The Radiation Explorer in the Far InfraRed prototype: technical overview and measurement performance

Luca Palchetti, Giovanni Bianchini

Italian National Research Council
Institute for Applied Physics
"Nello Carrara" - Florence (Italy)

L.Palchetti@ifac.cnr.it
Importance of the FIR spectral region
Water vapour and cirrus

- The FIR region can provide unique information on WV and cirrus clouds radiative effects with sensitivity to microphysics
- The FIR is strongly sensitive to mid-upper level tropospheric humidity that produces a peak in the cooling rate of the atmosphere

![Spectral cooling rate](image)

![H₂O Retrieval errors](image)

FORUM/EFTWVAC
ESA proposals
Historical overview
The REFIR project

Radiation Explorer in the Far InfraRed
Spectral characterization of the emitted radiance in the 100-1100 cm\(^{-1}\) range

- REFIR feasibility space mission, EU 1997-2000
- REFIR feasibility for Small Scientific Missions, ASI 1998-2001
- BB pre-development, ESA 2001-2003
  - ADGB-Dip. Fisica, Univ. Bologna, Italy
  - PI Rolando Rizzi
  - Selex-Galileo, Campi Bisenzio, Italy
  - Blackett Laboratory, Dep. Physics, ICSTM, London, UK
  - CNRS-SNCMP, Toulouse, France
  - Space Science Dep., CCRLC-RAL, Chilton, UK
  - DIFA, Univ. Basilicata, Potenza, Italy
  - Dip. Fisica, Univ. La Sapienza, Roma, Italy

- REFIR-BB laboratory applications, UniBas, IFAC 2000-2001
- REFIR-PAD ground-based and stratospheric balloon, IFAC 2003-present
  - IFAC-CNR, Firenze, Italy
  - DIFA, Univ. Basilicata, Potenza, Italy
  - IMAA-CNR, Potenza, Italy
  - ADGB-Dip. Fisica, Univ. Bologna, Italy

- Recent proposals for space missions:
  - FORUM
  - EFTWVAC
The REFIR-PAD prototype
Radiation Explorer in the Far-InfraRed – Prototype for Applications and Development

- Developed in 2003-2004
- Fourier Transform Spectrometer
- Broadband Ge on PET beam splitters and DLATGS pyroelectric room-temperature detectors
  - Spectral coverage = 100-1400 cm\(^{-1}\)
  - Resolution 0.25 cm\(^{-1}\) max. double-sided
  - NESR in the range 0.8-2.5 mW/(m\(^2\) sr cm\(^{-1}\)) with 30 s. acquisition time
- Small Payload: 62 cm dia., 55 kg weight, 50 W avg power
Optical configuration of interferometer

- 2 input / 2 output ports
- Martin-Puplett (polariser BSs) or Mach-Zehnder (amplitude BSs) interferometer
- Tilt and lateral shift compensation of moving mirrors
- 4x folding OPD
Two levels interferometer

- Folding around the moving mirror to obtain two levels containing input ports (lower level) and output ports (upper level)
- Horizontal tilt compensation
Broadband Beam Splitters

- Photolithographic wires on PET
- Single PET/PP layer
- Ge-PET/PP bilayer

20oct03  air 21°, 48%RH, RBB = 21°, HBB=81°, 20 meas.

Efficiency [au]

Ratio

Wavenumber (cm^{-1})

Germanium on 2 μm Mylar substrate vs. Mylar alone

Raw spectrum (a.u.)

Wavenumber (cm^{-1})
Wideband beam-splitters design

- Bilayer structures

BS Efficiency estimated for FORUM, Mylar-Ge, 25 deg of incidence

$\text{eff\_mylar-germanium\_OSA-FTS.agr}$

![Graph showing efficiency vs. wavenumber for different Ge and Mylar thickness combinations.](image)

- Efficiency 4RT
- Wavenumber ($\text{cm}^{-1}$)
- Various curves representing different Ge and Mylar thickness combinations.
REFIR-PAD FTS optical layout

CBB or space view

Moving RTMU

BSU

Focal planes

HBB

RBB

Atmosphere

Pointing Mirror
Interferogram Sampling

DLATGS pyroelectrics
Winston cones

Equal Time Sampling
Filtering and Resampling
Uncalibrated Spectra

Hot blackbody source ($T_M = 347$ K)  
$T_R = 302$ K, $T_{BS} = 302$ K

Channel 1

Channel 2

Amplitude (a. u.)

