Assimilation of AIRS & IASI at ECMWF

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Acknowledgements to Tony McNally, Richard Engelen & Rossana Dragani
Overview

● Introduction

● Assimilation Configuration
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  - Cloud Detection

● IASI First Guess Departures

● AIRS & IASI Forecast Impacts

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  - Cloud
  - Data Compression

● “Trace” Gases

● Conclusions
Introduction
What are Advanced Infrared Sounders?

- Infrared Spectrometers with high spectral resolution and thousands of channels.
- Allows sounding of the atmosphere with improved vertical resolution and accuracy.
- All such instruments are interferometers (except for the NASA/EOS Atmospheric Infrared Sounder (AIRS) which is a grating spectrometer).
<table>
<thead>
<tr>
<th>Instrument/ Satellite/ Launch</th>
<th>No. of Channels</th>
<th>Spectral Range</th>
<th>Spectral Resolution</th>
<th>IFOV</th>
<th>Type/ Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS/ Aqua(EOS-PM)/ May 2002</td>
<td>2378</td>
<td>650-2760 cm(^{-1})</td>
<td>~1 cm(^{-1})</td>
<td>13.5 km</td>
<td>Grating Spectrometer/ Polar</td>
</tr>
<tr>
<td>IASI/ MetOp/ October 2006</td>
<td>8461</td>
<td>645-2760 cm(^{-1})</td>
<td>0.5 cm(^{-1})</td>
<td>12 km</td>
<td>Interferometer/ Polar</td>
</tr>
<tr>
<td>CrIS/ NPOESS/ ??? ???</td>
<td>1400</td>
<td>635-2450 cm(^{-1})</td>
<td>1.125-4.5 cm(^{-1})</td>
<td>12 km</td>
<td>Interferometer/ Polar</td>
</tr>
<tr>
<td>GIFTS/ ???????/??????</td>
<td>1724</td>
<td>685-1130 cm(^{-1})</td>
<td>0.6 cm(^{-1})</td>
<td>4 km</td>
<td>Imaging Interferometer/ Geostationary</td>
</tr>
<tr>
<td>HES/ GOES-R/ 2012</td>
<td>?</td>
<td>650-1200 [1650-2150 cm(^{-1}) or 1210-1740 cm(^{-1})] 2150-2250</td>
<td>0.6 cm(^{-1})</td>
<td>4-10 km</td>
<td>Interferometer?/ Geostationary</td>
</tr>
</tbody>
</table>
Other Examples of Interferometers in Space

- The following have been used for atmospheric sounding but (for various reasons) their observations have not been assimilated into NWP models:
  - IRIS on NIMBUS 3 & 4 (1969-70)
  - IRIS on Mariner 9 (Mars, 1971)
  - IRIS on Voyager 1 & 2 (Giant Planets, 1979-89)
  - IMG on ADEOS (1996-97)
  - CIRS on Cassini (Saturn, 2004-)
  - PFS on Mars Express (Mars, 2003-)
  - TES on EOS-AURA (limb sounder, 2004-)
An IASI Spectrum

Brightness Temperature (K)

Wavelength (μm)

- CO₂
- H₂O
- O₃
- Shortwave window (with solar contribution)
- Longwave window
- Q-branch

ECMWF
IASI vs HIRS: The Thermal InfraRed
AIRS vs HIRS Jacobians in the 15μm CO₂ band

Selected AIRS Channels: 82(blue)-914(yellow)
HIRS vs IASI: Temperature Retrieval Accuracy

![Graph comparing HIRS and IASI temperature retrieval accuracy](image-url)
HIRS vs IASI: Humidity Retrieval Accuracy
HIRS vs IASI: Response to Important Atmospheric Structure

Response to a structure the observation of which would have improved the forecast of the reintensification of Hurricane Floyd over SW France and SW England on 12th September 1993. (Rabier et al., 1996)
Assimilation Configuration
Current Operational Configurations

AIRS
- Operational at ECMWF since October 2003
- 324 Channels Received in NRT
- One FOV in Nine
- Up to 155 channels may be assimilated (CO₂ and H₂O bands)

IASI
- Operational at ECMWF since 12th June 2007
- 8461 Channels Received in NRT
- All FOVS received; Only 1-in-4 used
- 366 Channels Routinely Monitored
- Up to 168 channels may be assimilated (CO₂ band only)
Assumed Noise for AIRS & IASI Assimilation

AIRS Instrument Noise
Assumed Observational Error
Clear Sky Background Departures
Assimilation Configuration:
Channel Selection
Why Select Channels?

