Extraction of Profile Information from Cloud Contaminated Radiances

W. L. Smith, D. K. Zhou, H-L Huang, and Jun Li (NASA LaRC and UW-CIMSS)

ECMWF Workshop on Assimilation of High Resolution Sounders in NWP (June 28 – July 1, 2004)

Isabel Pays Unwelcome Visit To Seaford VA

The 24-36 hour track forecast was good but the surge was missed by >1 meter

Can Hyerspectral Soundings Improve This!
NAST-I & AIRS Measurement Characteristics

Satellite AIRS (IR Grating Spectrometer)
- Spectral Range: 3.7 – 15.4 Microns
- Spectral Res: $\nu/\delta\nu = 1200$ (0.5-2.25 cm$^{-1}$)
- Ground Resolution: 13.5km @ nadir
- Swath Width: 1650 km

Aircraft NAST-I (IR Interferometer)
- Spectral Range: 3.5 - 16 Microns
- Spectral Res: $\delta\nu = 0.25$ cm$^{-1}$
- Ground Resolution: 2.5 km @ 20 km
- Swath Width: 40 km @ 20 km
Empirical Orthogonal Function (EOF)

NAST-I Regression Retrieval

For clear sky and opaque cloud:

\[
R = \varepsilon_{s,c} B_{s,c} \tau_{s,c} - \int_{P_{ac}}^0 B_d \tau^-(1 - \varepsilon_{s,c}) \tau_{s,c} \ dx \int_{P_{ac}}^0 B_d \tau^* \]

Radiance EOF Amplitudes

\[
C_i = \sum_{j=1}^{nc} R_{ij} E_{ji}
\]

\[
\begin{align*}
T_s, \\
\varepsilon_s(v), \\
T(p), \\
Q(p)
\end{align*}
\]

\[
= \sum_{i=1}^{n-1} K_{mi} C_i + K_{mn} P_s
\]

\[
R = \text{radiance} \\
\varepsilon_{s,c} = \text{surface or cloud emissivity} \\
B_{s,c} = \text{surface or cloud Planck radiance} \\
\tau = \text{transmittance between aircraft and atmospheric Pressure level (P)} \\
\tau_{s,c} = \text{atmospheric transmittance between aircraft and surface or cloud (P_{S,c})} \\
\tau^* = \text{atmospheric transmittance between surface or cloud P and aircraft} \\
P_{ac} = \text{aircraft pressure, } P_s = \text{surface pressure} \\
\Re = \text{radiance} \\
E = \text{radiance covariance EOFs} \\
C = \text{radiance EOF amplitudes} \\
T = \text{temperature} \\
Q = \text{H}_2\text{O mixing ratio} \\
K = \text{regression coefficients}
\]

- Physical Regression – EOFs and regression training based on calculated radiances
- Training should include cloud, sfc. emissivity, skin temp, and solar variability
- Null radiance errors assumed for PC specification and regression training
- EOF # selected by spatial radiance RMSD (observed minus retrieval) minimization
C-F* (July, 2002) NAST-I Vs Radiosondes

* Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL - FACE)
C-F Retrieval Vs Raob Mean and Stde (Clear Cases)

Florida Region
July 2002
Approaches to Dealing With Clouds

**Hole Hunting** - Requires small field of view. Produces soundings in clear IFOVs only.

**Cloud Clearing** - Provides sounding in clear air above and below broken clouds. Requires multi-spectral imager with broadband sounding channels to filter erroneous estimates. Results improve with decreasing field of view size.

**Cloud Equivalent Clear Radiance Retrieval** - Provides correct sounding down to near cloud top level with a erroneous sounding being produced below cloud level. Below an opaque overcast, an isothermal sounding results whereas for a semi-transparent or broken cloud condition, the sounding below the cloud will lie in-between the true sounding and the isothermal profile.

**Cloud-Training** - Provides sounding above and below semi-transparent and/or broken clouds, and above opaque overcast clouds. Enables cloud microphysical parameters to be retrieved for input to a physical/matrix inverse retrieval or the direct assimilation of radiances into the forecast model.
Spatial resolution is important for resolving clear radiances

MODIS True Color Image – 24 August, 2002
Hole Hunting - Requires small field of view

Global Average (August 24, 2002)

Probability of Cloud free FOVs within $(48 \text{ km})^2$ Scene Area Based on MODIS Observations (95 % Confident Clear)

Minimum # of Clear IFOVs

- Contiguous
- Sampling
- Geometry
- Assumed

We must be able to treat clouds in the retrieval!

