Current Sounding Capability from Satellite Meteorological Observation with Ultra-spectral Infrared Instruments

Daniel K. Zhou, Xu Liu, and Allen M. Larar and many others …

NASA Langley Research Center
Hampton, VA 23681, USA
1. Ultra-spectral IR Instruments
2. IR-only Retrieval Algorithm Introduction
3. Retrieval Simulation Analysis
4. Retrieval Demonstration from Real Satellite Measurements
5. Validation and Inter-comparison (JAIVEx)
6. Future Ultra-spectral IR Instruments on GEO Satellites
7. Summary
NPOESS Airborne Sounder Testbed (NAST) on ER-2, WB-57, Proteus aircraft since July 1998
AIRS: Since May 2002

Atmospheric InfraRed Sounder (AIRS) instrument (by NASA) on Aqua Satellite launched on 4 May 2002
Infrared Atmospheric Sounding Interferometer (IASI) instrument (by CNES / EUMETSAT) on MetOp-A Satellite launched on 19 October 2006
Retrieval Parameters from These Systems

Brightness Temperature or Radiance Spectrum

Geophysical Parameters

Retrievals under clear conditions:
- Surface properties (skin temp and emissivity).
- Atmospheric temperature and moisture profiles.
- Atmospheric CO and O₃ abundances.

Retrievals under cloudy conditions:
- Atmospheric profile through optically thin cirrus clouds and above optically thick clouds.
- Effective cloud parameters (i.e., cloud top pressure, particle size, and optical depth).
PART A: REGRESSION RETRIEVAL (Zhou et al., GRL 2005)
Using an all-seasonal-globally representative training database to diagnose 0-2 cloud layers from
training relative humidity profile:
A single cloud layer is inserted into the input training profile. Approximate lower level cloud using
opaque cloud representation.
Use parameterization of balloon and aircraft cloud microphysical data base to specify cloud effective
particle diameter and cloud optical depth:
Different cloud microphysical properties are simulated for same training profile using random
number generator to specify visible cloud optical depth within a reasonable range. Different habitats
can be specified (Hexagonal columns assumed here).
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.
Compute EOFs and Regressions from clear, cloudy, and mixed radiance data base:
Regress cloud, surface properties & atmospheric profile parameters against radiance EOFs.

PART B: 1-D VAR. PHYSICAL RETRIEVAL (Zhou et al., JAS 2007)
A one-dimensional (1-d) variational solution with the regularization algorithm (i.e., the minimum
information method) is chosen for physical retrieval methodology which uses the regression
solution as the initial guess.
Cloud optical/microphysical parameters, namely effective particle diameter and visible optical
thickness, are further refined with the radiances observed within the 10.4 μm to 12.5 μm window
region.
**HYBRID RETRIEVAL ALGORITHM FLOWCHART**

- **Statistical EOF Physical Regressions**
- **Simultaneous 1-D Var. Iterative Matrix Inversion**

**Flowchart Details**:
- **Calibrated spectral radiances**
- **Measured raw data**
- **Calibration**
- **Regression retrieval using “clear” coefficients**
- **Regression retrieval using “cloud height grouped” coefficients for water**
- **Regression retrieval using “cloud height grouped” coefficients for ice**
- **Regression retrieval using “all cloud” coefficients category to predetermine cloud height**
- **Historical training data with cloud parameters for radiance simulation including a realistic cloud radiative transfer calculation**
- **Cloud optical thickness and particle size**
- **Cloud parameter fixed for refining thermal properties**
- **Physical retrievals of atmospheric & cloud properties**

**General Matrix Inversion Solution**:
\[
\delta R = A \delta Q,
\]
where
\[
\delta Q = \left( A^T E A + \gamma I \right)^{-1} A^T E \left( \delta R + A \delta Q \right)
\]

where:
- \( n \) = iteration number; \( k \) = pressure (P) grid number
- \( Q \) = variables \([i.e., T(P), q(P), T_s, P_s, P_{cld}, \tau, D_e(\tau) \ldots]\)
- \( Q_0 \) = regression retrieval
- \( R_m \) = measured radiance
- \( R_c(Q) \) = calculated radiance from \( Q \)
- \( A \) = Jacobian Matrix
- \( A_j = (R_j(Q) - R_j(Q_0))/\delta Q_j \) for cloud parameters
- \( E \) = error covariance matrix
- \( \gamma \) = Lagrangian multiplier (optimized in the iteration)
**Synthetic analysis:** the truth profile (i.e., the radiosonde observation) is known and the retrieval can be directly compared with the truth to define retrieval accuracy due to (1) instrumental noise and (2) retrieval error introduced mainly by so-called “ill-posed” retrieval model. The disadvantage of this approach is that forward radiative transfer model error is not included.