- The volume of IASI data available is such that we do not have the computational resources to simulate and assimilate all these data in an operational timeframe.
- Not all channels are of equal use when assimilated into an NWP system.
- We choose channels that we wish to monitor (often with a view to future use).
- We choose a subset of these channels which we actively assimilate.
AIRS and IASI Channel Selection

- The 324 AIRS channels distributed by NOAA/NESDIS were chosen based on inspection of Jacobian widths and expected noise levels. (Susskind, Barnet & Blaisdell, 2003).

- All IASI channels are distributed to European Users via EUMETCAST. Distribution of IASI radiances via GTS is for 300 channels chosen according to Collard (2007).

- At ECMWF, for IASI we use the 300 channels above plus a further 66 channels.

These are the channels that are routinely monitored – not all are actively assimilated (see later).
IASI Channel Selection

- **Pre-screen channels**
  - Ignore channels with large contribution from un-assimilated trace gases.

- **Use the channel selection method of Rodgers (1996)**
  - Iterative method which adds each channel to the selection based on its ability to improve a chosen figure of merit (in this case degrees of freedom for signal).
  - Determine the channels which contribute most information to a number of atmospheric states and view angles.
  - Use multiple runs to reduce the effect of non-linearity and to focus on particular species.

- **Add extra channels that the Rogers method cannot choose**
  - E.g. Cloud detection channels.
Pre-screened channels
Selected Channels (1)

- 30 channels chosen from 15μm CO₂ band considering temperature assimilation only
- 36 channels from 707-760cm⁻¹ region – found to be particularly important when assimilating AIRS.
- 252 channels considering temperature and water vapour together
- 15 ozone channels
- 13 Channels in the solar-affected shortwave region

In ECMWF selection only:
- 22 channels used for monitoring (HIRS analogues and requested by CNES)
- Another 44 channels in the 707-760cm⁻¹ region
Selected Channels (2)

- Temperature
- Main run
- Ozone
- Solar/non-LTE
- Extra surface/cloud
Comparison of Actively Assimilated Channels (1)
Comparison of Actively Assimilated Channels (2)
Jacobians of 15μm CO₂ Band
Jacobians of 6.3μm H₂O Band

Chosen Channels
1st 10 Chosen Channels
Other Channels
Assimilation Configuration: Cloud Detection
Cloud detection scheme for Advanced Sounders

A non-linear pattern recognition algorithm is applied to departures of the observed radiance spectra from a computed clear-sky background spectra.

The large number of AIRS or IASI channels allows improved measurement of the cloud-top height compared to HIRS.

AIRS channel 226 at 13.5micron (peak about 600hPa)

AIRS channel 787 at 11.0 micron (surface sensing window channel)
Number of Clear Channels

- High Peaking Channels
- Window Channels
Cloud Detection Software is Available

- Cloud detection has been re-written to allow greater portability and to allow cloud detection of IASI

- *It is available for all to use from the NWPSAF*

- http://www.metoffice.gov.uk/research/interproj/nwpsaf/
Adaptive bias correction and QC

A typical distribution of (Obs-Calc) departures has a cold / warm tail due to residual cloud contamination. A boxcar QC window is often applied to remove the tail before estimating the bias.

However, successive applications of this (as in adaptive bias correction leads to a “dragging” of the mean by the cold tail. The speed and size of the drag depends on the number of iterations and the size of the boxcar window QC.
Cloud Detection and Bias Correction Interact

- Bias Correction
  - Clear Observations
  - Bias Corrected Observations
- Cloud Detection
IASI First Guess Departures
Looking at First Guess Departures

- Observed Radiances minus Radiances Predicted from Short Range Forecast from Previous Cycle
- First Guess Departures drive the increments

In the following slides:
- Clear-sky first guess departures
- The cloud detection uses the operational bias-correction
- The first-guess departures are NOT bias-corrected
First Guess
Departure Biases in 15μm CO₂ Band

Ordered by Wavenumber

Ordered by Jacobian Peak Pressure
First-Guess Departure
Standard Deviations in 15μm CO₂ Band

Calculated Std. Dev.

