Atmospheric (clear-sky and cloudy) and Surface Retrievals in Principal Component Space using the Havemann-Taylor Fast Radiative Transfer Code (HT-FRTC)

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Introduction
Motivation

Traditional radiative transfer models are too time-consuming to deal with modern IR hyperspectral sensors such as:

- IASI (Infrared Atmospheric Sounding Interferometer): ~ 8000 channels
- ARIES ~ 5000 channels

or SW hyperspectral imagers such as

- AVIRIS (Airborne Visible/Infrared Imaging Spectrometer): ~ 200 channels + high spatial resolution
- Hyperion (SW Imaging Spectrometer): ~ 200 channels + high spatial resolution
The HT-FRTC uses principal components, these can be ‘line-by-line’ sensor-independent principal components.

Works in the microwave, infrared and short-wave.

Does treat water vapour, ozone, carbon dioxide and 50 other trace gases (LBLRTM 12.2).

Does treat any spectrally resolved surface emissivity / reflectance.

Does include 20 different aerosols as well as water and ice clouds and liquid and frozen precipitation.

Incorporates an exact treatment of scattering as well as the Chou-scaling approximation.

Works for any sensor-height, for up and down-looking instruments (air / space borne or ground-based).

Is able to compute radiances, fluxes and transmittances.

Includes the solar and lunar source and can account for spherical earth.

A full hyperspectral radiance calculation takes less than one millisecond.

The HT-FRTC is used in a 1D-Var retrieval system in principal component space.
Using our accurate **line-by-line** (scattering) code, simulate line-by-line radiance (/transmittance/flux) spectra for many different cases.

This should include as many realistic combinations of atmospheric conditions, viewing angles and altitudes as possible.

We currently use a set of 1000 ECMWF profiles for this step.
Training the HT-FRTC

The set of all the generated radiance spectra are arranged together in a large $m \times n$ matrix.

We perform Singular Value Decomposition (SVD) on this matrix to obtain the Empirical Orthogonal Functions (EOF), Singular Values (SVs) and Principle Components (PCs).

The SVD is given by

$$A_{mn} = U_{mn} \times \Sigma_{nn} \times V^t_{nn}$$

- **EOF**: Represent the basic characteristics of the sensor and atmosphere.
- **SVs**: Sorted by size, give significance of each EOF.
- **PCs**: Depend on the actual atmospheric state for each training case.
Many of the EOF and SVs can be discarded, since any atmospheric conditions can be represented almost perfectly using only a set of leading EOF, SVs and a set of PC scores.

The PC scores for any given atmospheric case can be predicted by performing full line-by-line calculations at a few specific frequencies, inferred from the initial training dataset.

A similar process is used to represent surface reflectances, based on a training set of 500 surfaces from the ASTER and USGS spectral libraries.

We typically use 100 PCs for the radiances and 10-15 for the surface reflectances.
HT-FRTC fast model step

Input profile

Monochromatic RT at centroid frequencies

Spectral info at centroid freq

Pre-defined regression coefficients

Calculate PC scores

Output PC scores

Calculate spectrum

Output radiance spectrum

PC
Bias and standard deviation obtained for 100 random independent ECMWF profiles.
1D-Var Algorithm

1D-Var

Measurements $y(x)$ represented by first 100 PCs of obs. spectra

$y(x)$ provided by HT-FRTC code which works in PC space.

1D-Var

$J(x) = (x - x_0)^T B^{-1} (x - x_0) + (y - y(x))^T R^{-1} (y - y(x))$

Background state $x_0 = \text{NWP forecast}$

$B = \text{Error Cov. Background Profile}$

$R = \text{Error Cov. of Measurements}$

Output Atmospheric State $x$.

- Temp($z$)
- Wat. Vap. ($z$)
- Ozone. ($z$)
- Surf Temp. $T^*$
- 15 Emissivity PCs
- Clouds
- Aerosols

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Background error covariance matrices for temperature, humidity and ozone, from the European Centre for Medium Range Forecasting (ECMWF).

No cross-correlations between state variables apart from temperature and surface temperature.

Error covariances for aerosols are not known so we approximate those by:

\[ S_{ij} = \sigma^2 \exp\left(-\alpha \left| \ln(p_i) - \ln(p_j) \right| \right) \]

where \( P_i \) and \( P_j \) denote pressure levels.
Results – Longwave Retrievals
ARIES (Airborne Research Interferometer Evaluation) flies on the BAE-146 aircraft which is operated by the UK Met Office and the Natural Environment Research Council (NERC). It has about ~ 5000 channels in the 550 cm\(^{-1}\) to 3000 cm\(^{-1}\) spectral interval.