1 IASI is circular with a diameter of 12 Km, 2 CrIS is circular with a diameter of 14 km
Basic Cloud Clearing Methodology
(Assumes Horizontally Uniform Cloud Height and Cloud Microphysics)

\[ R_{clr}(\nu) = \frac{R_1(\nu) - N^*(\nu)R_2(\nu)}{1 - N^*(\nu)} \]

where \( N^*(\nu) = \varepsilon(\nu)N_1/\varepsilon_2(\nu)N_2 \).

\[ N^*(W) = \frac{R_1(W) - R_{clr}(\Delta W)}{R_2(W) - R_{clr}(\Delta W)} \]

\[ \hat{R}_{clr}(\Delta \nu) = \int \theta(\nu)R_{clr}(\nu)d\nu \]

Filter:
\[ |\hat{R}_{clr}(\Delta \nu) - R_{clr}(\Delta \nu)| \geq \delta \]

\( R_1(W) \) and \( R_2(W) \) are sounder window radiance measurements in FOVs 1 and 2. \( R_{clr}(\Delta W) \) is the clear window radiance measured by the imager. \( R_{clr}(\Delta \nu) \) is the clear radiance measured in the absorption channel(s) of the imager. \( \delta \) is the expected error, due to measurement noise, between the true and reconstructed imager clear radiances.
Spectrum measured at AIRS spectral resolution ($\delta \nu = \nu / 1200$ cm$^{-1}$) with MODIS Infrared channels and AIRS sounding spectral bands shown.
An AIRS/MODIS Cloud-Clearing Example


Study area for cloud clearing

AIRS Channel 763 (801.68 cm⁻¹) Brightness Temperature

AIRS Cloud Mask

Apply Cloud Clearing

Overcast

AIRS cloud detection from MODIS 1km cloud mask
AIRS Derived Clear Radiance Vs Clear Sky Neighbor

Clear neighbor for reference

Partly Cloudy FOV
(Line 74, column 55)

Partly Cloudy Neighbor

MODIS Classification Mask

Water  Land  Mixed cld  Mixed clr  Low cld  Mid cld  High cld  Mid cld  Low cld
Radiance difference between cloud-cleared FOV and clear neighbor FOV

For Widely Scattered Cloud (N*~0) “Clearing” Works!
AIRS Profile Retrievals Vs ECMWF Analysis

Cloud contaminated

Cloud-cleared

Clear neighbor

Cloud-cleared

Temperature

Water Vapor Mixing Ratio
Entire Granule Temperature RMS Difference (250 cases) Between AIRS and ECMWF (Scattered Clouds)*

* Jun Li (CIMSS, 2004)
Cloud Clearing with/without MODIS Imaging Data

40 x 40 km Sounding Area Clear Column Radiance* Yields (%)

<table>
<thead>
<tr>
<th>Spatial Resolution</th>
<th>3km</th>
<th>6km</th>
<th>9km</th>
<th>12 km</th>
<th>18 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of FOVs/ FOR</td>
<td>144</td>
<td>36</td>
<td>16</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>≥ 1 Observed Clear FOV/FOR (%)</td>
<td>46</td>
<td>40</td>
<td>33</td>
<td>28</td>
<td>21</td>
</tr>
<tr>
<td>Total (Clr + CCR) w/o MODIS (%)</td>
<td>66</td>
<td>62</td>
<td>56</td>
<td>53</td>
<td>45</td>
</tr>
<tr>
<td>Total with MODIS (%)</td>
<td>64</td>
<td>58</td>
<td>52</td>
<td>47</td>
<td>39</td>
</tr>
</tbody>
</table>

< 50 % yield, at 40 km spacing, for 12 km sounding resolution
∴ ∴ Needs to perform cloudy retrievals for AIRS/IASI/CrIS !

With MODIS
Errors Marginal!

Desired

Without MODIS
Errors too large!

Desired

*19 Different NAST-I Flights covering all season/all latitude cloud conditions
Cloud Equivalent Clear Radiance Retrieval

NAST-I Temp (K) Cross Section

NAST I-HOP June 12, 2002 Over Oklahoma

NAST-I RH (%) Vertical Cross Section

Clouds

Cloud Tops

Cloud Tops

Moist Layers

PBL Ht
Cirrus Cloud “Venetian Blind Effect”

These retrievals, uncorrected for cloud attenuation, demonstrate the ability of a high spatial resolution sounder to sense the spatial structure of moisture below a scattered and semi-transparent cirrus cloud cover.
Radiance spectral slope is sensitive to particle size
Radiance magnitude is sensitive to optical depth
**Cloud Retrieval Training!**

- Perform a realistic simulation of clouds for synthetic EOF radiance training
- Diagnose 0-2 cloud layers from radiosonde relative humidity profile
  - A single cloud layer (either ice or liquid) is inserted into the input radiosonde profile.
  - Approximate lower level cloud using opaque cloud representation (i.e., isothermal/saturated)

- Use parameterization of Heymsfeld’s* balloon and aircraft cloud microphysical data base (2003) to specify cloud effective particle radius, $r_e$, and cloud optical depth, $\tau$, (i.e., $r_e = a \tau^\alpha / [\tau - b\tau^\alpha]$).
  - Different habitats can be specified (Hexagonal columns assumed here)
  - Different clouds microphysical properties are simulated for same radiosonde using random number generator to specify visible cloud optical depth within a pre-specified range. 10% random error added to parameterized effective radius to account for real data scatter.