Observed Std. Dev.
First Guess Departure
Standard Deviations
and Biases in the
Longwave Window
First-Guess Departure Biases in Water Band
First –Guess Departure
Standard Deviations in Water Band

- Passive Channels
- Extra Monitoring Channels
- Ozone Channels
- CO Channels
- CH$_4$ Channels
- N$_2$O Channels

Calculated Std. Dev.
Observed Std. Dev.
First-Guess Departure
Standard Deviations in Shortwave Band

Passive Channels
Extra Monitoring Channels
Water Vapour Channels
CH₄ Channels
N₂O Channels

Observed Std. Dev.
Calculated Std. Dev.
AIRS & IASI Forecast Impacts
AIRS Impact at ECMWF

500hPa Geopotential Anomaly Correlation

The graph shows the anomaly correlation for 500hPa in both the Northern and Southern Hemispheres. The red dotted line represents the AIRS impact, while the black solid line represents the CTRL impact. The x-axis indicates the forecast range in hours, ranging from 0 to 168, while the y-axis represents the anomaly correlation, ranging from 70 to 100.
IASI Impact on SH Geopot. AC

Mean curves
500hPa Geopotential
Anomaly correlation forecast
S.hem Lat -90.0 to -20.0 Lon -180.0 to 180.0
Date: 20070308 00UTC to 20070308 00UTC
Mean calculation method: standard
Population: 85 (averaged)

- Red: No IASI
- Blue: With IASI

Forecast Day
0 1 2 3 4 5 6 7 8 9 10
30 40 50 60 70 80 90 100

ECMWF
IASI Forecast Scores Again: 500hPa Geopot. AC

NH Better

IASI Worse

ECMWF
AIRS Impact at ECMWF in Context – N. Hemis.

Mean curves

500hPa Geopotential
Anomaly correlation forecast
N.hem Lat 20.0 to 90.0 Lon -180.0 to 180.0
Date: 20041214 00UTC to 20050125 12UTC
Mean calculation method: standard
Population: 88 (averaged)

500hPa Geopotential
Anomaly Correlation

Northern Hemisphere
14th Dec 2004-25th Jan 2005

Forecast Day
AIRS Impact at ECMWF in Context – S. Hemis.

**Mean curves**

*500hPa Geopotential Anomaly correlation forecast*

- **Southern Lat -90.0 to -20.0 Lon -180.0 to 180.0**
- **Date:** 2004/12/14 00UTC to 2005/01/25 12UTC
- **Mean calculation method:** standard
- **Population:** 60 (averaged)

**500hPa Geopotential Anomaly Correlation**

- **Southern Hemisphere**
- **14th Dec 2004-25th Jan 2005**
Single instrument experiments

Anomaly correlation of 500hPa height for the **Southern Hemisphere** (average of 50 cases summer and winter 2003 verified with OPS analyses)
Challenges
Water Vapour
Use of Water Vapour Channels at ECMWF

- We get a small positive impact from using the water vapour channels
- We use a cloud detection scheme that uses the first guess departures in the water band itself
  - The signal from water vapour can mimic cloud
  - The resulting clear channels also tend to be those where water vapour departures are smallest
- We also assume 2K observation errors.
O-A Stats for NOAA-16 AMSU-B

Larger Assumed AIRS H$_2$O Errors = Better Fit to AMSU-B

NH Tropics SH
Solid=Ch.3
Dashed=Ch.4
Dotted=Ch.5
But....

- **In-band H₂O cloud detection with 2K assumed observation errors give small but positive impact**
- **Cross-band H₂O cloud detection gives worse impact than in-band unless assumed errors are > 6K!**
- **Water observation errors for AIRS are ~0.2K!**

For IASI we have a similar story…
**Std. Dev. of SH NOAA-17**

With **IASI** using cross-band cloud detection, a 2K error will degrade fit to AMSU-B unless many fewer channels are used.

**124 IASI H$_2$O Chans**
Obs Err = 2K  
Forecast Impact: -ve

**10 IASI H$_2$O Chans**
Obs Err = 1.5K  
Forecast Impact: Neutral

**124 IASI H$_2$O Chans**
Obs Err = 4K  
Forecast Impact: Neutral
Some Water Discussion (1)

- The water vapour channels have temperature sensitivity which is highly dependent on the water vapour profile.
- It is possible that water vapour signal is causing erroneous temperature increments.
- By removing the feedback of temperature information from the water vapour channels, it has been shown that this is not the case.
Some Water Discussion (2)

- We have to greatly inflate water vapour errors to avoid degrading the model
  - This is because of the large number of channels with error correlations between them (including bias)

- By assuming greatly increasing the water vapour observation errors we are negating the influence of inter-channel differences that allow us greater vertical resolution
  - Can we do a better job?
Cloud
Cloud

- Cloud in the field of view can greatly affect our ability to use IR radiances.
- Studies have shown that the most important areas to measure for accurate forecasts often have cloud.
- We need to identify strategies to deal with cloud.
Dealing with Cloud

- Use only clear fields of view
  - Low (~5%) yield

- Use only channels unaffected by cloud
  - Low yield in lower tropospheric channels

- Cloud clearing
  - Simulate a clear observation by using multiple fields of view and assume that only cloud fraction changes between them

- Simultaneous retrieval of cloud optical properties
  - These observations are rich in cloud information
Data Compression
Data Compression

- Advanced IR sounder radiances contain a lot of information (~30 pieces) …
- …but there are two orders of magnitude more channels.
- Hence there is a large amount of redundancy
- How can we use these data more efficiently?
Why is data compression important?

