Spectrally resolved measurement of the downwelling longwave radiance from an high-altitude station

*Spectroscopic issues in the data analysis*

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Outline

The REFIR instrument

• Overview of the REFIR-PAD spectroradiometer
• Level 1 and level 2 data analysis of REFIR-PAD measurements

The winter 2007 ground-based campaign

• Retrieval of atmospheric variables from REFIR-PAD data

Spectroscopic issues in the data analysis

• Three case studies in clear sky conditions, varying PWV
• Comparison with residuals from balloon-borne measurements

Conclusions
The REFIR-PAD instrument

Radiation Explorer in the Far InfraRed - Prototype for Application and Development
# REFIR-PAD characteristics

## Instrument specifications:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Instrument type</td>
<td>Mach-Zender non-polarising FTS</td>
</tr>
<tr>
<td>Beam splitter</td>
<td>Ge-coated Mylar (0.85 µm/2 µm)</td>
</tr>
<tr>
<td>Spectral bandwidth</td>
<td>100-1400 cm(^{-1})</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>up to 0.25 cm(^{-1}) (double-sided)</td>
</tr>
<tr>
<td>Optical throughput</td>
<td>0.01 cm(^2)sr</td>
</tr>
<tr>
<td>Field of view</td>
<td>133 mrad</td>
</tr>
<tr>
<td>Detector type</td>
<td>Pyroelectric (DLATGS)</td>
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<tr>
<td>Acquisition time</td>
<td>30-120 s</td>
</tr>
<tr>
<td>Acquisition frequency</td>
<td>20 kHz</td>
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<tr>
<td>Weight</td>
<td>55 kg</td>
</tr>
<tr>
<td>Power consumption</td>
<td>~50 W</td>
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</tbody>
</table>

→ Room temperature operation ←
Level 1 data analysis

- Data resampling on reference laser fringes (Brault)
- Transformation and low-resolution phase correction
- Calibration through on-board reference blackbodies
- Estimation of random (NESR) and systematic (calibration error) components of measurement uncertainty

ACPD, 8, 367-401, 2008
Sample spectra

Typical Downwelling Longwave Radiance spectra resulting from 10-minute REFIR-PAD acquisition sequences, 0.5 cm$^{-1}$ resolution

- Wide spectral range, $\sim 300 - 1100$ cm$^{-1}$, depending on water vapour content for the FIR region
- SNR better than 100 in the FIR for a single acquisition sequence (4 atmospheric spectra + 4 calibrations)
Level 2 data analysis

Forward model:

- LBLRTM version 11.3 radiative transfer model
- HITRAN 2004 spectroscopic database with 2006 updates (H$_2$O, HNO$_3$, N$_2$O)
- MT_CKD version 2.1 continuum model

Retrieval code:

- Least $\chi^2$ routine based on the MINUIT function minimization libraries (CERN)
- no constraints on fitted variables
Sensitivity to parameters

Analysis of Jacobian matrices for H$_2$O and Temperature:

- Spectral range used for retrieval: 300-650 cm$^{-1}$
- Data show sensitivity to atmospheric parameters up to 7-8 km
Vertical resolution

SVD decomposition of H₂O and T Jacobians, MLW standard atmosphere

Singolar Value Decomposition of Jacobian matrices:

- Main retrieval product (maximum sensitivity): total Precipitable Water Vapour (PWV)
- Vertical resolution 1-2 km: limited information on vertical profiles (2-3 points per variable)
- Presence of clouds give an extra atmospheric variable to be considered in the retrieval
Fitting without clouds

No cloud contribution in forward model → overestimation of “high” water vapour → wrong PWV
Effect of clouds on retrieval

Measurements were performed only in visually clear sky conditions → possible problem due to subvisible cirrus clouds

- Cloud model included in forward model (LOWTRAN 7)
- Only one parameter retrieved: cloud optical density
- No sensitivity to cloud geometry if cloud layer above 7-8 km
Fitting with clouds

Added effect of clouds in forward model $\rightarrow$ correct PWV and vertical structure

![Graph showing radiance vs. wavenumber for measurement and data fit with clouds.](image-url)
The ECOWAR-COBRA campaign

ECOWAR: Earth COoling by WAter vapour R emission
COBRA: Campagna di Osservazioni della Banda Rotazionale del vapor d’Acqua

Spectrally resolved observations of Earth’s emission spectrum in the water vapour rotational band (17-50 micron) to test models of atmospheric radiative transfer
(Italian Ministry of University and Research, DM n. 287 23 feb. 2005, project # 2005025202)