### Under Clear Conditions over Water:
- **No. of Samples:** 6262  
- **Ts Bias:** 0.05 K  
- **Ts STDE:** 0.97 K

### Under Clear Conditions over Land:
- **No. of Samples:** 5868  
- **Ts Bias:** 0.25  
- **Ts STDE:** 1.42
Under Cloudy Conditions:

- No. of Samples: 3172
- Hc Bias: 0.29 km
- Hc STDE: 1.66 km
- COT Bias: -0.25
- COT STDE: 0.79
- De Bias: -2.48 μm
- De STDE: 11.60 μm
Variance of Test Dataset and IASI Retrievals

Under Clear Conditions

Under Cloudy Conditions
IASI Retrieval Demo: Cloud Parameters & Ts

Cloud Top Height (km)

Cloud Optical Depth

Cloud Particle Diameter (\mu m)

Surf Temp (K)

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
IASI vs. GOES-12: Cloud

20 Aug. 2007

Cloud Top Height (km)

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
IASI Retrieval Demo: Moisture Distribution

20 Aug. 2007

RH Horizontal Distribution (%)  24.49 km

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
**Location/dates:**
Ellington Field (EFD), Houston, TX, 14 Apr – 4 May, 2007.

**Aircraft:**
- NASA WB-57 (NAST-I, NAST-M, S-HIS);
- UK FAAM BAe146-301 (ARIES, MARSS, SWS; dropsondes; in-situ cloud phys. & trace species; etc.).

**Satellites:**
- Metop (IASI, AMSU, MHS, AVHRR, HIRS).
- A-train (Aqua AIRS, AMSU, HSB, MODIS; Aura TES; CloudSat; and Calipso).

**Ground-sites:**
- DOE ARM CART ground site (radiosondes, lidar, etc.)

**Participants:**
- include NASA, UW, MIT, IPO, NOAA, UKMO, EUMETSAT, ECMWF, …

---

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
Retrieval Consistency Check: fitting residual

**Fitting Residual:** STD of the difference between measured and retrieval simulated brightness temperature over physical retrieval channels.

Clear Fitting Residual

Cloudy Fitting Residual
Retrieval Consistency Check: Fitting Statistics

Clear fitting sample (35.36N, 93.67W)

Cloudy fitting sample (27.51N, 96.18W)

Clear fitting statistics over 4786 samples

Cloudy fitting statistics over 483 samples
IASI Retrieval: Cloud Parameters

GOES-12 IR image

Eff. cloud top height (km)

Cloud eff. Optical depth

Cloud eff. particle diameter (µm)
IASI Retrieval: Surface Parameters

Surface Skin Temperature (K)

Water Emissivity Sample

Surface Emissivity @ 12 µm

Land Emissivity Sample

Surface Emissivity @ 11µm

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
IASI Retrieval: ΔTemp and RH Fields
IASI Retrievals vs. Radiosondes

Radiosonde and IASI retrieval comparison and statistical profiles over 20 radiosondes

Note:
12:00 UTC = 07:00 Local
15:48 UTC = 10:48 Local

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
High-Vertically-Resolved Retrievals

- Dropsondes
- Radiosondes
- Temp Deviation from the Mean (K)
- Relative Humidity (%)

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
1. The retrieval improvement based on the EOF statistical regression through physical iterative retrieval is only contributed by IASI measurements as the minimum information methodology used.

2. A high-vertically-resolved atmospheric structure is captured very well by IASI measurements and/or retrievals; not only in the troposphere, but also in the boundary layer.
IASI (15:48 UTC) vs. AIRS (19:30 UTC)

**IASI Retrieval**
- Temp Deviation from the Mean (K)
- Relative Humidity (%)

**AIRS Retrieval Interpolated to IASI FOV**
- Temp Deviation from the Mean (K)
- Relative Humidity (%)
NAST-I: Connection between IASI and AIRS

Difference is mainly due to
• instrument difference between IASI and AIRS,
• spatial resolution difference between NAST-I and IASI (or AIRS), and
• retrieval uncertainty including radiative transfer models difference.
1. A state-of-the-art IR-only retrieval algorithm has been developed with an all-seasonal globally representative EOF physical regression and followed by 1-D Var. physical iterative retrieval for IASI, AIRS, and NAST-I.

2. The benefits of this retrieval are to produce atmospheric structure with a single FOV horizontal resolution (12 km for IASI and AIRS), accurate profiles above the cloud (at least) or down to the surface, surface parameters, and/or cloud microphysical parameters.

3. Initial case validation indicates that surface, cloud, and atmospheric structure (include TBL) are well captured by IASI and AIRS measurements. Coincident dropsondes during the IASI and AIRS overpasses are used to validate atmospheric conditions, and accurate retrievals are obtained with an expected vertical resolution.

