H$_2$O/CO$_2$ spectroscopy and forward/inverse radiative transfer modelling assessment in the longwave thermal band with FTIR instrumentation and perspectives for FORUM.

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OUTLINE

• Review of work performed by my group on the issue of validation and consistency of spectroscopy and forward modelling with emphasis on H₂O and CO₂
  • Radiative Transfer basics, σ-IASI-as
  • Inverse modelling, δ-IASI
  • Application to REFIR and I-BEST (H₂O continuum absorption) and perspective for FORUM
  • Application to IASI
    • CO₂ spectroscopy and line mixing consistency and perspective for FORUM
    • The issue of surface emissivity and perspective for FORUM

Conclusions
Forward modelling

$\sigma$-IASI
σ-IASI-as: spectral data base

- σ-IASI uses LBLRTM share the Atmospheric Environmental Research or AER v3.4 line parameter data base with the continuum absorption MT_CKD 2.7 (see [http://rtweb.aer.com/lblrtm_frame.html](http://rtweb.aer.com/lblrtm_frame.html)). The AER line data base adopts HITRAN2012 with exceptions for H₂O, CO₂ and O₂, for which AER v3.4 adopts also its own spectroscopic parameters and modelling.
- The model σ-IASI also includes a proper treatment of H₂O self-broadening
Summary of Features

User defined input to the code.
For the parameters listed below the code calculates Analytical Jacobian derivative matrices

Atmosphere: T and Gas concentration profiles:
- H₂O
- HDO
- CO₂
- O₃
- N₂O
- CO
- CH₄
- SO₂
- HNO₃
- NH₃
- OCS
- CF₄

AEROSOLS:
- SEA SALT
- DESERT DUST
- BLACK CARBONS
- ORGANIC HAZE
- METEORIC DUST
- H₂SO₄ DROPLETS
- AMMONIUM SULFATE
- HEMATITE DUST
- DESERT SAND (SILICA)
- VOLCANIC ASH

Surface:
- Ts
- Emissivity Spectrum

Spectroscopy:
- H₂O self-continuum coefficients
- H₂O foreign-continuum coefficients
- CO₂ continuum coefficients

CLOUDS:
- WATER DROPLETS
- ICE CRYSTALS
Level 1 data: Example of Upwelling and Downwelling Spectral Radiance. $\sigma$-IASI covers the spectral range 5 to 2760 cm$^{-1}$
Level 1 Data: 3 Different Instruments

IASI-NG radiance \( [W \text{ m}^{-2} \text{ sr}^{-1} (\text{cm}^{-1})^{-1}] \)

IASI radiance \( [W \text{ m}^{-2} \text{ sr}^{-1} (\text{cm}^{-1})^{-1}] \)

IASI and MTG-IRS radiance \( [W\text{m}^{-2}\text{sr}^{-1}(\text{cm}^{-1})^{-1}] \)

Wave number (cm\(^{-1}\))
Inverse Modelling

δ-IASI
We have developed a Level 2 processor for IASI. We use the whole IASI spectral coverage (8461 channels) and simultaneously retrieve parameters and gas species.
IASI LEVEL 2 PROCESSOR: Dimensionality reduction is achieved through **Random Projections**

where the elements of the matrix $\Phi$ are identically distributed random variables from a Gaussian density probability function with zero mean and variance $1/M$, where $M$ is the number of elements of the radiance $R$.

$$c = \Phi R$$

$$\left(S_a^{-1} + \tilde{K}^t\tilde{S}_o^{-1}\tilde{K}\right)x = \tilde{K}^t\tilde{S}_o^{-1}\tilde{y}$$

$$\tilde{y} = \Phi y; \quad \tilde{K} = \Phi K; \quad \tilde{S}_o = \Phi S_o \Phi^t$$

Usual equations for Optimal Estimation are transformed accordingly.
Random Projections are used for dimensionality reduction

\[ c_i = \sum_{j=1}^{M} \phi_{ij} R_j; \ i = 1, \ldots, m; \ j = 1, \ldots, M; \quad m \ll M \]

Where the elements \( \phi_{ij} \) are independent and identically distributed random variables from a Gaussian density probability density function with mean zero and variance \( 1/M \)

In our case \( R_j \) is the element of radiance vector of size \( M \).
The radiance vector is not sparse, so we do not expect a good performance for the reconstructed signal. However, we are not interested in the reconstructed signal since we can directly perform the retrieval within the c-space.
Random Projections

The transform has the *Restricted Isometry Property* (RIP)


\[1 - \delta \leq \frac{\|\Phi R\|}{\|R\|} \leq 1 + \delta\]

For some \(\delta > 0\)