Phase (radian)

Wavenumber (cm$^{-1}$)
Scanning mirror performances

![Image of a scanning mirror]

**Graphs:**
- **RTMU tilt error**
  - **Vertical**
  - **Horizontal**
- **REFIR-PAD, Scan mirror speed**
- **Speed error power spectrum**

Luca Palchetti (IFAC-CNR)
Radiometric calibration

- Uncalibrated complex spectrum $S(\sigma)$ given by:

$$S(\sigma) = F_1(\sigma)L(\sigma) - F_2(\sigma)L_{RBB}(\sigma)$$

- Calibration with 2 views of reference sources: HBB, CBB. With $L_{RBB}$ is constant we have:

$$L(\sigma) = \mathbb{I}R \left\{ \frac{S(\sigma) - S_{CBB}(\sigma)}{S_{HBB}(\sigma) - S_{CBB}(\sigma)} \cdot (L_{HBB}(\sigma) - L_{CBB}(\sigma)) + L_{CBB}(\sigma) \right\}$$

- The used optical layout allows the best way to have access to all the sources and with minimum phase errors.
Black-body calibration sources

- RBB for reference input
- HBB/CBB for calibration
- Cylinder + cone cavity
- Xylan© coated surface
- Emissivity estim. ~ 0.99
- PT100 temperature meas.
- $\Delta T < 0.3$ K

Thermal images

- RBB cooled
- RBB heated
- HBB/CBB heated
NERS

Nadir looking

\[ NESR = \sqrt{\frac{1}{N}} + \frac{2}{n} \left( \frac{S_{h} - S_{c}}{S_{h} - S_{c}} \right)^{2} \frac{\Delta S}{F_{1}} \]

Zenith looking
Calibration Error

\[ \Delta L = \sqrt{\Delta B_r^2 + \left( \frac{S}{S_h - S_c} \right)^2 (\Delta B_h^2 + \Delta B_c^2)} \]

Estimate with \( \Delta T_{BB} = 0.3 \) K

![Graph showing calibration error with wavenumber (cm\(^{-1}\)) on the x-axis and calibration error (W/(m\(^2\) sr cm\(^{-1}\)) on the y-axis for different angles and zenith.]
# The REFIR-PAD Experiment

## Balloon-borne and Ground-based Campaigns

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Meas. time (min)</th>
<th>Spectral band (cm⁻¹)</th>
<th>Resol. (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Teresina, Brazil</strong> *</td>
<td>30 June 2005</td>
<td>8:05–15:48</td>
<td>6.4</td>
<td>100–1100</td>
</tr>
<tr>
<td><strong>Monte Morello, Italy †</strong></td>
<td>6 February 2006</td>
<td>16:26–17:58</td>
<td>5.1</td>
<td>350–850</td>
</tr>
<tr>
<td>**Monte Gomito, Italy **‡</td>
<td>13 March 2006</td>
<td>16:20–9:30 (+1 d)</td>
<td>6.1/9.9</td>
<td>350–1100</td>
</tr>
<tr>
<td><strong>Testa Grigia, Italy §</strong></td>
<td>4 March 2007</td>
<td>19:20–23:39</td>
<td>5.1</td>
<td>240–1400</td>
</tr>
<tr>
<td></td>
<td>5 March 2007</td>
<td>17:54–0:43 (+1 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>11 March 2007</td>
<td>16:22–2:06 (+1 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 March 2007</td>
<td>8:44–15:45</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 March 2007</td>
<td>17:55–23:02</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13 March 2007</td>
<td>9:15–14:03</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13 March 2007</td>
<td>18:21–8:04 (+1 d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Breuil-Cervin, Italy$</strong></td>
<td>15 March 2007</td>
<td>15:14–23:09</td>
<td>5.1</td>
<td>350–1400</td>
</tr>
<tr>
<td><strong>Pagosa Springs, USA¶</strong></td>
<td>22 April 2009</td>
<td>17:15–19:58</td>
<td>5.1</td>
<td>350–1400</td>
</tr>
<tr>
<td></td>
<td>24 April 2009</td>
<td>11:30–17:58</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>27 April 2009</td>
<td>12:34–18:05</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>28 April 2009</td>
<td>14:09–17:59</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>29 April 2009</td>
<td>19:04–23:29</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cerro Toco, Chile</strong> ‖</td>
<td>from 21 August 2009</td>
<td>-</td>
<td>5.1</td>
<td>100–1500</td>
</tr>
<tr>
<td></td>
<td>- - - 37 days - - - to 24 October 2009</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* OLR from balloon at 34 km, 5.078° S, 42.874° W
† DLR from ground at 610 m a.s.l., 43.844° N, 11.246° E
‡ DLR from ground at 1892 m a.s.l., 44.128° N, 10.644° E
§ DLR from ground at 3480 m a.s.l., 45.933° N, 7.7° E
¶ DLR from ground at 1990 m a.s.l., 45.933° N, 7.6° E
$ DLR from ground at 2329 m a.s.l., 37.28° N, 107.08° W
‖ DLR from ground at 5340 m a.s.l., 23° S, 68° E
Atmospheric measurements and STD

