Recent Advances in Hyperspectral Infrared Sounding Retrieval Science at the CIMSS

Jun Li#, Jinlong Li, Elisabeth Weisz, Chian-Yi Liu, Eva Borbas and Allen Huang*
Cooperative Institute for Meteorological Satellite Studies
University of Wisconsin-Madison
1225 West Dayton Street
Madison, WI 53706

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#: Retrieval Team Leader; *: Presenter
Improved Information Content requires the “state-of-the-art” processing approaches to capitalize it!
Hyperspectral IR surface, and cloud modeling and multi-sensors/platforms Synergy

- The use of improved IR surface emissivity database/model in improving boundary layer sounding;
- The treatment of cloud microphysical property in cloud contaminated retrieval;
- Synergistic soundings from multiple sensors on the same platform;
- Synergistic soundings from multiple sensors on different platforms.
IR surface emissivity has consequential spectral and spatial variation.
MSG SEVIRI retrieved TPW product coverage for a uniform spectral emissivity (=0.95 left) and for the spectral emissivities taken from the UW/CIMSS BF emissivity database (right). Note the bad coverage, i.e. non-successful retrievals, over the large desert areas. (03 October 2007, 0600 UTC, box size is 15 x 15 MSG pixels)

Marianne Koenig and Estelle de Coning: The MSG Global Instability Indices Product and its Use as a Nowcasting Tool. Submitted to “Weather and Forecasting”
Approaches for surface emissivity treatment in retrieval

- Emissivity spectrum is expressed in eigenvectors (derived from laboratory measurements)
- Regression retrieval are used as the first guess
- Simultaneous retrieval of emissivity spectrum and sounding in physical iterative approach
Retrieval Algorithm (Li et al. 2007 – GRL)

Atmospheric measurement equation

\[ y = F(x) + e \]
\[ y = (R_1, R_2, ..., R_n)^T; \]
\[ x = (t(p); w(p); o(p); t_s; \varepsilon_1, ..., \varepsilon_n)^T \]

Emissivity eigenvector coefficients

Regularization and discrepancy principle (Li and Huang 1999)

(Cost function)

\[ J(x) = (y_m - y_c(x))^T E^{-1} (y_m - y_c(x)) + (x - x_0)^T \gamma S_0^{-1} (x - x_0) \]

Too many parameters to retrieve if including all channels’ emissivities !!!

EOF expansion

\[ x = \sum_i a_i \phi_i = a \phi; \]
\[ \phi: \text{eigenvector matrix}; \]
\[ a: \text{eigenvector coefficients \ to be retrieved} \]
Hyperspectral IR emissivity spectrum data base – from laboratory measurements

Database processed by E. Borbas (CIMSS)

Hyperspectral IR emissivity spectrum data base – from laboratory measurements

AIRS spectral coverage

IASI spectral coverage

The first 10 emissivity eigenvectors
Regression retrieval:
- T, W, O₃ profiles,
- Ts, Emisssivity

Three types of physical retrieval
1. Using constant emissivities of 0.98 and fixed in iterations.
2. Using regression emissivities and fixed in iterations.
Simulated Retrieval for Desert
(32 profiles)

Emissivity

Tskin RMS (K)

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Reg</td>
<td>0.624</td>
</tr>
<tr>
<td>Rtv</td>
<td>0.540</td>
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<tr>
<td>Fixed emis</td>
<td>0.822</td>
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<tr>
<td>Emis=0.98</td>
<td>9.544</td>
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Figure 1 from Li and Li [2008 – GRL]: The AIRS 9.3 mm surface emissivity retrieval images overlaying on AIRS brightness temperature (K) image (black/white) for Granule 002 on 06 January 2004 with (top left) 0.98 (constant spatially and spectrally) as first guess and (middle left) regression as first guess, respectively. (top right) The difference image and (middle right) the histogram of differences. (bottom left) The IGBP ecosystem land type map, and (bottom right) the location of the AIRS granule over central African.
Re-group from IGBP category:
Forests: Evergreen needle forests; Deciduous needle forests; Deciduous broad forests; mixed forests;
Shrubs: Opened shrubs; Closed shrubs;
Savanna: Woody savanna; Savanna;
Cropland: Cropland; Crop mosaic;
Snow/Ice: Snow; Ice; Tundra;
Desert: Desert/Barren;
With altered emissivity

Simultaneous method
Emissivity Validation
A case study
AIRS granule January 15 2004 00:03 UTC, 12 μm radiances

