiance measured in clear sky and cloudy conditions during the passage of a cloud through the instrument IFOV. The wideband spectrally resolved coverage has allowed a quantification of the effect of the cloud in the whole emission spectrum. In this case, we see that the cloud causes a cooling in the 700–1000 cm^{-1} region and does not affect the atmospheric emission below 500 cm^{-1}.

The different behaviour in the two spectral regions is an important piece of information about cloud characteristics that can be exploited in a comprehensive retrieval approach of the REFIR-PAD measurements. In particular, REFIR-PAD is expected to be sensitive to the properties of high altitude cirrus clouds that have important signatures in the 200–500 cm^{-1} range (Evans et al., 1999; Yang at al., 2003).

4 Conclusions

The first spectral measurement of the wideband thermal emission of the Earth's atmosphere was performed from a stratospheric balloon using the REFIR-PAD instrument in the 100–1400 cm^{-1} spectral range at 0.5 cm^{-1} resolution.

An important technical feature of these new measurements is the use of an uncooled instrument with uncooled detectors. An important scientific feature is the observation of the FIR component of the emitted radiation, which can not be neglected for a proper modelling of long term climate changes. The combination of the two features opens new perspectives in space-borne observations of the atmosphere.

The measurements allow the clear identification of the effects of clouds and the vertical distributions of water vapour and temperature. A comprehensive work is in progress for the simultaneous quantification of the different components of the system.

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