The transform has the restricted isometry property, and preserves the information content in the spectrum.
We expect RP to be more effective than other dimensionality reduction tools because with RP we can randomize the forward model error or bias (1/3)

\[ R = r_{th} + \varepsilon \quad \text{Data equation} \]

- where \( R \) is the radiance vector (of size \( M=8461 \)), \( r_{th} \) is the true signal and \( \varepsilon \) is a Gaussian noise term with zero mean and known covariance, \( S_\varepsilon \)

- Within a physical inverse scheme the true signal is modelled through the Radiative Transfer Equation, which relates the atmospheric state vector, \( \nu \) to the spectral radiance through a functional relationship
  \[ r_{th} = F(\nu) + b, \]

- Therefore, we have

\[ R = F(\nu) + \varepsilon + b \]

The Bias is highly systematic, no zero mean, and is not Gaussian
We expect RP to be more effective than other dimensionality reduction tools because with RP we can randomize the forward model error or bias (2/3)

• Under RP the whole noise term transform as the radiance vector

\[ \tilde{\epsilon} = \Phi(\epsilon + b) \]

• \( \tilde{\epsilon}_i = \frac{1}{M} \sum_{j=1}^{M} \Phi_{ij} \epsilon_j + \frac{1}{M} \sum_{j=1}^{M} \Phi_{ij} b_j; \ i = 1, \ldots, m \)

\[
\begin{cases}
E(\tilde{\epsilon}_i) = 0; & i = 1, \ldots, m \\
E(\tilde{\epsilon}_i \tilde{\epsilon}_j) = 0; & i = 1, \ldots, m; j = 1, \ldots, m; i \neq j \\
E(\tilde{\epsilon}_i^2) = \tilde{s}^2 = \frac{1}{M} \sum_{j=1}^{M} s_{\epsilon,j}^2 + \frac{1}{M} \sum_{j=1}^{M} s_{b,j}^2; & i = 1, \ldots, m
\end{cases}
\]

Instrument noise variance

Forward model bias power
We expect RP to be more effective than other dimensionality reduction tools because with RP we can randomize the forward model error or bias (3/3)

- Under RP the whole noise term, with no-zero mean and non-Gaussian distribution, collapses to a single scalar variance

\[S_{\varepsilon+b} \rightarrow \tilde{s}^2 \times I_m\]

- \(M \times M\) \((8461 \times 8461) \rightarrow 1\)
Demonstration of random projections applied to the retrieval problem of geophysical parameters from hyper-spectral infrared observations

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CO₂ spectroscopy and forward/inverse radiative transfer modelling in the thermal band using IASI spectra.

C. Serio A,1,2, G. Masiello A, C. Camy-Peyret B, G. Liuzzi C

https://doi.org/10.1016/j.jqsrt.2016.10.020


Event: SPIE Remote Sensing, 2018, Berlin, Germany
Some Results

H$_2$O Continuum
**ECOWAR**: Earth COoling by WAter vapour Radiation

**COBRA**: Campagna di Osservazioni della Banda Rotazionale del vapor d’Acqua

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**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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- Centro Nazionale di Meteorologia e Climatologia Aeronautica
- City of Valtournenche (Breuil-Cervinia)
Night 10-11 March 2007
I-BEST (DTGS)

Serie di 60 spettri (2 min 18 sec/spettro), 20:59 alle 23:17 ora locale

wave number (cm$^{-1}$)

Spectrum (Watt/m$^2$.cm$^{-1}$)
Night 12-13 March 2007, Example of spectrum recorded by the I-BEST (MCT detector)
Night 12-13 March 2007
REFIR/PAD, Testa Grigia 3500 m
BASIL

Cervinia, Lat: 45°55'57" N, Long: 7°37'42" E, Site elevation: 1990 m

12 March 2007 – Water Vapour mixing ratio

Δz = 300 m, ΔT = 1 min
Cooling Rates

- Cooling rate computed for the U.S. Standard atmosphere (Left)
- Difference introduced by new coefficients in the spectral range between 240 – 590 cm\(^{-1}\) (new coefficients – MT_CKD 2.1) (Right)
- Differences are positive lower in the Atmosphere.
Validation of the water vapor continuum MT_CKD version 2.5.2
How important is the adjustment of line parameters performed with the compilation AER 3.0? Is this adjustment crucial to perform a good fit of observations within the spectral range 350 to 600 cm$^{-1}$?
Fig. 7. Retrieved continuum coefficients using the two data sets and the two different line compilations considered in this work (tabulated values are available on request from the authors).
Validation of H$_2$O continuum absorption models in the wave number range 180–600 cm$^{-1}$ with atmospheric emitted spectral radiance measured at the Antarctica Dome-C site

Giuliano Liuzzi, Guido Masiello, Carmine Serio, Luca Palchetti, and Giovanni Bianchini

With the objective of getting a better insight into understanding whether or not AER line database 3.2 improves over the current HITRAN version, we have found that there is experimental evidence for the AER line compilation. This evidence justifies the need of adjusting the water vapour line half widths in the spectral range 350 to 600 cm$^{-1}$. Also there is further experimental evidence that a similar adjustment is needed also in the range below 350 cm$^{-1}$, where we have observed the larger misfit between observations and calculations.