Atmospheric state from ECMWF analyses

(Borbas et al. 2008, ITSC16)
Emissivity

BF (black), HSR (blue) using MYD11 collection 4

(Borbas et al. 2008, ITSC16)
BT Residuals (Calc - Obs) (LW)

- HSR improvement over lin. int. BF
- O₃ band
- C5 improvement
- Problem in MYD11 C5
- 8-9.5 μm dBt > 6 K

(Borbas et al. 2008, ITSC16)
BT Residuals (Calc - Obs) (SW)

HSRemis V4
HSRemis V5
BFemis V4
BFemis V5
AIRSL2 emis
UW AIRS emis

Difference

Wavenumber [cm⁻¹]

Brightness Temperature [K]

HSR improvement over lin. int. BF

UW AIRS emissivity agrees very well with C5 HSRemis / C5 improvement vs C4

AIRS L2 std product underestimates emissivity in SW

(Borbas et al. 2008, ITSC16)
Handling clouds

- Only limited coverage is clear for IR radiances
- Soundings in cloudy regions are more important for forecast
- SFOV sounding products at high vertical and spatial resolution are important for monitoring/predicting mesoscale features in regional forecast models.
Our goal is to provide a physically based optimal retrieval algorithm to simultaneously derive T, Q, O₃ profiles, surface parameters and cloud parameters from hyperspectral IR measurements (e.g. from AIRS, IASI, CrIS) alone at single FOV resolution.
Fast cloudy radiative transfer model

- Developed in collaboration with Texas A&M University (H. Wei, P. Yang)
- Cloudy radiances can be computed from coupled clear-sky optical thickness (computed by SARTA) and cloud single-scattering properties.

\[ R = R_0 F_T \tau_c + (1 - F_T - F_R) B_c \tau_c - \int_0^{p_c} B d\tau + F_R \tau_c \int_0^{p_c} B_c d\tau^* \]

- Reflectance (albedo) and transmissive functions for various CPS (Cloud Particle Size) and COT can be obtained from a pre-described parameterization of the bulk single-scattering properties of ice and water clouds.

- Ice clouds: assumption of aggregates, hexagonal geometries and droxtals for large (>300 μm), moderate (50 - 300 μm) and small particles (0-50 μm) respectively.

- Water clouds: assumption of spherical droplets and application of classical Lorenz-Mie theory.
Whole sounding in broken clouds and above-cloud sounding in thick clouds can be derived.
Regression

**CLEAR**
- Training data set (SeeBor V5)
- Radiance calculations
  - SARTA v1.7 (UMBC)
- BT and Scanang Classification
- Clear Regr Coeffs
- T, Q, O3, STemp, Emissivity at single FOV

**CLOUDY**
- Cloudy Training data set (ice, water)
- Radiance calculations
  - Fast RT cloud model (Wei, Yang)
- Additional Predictors
  - (spres, solzen)
- Scanang Classification
- Ice Cloud Regr Coeffs
- Water Cloud Regr Coeffs
- T, Q, O3, STemp, CTOP, COT at single FOV

PC regression
\[ C = dXA^T (AA^T)^{-1} \]

Regression RTV
\[ X = \hat{X}_{tr} + CA_{obs} \]

To physical inversion
From 15704 profiles, profiles 4017 profiles are water clouds and 2162 are ice clouds

SEEBOR V5 profiles: 15704 clear (red), 4017 water (blue), 2162 ice (cyan)
Physical Inversion

Cost function for a quasi non-linear case:

\[ J = (y - F(x))^T S_\varepsilon^{-1} (y - F(x)) + (x - x_a) S_a^{-1} (x - x_a) \]

Newton-Gauss Iteration with regularization parameter \( \gamma \):

\[ x_{i+1} = x_a + (K_i^T S_\varepsilon^{-1} K_i + \gamma S_a^{-1})^{-1} K_i^T S_\varepsilon^{-1} [y - F(x_i) + K_i (x_i - x_a)] \]

- \( x, x_a \): current /a priori atmospheric state vector
- \( K \): Jacobian
- \( S_a, S_\varepsilon \): A priori / measurement covariance matrix
- \( F \): Forward model

Transform to EOF space:

\[ c_{i+1} = (\tilde{K}_i^T S_\varepsilon^{-1} \tilde{K}_i + \gamma \tilde{S}_a^{-1})^{-1} \tilde{K}_i^T S_\varepsilon^{-1} [y - F(x_i) + \tilde{K}_i c_i] \]