- Very large data volumes need to be communicated in near-real time (e.g., EUMETSAT to NWP centres)
- Simulation of spectra (needed for assimilation) is costly
- Assimilation is costly
- Data storage
Efficient use of channels

- **All channels:**
  - 1000s of Channels
  - Not very efficient

- **Selected Channels:**
  - 50-1000 Channels
  - Simplest method
  - What we currently use
  - Throws away a lot of information

- **Selected Channels + Grouping (“Superchannels”):**
  - Reduced Number of Channels
  - Lower noise per channel used
  - Weighting Functions are Less Sharp?
Efficient use of channels (contd.)

● Assimilating Retrievals:
  - The old way
  - We can pass a smaller number of variables to the 3D/4DVar stage
  - No expensive RT modelling required at 3D/4DVar stage
  - Two main issues:
    ▪ Inter-level correlations
    ▪ A priori data

● Principal Components and Reconstructed Radiances...
The complete AIRS spectrum can be compressed using a truncated principal component analysis (e.g. 200PCAs vs 2300 rads)

Leading eigenvectors (200, say) of covariance of spectra from (large) training set

\[ p = V^T (y - \bar{y}) \]

- To use PCs in assimilation requires an efficient RT model to calculate PCs directly
- PCs are more difficult to interpret physically than radiances

N.B. This is usually performed in noise-normalised radiance space

This allows data to be transported efficiently
Spectral data compression and de-noising

The complete AIRS spectrum can be compressed using a truncated principal component analysis (e.g. 200PCAs v 2300 rads)

Leading eigenvectors (200, say)
of covariance of spectra from
(large) training set

Each reconstructed channel is a linear combination of all the original channels and the data is significantly de-noised.

If \( N \) PCs are used all the information is contained in \( N \) reconstructed channels (theoretically)

\[
p = V^T(y - \bar{y}) \quad \quad \quad y_R = \bar{y} + Vp
\]
AIRS Reconstructed Radiances

- Data are supplied in near-real time by NOAA/NESDIS in the same format as the “real” radiances.
- The same channels are supplied, except some “popping” channels are missing.
- Based on 200 PCs
- QC Flag supplied
First Guess Departures for AIRS are Reduced

Instrument noise is the main contributor to FG departure in the 15μm CO₂ band only.

Original
Reconstructed
Spatial Denoising

AIRS Channel 99
(674.4 cm\(^{-1}\), 14.83 \(\mu\)m, ~15 hPa)

"Denoised"

Brightness Temperature (K)

Limb brightening
A look at Reconstructed Radiances’ Errors

Instrument noise is dominant and diagonal. Correlated noise is from background error.

Reconstructed Radiances
Instrument noise is reduced (std. dev. is approximately halved) but has become correlated.

Covariances of background departures for clear observations in 15μm CO₂ band
Improvements in Cloud Detection

ECMWF Scheme:
- Ranks Channels Height
- Applies low-pass filter
- Tests for non-zero gradient

< 2% of Channels are flagged differently for RR vs Normal radiances
Forecast Impact of Reconstructed Radiances

Essentially Neutral
“Trace” Gases
AIRS observations are used for CO₂ data assimilation within the GEMS project. Although the signal is small, it does improve the fit to independent aircraft observations as shown in the figure. In the next few months IASI will be implemented in the CO₂ assimilation as well.

The flight data over Hawaii were provided by Pieter Tans, NOAA/ESRL.

Courtesy of Richard Engelen and Soumia Serrar
Assimilation of AIRS O₃-sensitive IR channels

- Two exp (T159L91), 15 Sep–14 Dec
  - CTRL: Op. set up
  - AIRS: CTRL +36 ch. assimilated in [1003-1286] cm⁻¹

- Radiances over land blacklisted.
- TCO is reduced in the tropics, increased at HL in the NH

Temperal mean total column ozone difference (CTRL-AIRS) in DU
01 Oct 2006 00UTC - 14 Dec 2006 18UTC

Courtesy Rossana Dragani
Conclusions

- AIRS and IASI have been operational at ECMWF since October 2003 and June 2007 respectively.

- IASI and AIRS have demonstrated positive impacts on the ECMWF NWP model and form an important part of the assimilation system.

- To make better use of the full dataset we need to address:
  - Water vapour assimilation
  - Assimilation in cloudy areas
  - Efficient use of more of the spectrum
  - Use over land
Time for Lunch!!!