Cerro Toco 2009
From clear sky to cirrus cover

![Graph showing atmospheric measurements and STD](image-url)
Products

TOA irradiance Error = 1.3 W/m\(^2\)

OLR accuracy = 0.3K

VMR\(_{H2O}\) error = 22-35% from 0 to 17 km

Retrieval of PWV, error = 5%
FIR ground-based measurement opportunity 2011-2013

- Deployment of REFIR-PAD at the Italian-French station of Concordia on the Antarctic plateau (Dome-C) on Dec. 2011

PNRA-Programma Nazionale di Ricerche in Antartide

Dome C - Antarctica
(74°30’ S, 123°00’ E, 3.280 m)

PRANA project

- Scientific Objective
  - Study of the radiative properties of WV and clouds in the FIR spectral region

- Available instruments
  - REFIR-PAD
  - Backscatter LIDAR
  - Radiosoundings
FORUM and EFTWVAC
Main mission objectives

- Study of the forcing/feedback effect on the climate system of the atmospheric water, in the form of both vapour and clouds, by measuring from space on a global scale for the first time the spectrally-resolved emission of the Earth in a broad spectral range that includes the FIR region.

- Far Infrared Outgoing Radiation Understanding Monitoring
  - Polar satellite

- Emission Fingerprints of Tropical Water Vapour and Clouds
  - ISS
Space mission opportunities

**FORUM - 2010-11**  
ESA – Earth Explorer Opportunity Mission EE8 results

- FORUM was in a short list of 4 but it was not financed. ESAC recognises “the very high scientific interest in a radiation mission, measuring the far infra-red spectrum for the first time and examining important dependencies on cirrus cloud properties”.

- ESAC committee recommended that ESA initiate a study, to better identify the benefits of a FORUM-type mission (wavelength coverage, radiometric performance, etc.). This is under investigation.

**EFTWVAC - 2011-12**  
ESA – AO for ISS Experiments relevant to study of Global Climate Change

- A national support for the deployment on the ISS is also under investigation.
Specific objectives
Instrument requirements

- Spectrally resolved observation of the OLR for the attribution of the changes of total Earth irradiance to the underlying climatic parameters (H\textsubscript{2}O, CH\textsubscript{4}, O\textsubscript{3}, etc.)
  - Spectral range = 100-1600 cm\textsuperscript{-1}
  - Radiometric accuracy = 0.1 K
  - Observing mode = nadir

- Determination of the atmospheric state (improved WV profiles in the upper troposphere) and assessment of its relationship with the LW spectral radiance and irradiance.
  - OPD = ± 2.5 cm (0.2 cm\textsuperscript{-1} resolution)
  - NESR = 0.2 mW/m\textsuperscript{2}-sr-cm\textsuperscript{-1}
  - Max resolving power, R\text{max} = 2500

- Improved cloud characterisation using the new information present in the FIR, and assessment of the LW contribution of clouds to the ERB.
  - Ground pixel = 12 km
  - Thermal imager (10.5-12.5 μm) for identifying pixel contamination
Imaging capability

- Resolution requirements
  - 0.2 cm\(^{-1}\) (H\(_2\)O retrieval) in 100-500 cm\(^{-1}\) → Rmax = 2500
  - 0.4 cm\(^{-1}\) (T retrieval) in 500-800 cm\(^{-1}\) → Rmax = 2000
  - 1 cm\(^{-1}\) (fingerprints) in 800-1600 cm\(^{-1}\) → Rmax = 1600
- Aperture limit on Rmax for a FOV = 7 pixels (optical throughput of single pixel = 0.01 cm\(^2\) sr)
  - Limit on Rmax-central = 17000
  - Limit on Rmax-off axis = 2100
Performances

Expected radiometric precision

- NESR requirement (blue curve) compared to the estimation performed for the FIR FTS of FORUM/EFTWVAC based on REFIR-PAD performances
FTS optomechanical design

- FTS specifications
  - 14 uncooled pyroelectrics ($D^* \approx 10^9 \text{ cm}^{\frac{1}{2}} \text{Hz/W}$)
  - Sampling rate = 1.25 kHz
  - Acquisition time = 32 s
  - Weight = 70 kg
  - Power = 40 W
  - $T_{\text{BB}}$ abs. cal. = 50 mK
- EI = Embedded Imager

\[1 \text{ m}\]
Acknowledgements and References

**Acknowledgements**

- Financial support for ESA proposal provided by the project POR-CREO-FESR-2007-2013, CTOTUS of the Italian Regione Toscana.

**References**

- G. Bianchini, et al., Water vapor sounding with the far infrared REFIR-PAD spectroradiometer from a high-altitude ground-based station during the ECOWAR campaign, J. Geophys. Res. 116, D02310, 2011.