4. JAIVEx has provided the data needed to validated retrieval algorithm and its products which allows us to assess the instrument ability and/or performance.

5. Retrievals with global coverage are under investigation for detailed retrieval assessment. It is greatly desired that these products be used for testing the impact on Atmospheric Data Assimilation and/or Numerical Weather Prediction.
Fine-scale atmospheric horizontal features with high vertical resolution from satellite global observations with advanced ultra-spectral instruments have been realized for the first time.
4-d Digital Movie Camera:

2-d Horizontal: Large area format focal plane detector arrays.

Vertical: Fourier transform spectrometer

Time: Geostationary satellite

Revolutionary Technology for Observing Atmospheric Temperature, Moisture, Winds, and the Transport of Pollutant Gases

An Opportunity for Greatly Improved Environmental Forecasts

“GIFTS”
Wind Profile Objective:
High resolution, vertical (1-2 km) and horizontal (50 km), cloud and water vapor wind profiles with a 4 m/s accuracy.

An algorithm to derive clear-sky, altitude-resolved atmospheric motion vectors (AMV) is being developed and evaluated using simulated ultra-spectral data based on the GIFTS instrument [Velden et al., 2004; 2005].
GIFTS Science Objectives

Science Products:
- Water vapor (soundings, fluxes, winds): $\varepsilon < 20\%$ per 1-2 km layers
- Temperature (sounding, stability): $\varepsilon < 1^\circ\text{K}$ per 1-2 km layers
- Wind Velocity: $\varepsilon < 4 \text{ m/s}$ per 2 km layers
- Carbon monoxide concentration (2 Layers): $\varepsilon < 10\%$ per 5 km layers
- Ozone concentration (4 Layers): $\varepsilon < 10\%$ per 8 km layers
- Surface Temperature: $\varepsilon < 0.3^\circ\text{K}$ for sea; $\varepsilon < 1^\circ\text{K}$ for land
- Aerosol Concentration and Depth: $\varepsilon < \text{TBD}$
- Clouds (altitude, optical / microphysical properties, “winds”) [not fully legible]

GIFTS Sampling Characteristics:
- Two 128x 128 Infrared focal plane detector arrays with 4 km footprint size
- A 512 x 512 Visible focal plane detector arrays with 1 km footprint size
- Field of Regard 512 km x 512 km at satellite sub-point
- 11 second full spectral resolution integration time per Field of Regard
- $\sim 80,000$ Atmospheric Soundings every minute

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
Spectral Radiance Accuracy Objective:

- **Spectral Coverage:** 680-1150 cm\(^{-1}\) and 1650-2250 cm\(^{-1}\)
- **Spectral Resolution:** 0.6 cm\(^{-1}\), unapodized
- **Spectral Stability:** 1 part per 106 (3 sigma)
- **Absolute Radiometric Accuracy:** 1.0 K (3 sigma)
- **Radiometric Noise:**
  - LW Band: 0.4 (mW/m\(^2\) cm\(^{-1}\) str)
  - SW Band: 0.06 (mW/m\(^2\) cm\(^{-1}\) str)
GIFTS EDU Ground Based Experiment

The 3rd CSA-IAA Conference; Shanghai, China; Oct. 29 – Nov. 1, 2008
To demonstrate GIFTS 4-D observation ability with the GIFTS EDU on the ground, an experiment called Outgas Monitoring Event (OME) is designed to monitor both temporal and spatial variations of the atmosphere with the GIFTS EDU when Sulfur Hexafluoride (SF$_6$) gas is released in the near field.
Ground Based Experiment: OME

To demonstrate GIFTS 4-D observation ability with the GIFTS EDU on the ground, an experiment called Outgas Monitoring Event (OME) is designed to monitor both temporal and spatial variations of the atmosphere with the GIFTS EDU when Sulfur Hexafluoride (SF₆) gas is released in the near field.

Illustrations of SF6 outgas measurements provided by the GIFTS EDU on 18 September 2006 – a demonstration of the GIFTS image tracking ability.
One of the fundamental advantages of the GIFTS concept is illustrated by the spectral images shown in the video below, an example of the lunar and atmospheric images obtained with two GIFTS infrared detector arrays indicating that the lunar and atmosphere image is a function of wavenumber.

Illustrations of lunar and atmospheric measurements provided by the GIFTS EDU on 11 September 2006 – a demonstration of the GIFTS imaging spectrometer measurement ability.
Fine-scale atmospheric horizontal features with high vertical resolution from satellite global observations with advanced ultra-spectral instruments have been realized for the first time.

GIFTS EDU imaging and tracking capability demonstrates that quasi-continuous measurements of the moisture flux can be obtained for timely forecasts of storm intensity changes.