- \( c = \tilde{x} - \tilde{x}_a \)
- \( \tilde{K} = K \phi \)
- \( \tilde{S}_a = \phi^T S_a \phi \)
- \( \phi \): eigenvector matrix
Physical Inversion - flow chart

Regression
T,Q,O3,ctp,cot,de,emiss

Forward model calculations

Jacobian calculations

dy = y − yc

dy_i < dy_{i-1}

Next iteration

Decrease γ

Physical Inversion

Update Profiles

# fails < f max
# iterations < it max
dy > dy_{crit}

no

no (fail)

Increase γ

Physical RTV results
T,Q,O3,ctp,cot,de,emiss

Eigenvector matrix φ
Matrices S_1 and S_ε

1695 cm⁻¹
1350 cm⁻¹
1210 cm⁻¹

COT Jac
Q Jac

Physical Inversion

flow chart
**Hurricane Isabel case study**

- **Eye**
- **Environment**

### AIRS Retrieval: G171, 09-13-2003
- Cloud Top Pressure [mbar]

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<thead>
<tr>
<th></th>
<th>Eye</th>
<th>Environment</th>
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<tbody>
<tr>
<td>AIRS Index</td>
<td>19 / 118</td>
<td>66 / 129</td>
</tr>
<tr>
<td>Lat / Lon [°]</td>
<td>22.4 / -61.9</td>
<td>25.3 / -55.7</td>
</tr>
<tr>
<td>Cld Frac</td>
<td>0.88</td>
<td>0.51</td>
</tr>
<tr>
<td>Ctop [hPa]</td>
<td>732.0</td>
<td>568.3</td>
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</table>
Hurricane Isabel case study
Retrieved Ozone along Footprints 80

Cloudy RTV

ECMWF

Radiance at 911 cm\(^{-1}\)
Gran 11, Footprints 80

Footprints 80: AIRS RTV Ozone [ppmv]

Footprints 80: ECMWF Anl Ozone [ppmv]
Case Study 1: 07-22-2006, AIRS granule 8 (asc)
“Interesting SH 2-layer cloud structure”
Examples of Relative Humidity RTV and ECMWF profiles

Selected profiles from AIRS G011, Sept-8, 2006.
AIRS BT Spectrum at ARM

Temp. Inversion Sounding with Cirrus cloud contamination At ARM site

Granule 092, 12-15-2006
BT at 811.2 cm⁻¹

Lat/Lon: 36.6/-97.4
Synergistic use of imager/sounder for sounding performance improvement

- Advanced IR sounder has limited information BELOW clouds
- IR imager data has high spatial resolution, which give “clear holes” within partially cloudy sounder footprints
- Cloudy soundings can be improved through imager/sounder cloud-clearing, or imager/sounder direct sounding approach
Cloud Clearing (Li et al., 2005)

- Cloud clearing of hyperspectral radiance is dealing with “clear” scene.
- It may encounter with instrumental noise problem.
AIRS BT (11.7 μm) image (granule 184)

AIRS/ECMWF/Dropsonde comparison (Sept. 24, 2004)

Dropsonde location
Imager/Sounder CC Pros/Cons

- **Advantages**
  - No cloudy RTM needed

- **Disadvantages**
  - Limited cloudy (uniform) situations
  - Noise amplification in cloud-cleared radiances
Imager/Sounder direct sounding - Retrieval Simulations

- With clear MODIS pixels information, RMSE is reduced in AIRS cloudy retrieval, especially in atmospheric boundary layer.
Case Study (1)
Granule 196, 09 May 2003
Summary & Conclusions (1/2)

- Handling surface IR emissivity is critical for the improved hyperspectral IR sounding retrieval, since suboptimal treatment of surface emissivity is not only negatively affecting the boundary layer sounding performance but it is also degrade profile in mid-tropospheric layers:
  - CIMSS has developed retrieval algorithm with improved initial emissivity (Seebor databases, et al.) and simultaneously retrieve emissivity spectrum (in P.C. domain) together with sounding profiles in clear skies.
  - In cloudy skies, the emissivity is fixed with the initial guess assigned from the database;
Summary & Conclusions – (2/2)

- IR alone cloudy sounding algorithm has been developed for simultaneous retrieval of cloud properties and soundings:
  - Future work will focus on the effective treatment of cloud parameterization especially those variables such as size, and optical thickness and phase.
- Synergistic use of sounder and imager measurements are demonstrated with limited case studies:
  - For now preprocessing of the co-registration between and the optimal use of the clear/cloudy sounding sub-pixels (imager IFVOs) are the road blocks.