- Use LBLRTM/DISORT “lookup table” to specify cloud radiative properties
  - Spectral transmittance and reflectance for ice and liquid clouds interpolated from multi-dimensional look-up table based on DISORT multiple scattering calculations for the (wavenumber range 500 – 2500 cm$^{-1}$, zenith angle 0 – 80 deg., $D_{eff}$ (Ice: 10 – 157 um, Liquid: 2 – 100 um), OD(vis) (Ice: 0.04 - 100, Liquid 0.06 – 150)

- Compute EOFs and Regressions from cloudy radiance data base
  - Regress cloud properties ($p$, $\tau$, $r_e$) and surface and profile parameters against radiance EOFs
  - For small optical depth, output entire profile down to surface or lower opaque cloud level
  - For large upper level cloud optical depth, output profile above the upper cloud level

---

Semi-transparent Cloud ($\tau \leq 1$) Training Skill

**Procedure for Finding Correct Upper Level Cloud Height:**

1. Predict cloud pressure height using uncategorized statistics (i.e., without pressure grouping).
2. Predict cloud pressure height, $p(n)$ using categorized statistics for $p(n-1)$ cloud height obtained in (1).
3. Use statistics for cloud height $p(n)$ to predict an $n+1$ cloud height $p(n+1)$.
4. Compare new cloud height, $p(n+1)$ with previously determined cloud height, $p(n)$:
   - **(a)** if $p(n+1) = p(n)$: obtain geophysical parameter retrievals using statistics for $p(n+1)$
   - **(b)** if $p(n+1) \neq p(n)$: let $p(n) = p(n+1)$ and predict a new $p(n+1)$ using $p(n)$ cloud statistics
5. Repeat step (4) until convergence in cloud height is obtained, and parameter retrievals, is obtained.

Can Sound Below Cirrus Cloud!
ATReC ER-2 Deployment

- ATReC (November 18 - December 15, 2003, Bangor, Maine). The Atlantic-THORPEX Regional Campaign (ATReC) focused on reducing the number and size of significant weather forecast errors over Europe and the eastern USA by infusing extra remote sensing and in-situ observations over sensitive (i.e. oceanic) regions. ER-2 flights contributed to ATReC as focusing on satellite sensor validation underflights (TERRA, AQUA, & DMSP).

- NAST Research Objective: Profiling under complex cloud conditions

Aircraft Payload Included:

- NASA ER-2 (NAST-I, NAST-M, S-HIS, MAS, CPL, in-situ O3 Dropsondes (NOAA G-4 and Cessna Citation)

Satellite Platforms Included: Aqua, DMSP, Terra, and WindSat/Coriolis
December 5, ATReC Cloud Results
December 5, ATReC Cloud Results
December 5, ATReC Profile Results

Temp (K) at 300 mb (~9.2 km)

Temp (K) at 700 mb (~3 km)

RH (%) at 300 mb (~9.2 km)

RH (%) at 700 mb (~3 km)
AIRS Vs NAST-I Cloud Properties
AIRS Vs NAST-I Profile Properties

Temp (K) at 500 mb (~5.6 km)

Temp (K) at 700 mb (~3 km)
Example Profile Comparisons

TEMPERATURE DropS (184814)

RH(%) DropS (184814)

TEMPERATURE DropS (191659)

RH(%) DropS (191659)
Conclusions

• **High spatial resolution**
  – Sampling clear air
  – Optimizing cloudy sky retrievals

• **Cloud clearing**
  – Cloud clearing is useful for sounding under scattered clouds
  – AIRS can benefit from 1 km MODIS sounding channels
  – Cloud clearing causes loss of spatial resolution and clear air bias

• **Cloud training**
  – Permits sounding beneath semi-transparent cloud (i.e., thin cirrus)
  – Permits sounding to cloud level for opaque cloud conditions
  – Retrieved cloud properties can be used for 1-d Var Retrieval or for the direct assimilation of radiances into forecast model

---

**Ultimate approach for sounding retrieval or radiance assimilation with clouded hyperspectral radiances should employ a combination of cloud clearing and cloud training algorithms**