To sum up, we conclude that this new set of Antarctica Dome-C REFIR observations definitely validates the current MT-CKD 2.5.2 model parameterization, even if our results do show that further improvements are possible and the need to strengthen the lines, rather than continuum, parameterization in the range below 350 cm$^{-1}$. These improvements are both of interest to spectroscopy itself, and applications to the study of climate processes and related feedback on radiative forcing.
Jacobian: H₂O Foreign continuum: the derivative is taken with respect to the log of Symmetrized Power Spectral Density Function, \( \tilde{C}_f \) (cm\(^{-2}\) molecule\(^{-1}\) cm\(^{-2}\))\(^{-1}\). The Jacobian is in units of W m\(^{-2}\) sr\(^{-1}\) (cm\(^{-1}\))\(^{-1}\).
Jacobian: $H_2O$ Foreign continuum: the derivative is taken with respect to the Symmetrized Power Spectral Density Function, $\tilde{C}_f$ \((cm^{-2} \text{ molecule}^{-1} \text{ cm}^{-2})^{-1}\) (Zoom in the spectral range 0 to 500 cm\(^{-1}\) )

Tropical Atmosphere
Some Results

CO₂ spectroscopy and forward modelling validation
Since 2014 we are acquiring IASI spectra over a sea surface target area close to NOAA Mauna Loa Station.
Forward Calculations based on ECMWF analysis, space&time collocated with IASI observations, results averaged over 169 night-time IASI spectra. February 2015, CO$_2$ measured at the station 400.20 ppmv......
..upon retrieval (imposing the ECMWF analysis for T, H₂O)

CO₂ retrieval (monthly average)  
385.36±0.60 ppmv
The satellite retrieved CO$_2$ is normally negative biased with respect to in situ observations.
The same happens in the SWIR, e.g., the GOSAT-SWIR is debiased by comparison with in situ observations (1.6 and 2.1 μm).
Checking spectral residual in the longwave with Radiosonde Observations

Manus island

RAOB set (launches collocated with 19 IASI spectra)

Table 1: List of IASI soundings for the 2014 used in the analysis and correspondence with radiosonde launches. psec is in the IP0V number (1-4) within the given FOR.
Accuracy of collocation, lateral shift smaller than 50 km
The bias nearly disappears for tropospheric channels, results averaged on 19 IASI spectra.
Comparison ECMWF vs RAOB

ECMWF, HAWAII

RAOB (and ECMWF in the stratosphere), MANUS
..upon retrieval.....

CO2 retrieval: 399.54±1.80 ppmv;

CO2 observed at Manus: 399.98±0.23 ppmv

(average over the 19 soundings)
Extending the spectral range to the first IASI band
Perspective for Forum
Perspectives for FORUM

CO$_2$ Jacobian Derivative for a Tropical atmosphere (units W m$^{-2}$ sr$^{-1}$ (cm$^{-1}$)$^{-1}$ pp$^{-1}$)
Emissivity in the far infrared. There is no laboratory data base covering the far infrared. Lab data goes from $\approx 700$ cm$^{-1}$ to shortwave.
With our $\sigma$-IASI/$\delta$-IASI package we can retrieve the emissivity spectrum over the full spectral coverage of the given instrument (example from IASI)

Masiello and Serio (2013) doi:10.1364/AO.52.002428
Physical Retrieval of Land Surface Emissivity Spectra from Hyper-Spectral Infrared Observations and Validation with In Situ Measurements

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Emissivity Validation
CONCLUDING REMARKS

- **LBLRTM** provides the best state-of-art radiative transfer and water vapour line and continuum compilation.
- For the far infrared we expect AER line compilation to be better than those provided by HITRAN.

- Using a model kit approach we have developed a suite of forward/inverse models, which can be used to assess consistency and validation of spectroscopy and radiative transfer and in fact they have allowed us to validate:
  - H2O spectroscopy and forward modelling in the far infrared
  - CO2 spectroscopy and forward modelling in the thermal infrared

- **FORUM** can play an important role for a better assessment of:
  - Validation of H₂O spectroscopy, hence better L2 products
  - Validation of CO₂ spectroscopy, hence better L2 products
  - The very first data-base of surface emissivity and features in the far infrared for temperate-to-cold climate regions.
For further information visit our website
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