Blister containing ARIES and other radiometers
Clear-Sky LW Retrievals from ARIES

Night-Time flight B284 of JAIVEx Campaign

Measurements taken over the Oklahoma ARM Site

Temperature Retrievals from 1700 radiance measurements

Humidity Retrievals from 1700 radiance measurements
There is a good agreement between the retrieved and the inferred surface emissivities (thanks to Stuart Newman).

1700 surface emissivity profiles obtained from the high altitude radiance measurements.
The inferred surface emissivities tend to have a much ‘flatter’ spectrum.

Agreement between individual footprints is relatively good.

At low level the ARIES measurements have an field of view of ~50 m so we are able to resolve small features.
Clear-Sky LW Retrievals from IASI
LW Cloudy Retrievals from IASI

MODIS Image 1114Z
2nd March 2010
LW Cloudy Retrievals from IASI

Temperature retrievals:

- clear-sky
- grey cloud
- ice cloud
LW Cloudy Retrievals from IASI

Relative humidity retrievals:

- clear-sky
- grey cloud
- ice cloud
LW Cloudy Retrievals over Land from ARIES and IASI
LW Cloudy Retrievals: Temperature from ARIES and IASI

Temperature retrievals

Pressure (hPa)

Temperature (K) (adjusted by lapse rate)

ECMWF model
Retrievals

ECMWF model
Dropsondes
Retrievals

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LW Cloudy Retrievals: Relative humidity from ARIES and IASI
### LW Cloudy Retrievals from ARIES and IASI: Cirrus properties

<table>
<thead>
<tr>
<th></th>
<th>Background values</th>
<th>Run 7</th>
<th>Run 8</th>
<th>Run 9</th>
<th>IASI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cirrus IWC</strong></td>
<td>10 mg m(^{-3})</td>
<td>26±8 mg m(^{-3})</td>
<td>23±14 mg m(^{-3})</td>
<td>24±6 mg m(^{-3})</td>
<td>20±7 mg m(^{-3})</td>
</tr>
<tr>
<td><strong>Cirrus cloud top pressure</strong></td>
<td>Flight level</td>
<td>302±1 hPa</td>
<td>315±6 hPa</td>
<td>323±7 hPa</td>
<td>313±15 hPa</td>
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<tr>
<td><strong>Cirrus cloud thickness</strong></td>
<td>10 hPa</td>
<td>14±3 hPa</td>
<td>13±6 hPa</td>
<td>18±4 hPa</td>
<td>11±5 hPa</td>
</tr>
<tr>
<td></td>
<td>(200 m)</td>
<td>(280±60 m)</td>
<td>(260±120 m)</td>
<td>(360±80 m)</td>
<td>(220±100 m)</td>
</tr>
<tr>
<td><strong>Cirrus cloud fraction</strong></td>
<td>1.00</td>
<td>1.06±0.03</td>
<td>0.98±0.04</td>
<td>1.01±0.03</td>
<td>0.96±0.05</td>
</tr>
</tbody>
</table>
LW Cloudy Retrievals from ARIES and IASI: Surface properties

<table>
<thead>
<tr>
<th>Surface temperature</th>
<th>Run 7</th>
<th>Run 8</th>
<th>Run 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background values</td>
<td>275.5 K</td>
<td>274.9 K</td>
<td>276.3 K</td>
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<tr>
<td>(NWP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retrievals</td>
<td>274.6±0.4 K</td>
<td>274.3±0.8 K</td>
<td>275.5±0.5 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(IASI</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>274.5±0.5 K</td>
</tr>
</tbody>
</table>
Results – Short-Wave Retrievals
RGB False Colour Plot:
- Red: 1.6 µm
- Green: 0.8 µm
- Blue: 0.6 µm

Beijing 19/05/2001

Beijing 03/05/2001
Temperature and humidity retrieved from centroid of cluster 1.

Aerosol profile retrieved from centroid of cluster 1. Aerosol used: Aged organic carbon.
Hyperion EO1 Surface Reflectance Retrievals – Beijing – Clear Sky (19/05/01)

Cluster 1
Cluster 7
Surface Reflectance Retrievals – Beijing – Aerosol (03/05/01)

Cluster 1

Retrieval performed using ‘Aged Organic Carbon’.
Surface Reflectance Retrievals – Beijing – Aerosol (03/05/01)

Cluster 7
Cluster 13

Clear – Sky Retrieval (19/05/01)
Aerosol Retrieval (03/05/01)

Clear – Sky Retrieval (19/05/01)
Aerosol Retrieval (03/05/01)