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Thanks to the city of Valtournenche
REFIR-PAD at Testa Grigia

- Instrument installed in a C.N.R. high-altitude station in the italian-swiss Alps (3480 m. a.s.l.)
- During the campaign > 60 h of measurements on 7 days were acquired
- Measurements were performed in cold, dry conditions
- Meteorological conditions: mostly clear sky, subvisible cirrus present in few cases, varying PWV
Sample retrieval

REFIR-PAD PWV measurements, Testa Grigia, 3/2007

REFIR-PAD retrieval results for PWV, vertical water vapour structure and clouds optical density during the 2007 ECOWAR-COBRA campaign

- PWV values measured ranging from < 0.5 mm to 3-3.5 mm
- No clouds were detected in about 70% of the measurement time
Clear-sky case studies

Three case studies featuring:

- Three different PWV values measured: 0.5 mm, 2 mm and 3 mm
- Almost constant PWV values for the duration of about 20 sequences (≈ 3 h)
- Clear sky condition as detected by the retrieval process
Fitting residuals

REFIR-PAD fitting residuals
Average residuals from about 20 independent fits each

Systematic uncertainty
LBLRTM fits, no cloud, 300-650

PWV = 0.5 mm

PWV = 3 mm

PWV = 2 mm

Wavenumber (cm$^{-1}$)
Validation: synthetic spectra

Test with simulations:

- Synthetic spectra using the same forward model used for retrieval
- Water vapour and temperature profiles interpolated from soundings
Residuals with synthetic spectra

REFIR-PAD fitting residuals
Average residuals from about 20 independent fits each

Systematic uncertainty
LBLRTM fit of simulated data
Sensitivity to continuum

Fitting residuals - no cloud
REFIR-PAD fitted spectra average residuals (about 20 spectra each)

Wavenumber (cm⁻¹)

300 350 400 450 500 550 600 650

Fitting residuals - no cloud
REFIR-PAD fitted spectra average residuals (about 20 spectra each)
Balloon-borne nadir measurements

Stratospheric balloon launched in July, 2005 from Teresina, in the state of Piauí (North-East Brazil), 5.1 S 42.9 W, in mostly clear sky conditions.

Acknowledgements: The CNES balloon launch team.

Flight duration of about 9.5 h, of which 7.5 at the floating altitude of 34 km for a total distance covered of 270 km.

First spectrally resolved measurement of the OLR in the far-infrared with uncooled detectors

Nadir vs. zenith radiance

REFIR-PAD sample measurements, radiance units

- Nadir (34 km, tropical)
- Zenith (3.5 km, mlw dry)
- Zenith (3.5 km, mlw wet)
Nadir vs. zenith residuals

REFIR-PAD residuals comparison

Teresina 2005 (all flight, multiplied by -2.0) vs. Testa Grigia 2007 (18 sequences from 05/03)
Nadir vs. zenith radiance

REFIR-PAD sample measurements, radiance units

Radiance (W/m² sr cm⁻¹)

Wavenumber (cm⁻¹)

zenith (3.5 km, mlw dry)
zenith (3.5 km, mlw wet)
nadir (34 km, tropical), -2.0x
Conclusions

Spectroscopic issues in the far-infrared

• Analysis of REFIR-PAD measured downwelling radiances show evidence of systematic effects above measurement uncertainty
• Tests performed suggest that effects are not due to the instrument itself nor due to the analysis method
• Both continuum model and spectroscopic database issues could be present, solving which could improve greatly REFIR-PAD data products quality
Spare slides
Instrumental line shape

Equation: \( \text{ILS}(\sigma) = 0.9 \text{Sinc}(\sigma) + 0.1 \text{Sinc}^2(\sigma) \)

Instrumental line shape as a linear combination of sinc and sinc²
Combination coefficient fitted and averaged over multiple spectra
Residuals in literature

Clough, ASSFTS 2003
PWV $\approx 3$ mm

Clough, IRS 2004
PWV $\approx 0.2$ mm
Residuals comparisons

REFIR-PAD fitting residuals

Average residuals from about 20 independent fits each

Systematic uncertainty
LBLRTM fits, no cloud, 300-650

AERI, SHEBA 10/1997, PWV = 3.5 mm, LBLRTM, MT_CKD 1.0

AERI, ARM-NSA 03/2001, PWV = 0.2 mm, LBLRTM, MT_CKD 1.0

PWV = 0.5 mm

PWV = 3 mm

PWV = 2 mm

Wavenumber (cm$^{-1}$)

$W/m^2sr$ cm$^{-1}$