Development of physical retrieval algorithm for clear sky atmospheric profiles from SEVIRI, GOES Sounder and ABI infrared radiances

Jun Li

Cooperative Institute for Meteorological Satellite Studies
University of Wisconsin-Madison, Madison, WI 53706, U.S.A.

Jun.Li@ssec.wisc.edu, http://www.ssec.wisc.edu/~jli

Thanks to many CIMSS, STAR and EUMETSAT collaborators

28 November 2007
CDOP NWC SAF Workshop on Physical Retrieval of Clear Air Parameters from SEVIRI Agenda
Outline

• Introduction to GOES Sounder and ABI IR bands
• Algorithm development
• Results and validation
• Applications
Considerations

• Build upon the legacy operational GOES Sounder SFOV (Single Field of View) sounding algorithms for soundings and related nowcasting products

• Combing forecast information and IR radiances

• Incorporate temporal continuities into processing

• Better handling surface IR emissivities
ABI (blue) and current GOES sounder (green) spectral coverage compared showing a high spectral resolution brightness temperature spectrum (black). ABI has few bands for upper level temperature. (Figure from Tim Schmit at STAR)
**Description: GOES-I(8)/P Sounders**

- 19 channels (18 Infrared; 1 Visible)
- Spatial resolution: ~ 10km
- Hourly scanning over CONUS and adjacent waters
- Products include standard imagery and derived, Level-2 products
SEVIRI (blue) has only four sounding bands (one CO2, one O3 and two H2O) (Figure from Mat Gunshor at CIMSS)
## ABI IR Bands

<table>
<thead>
<tr>
<th></th>
<th>Wavelength Range</th>
<th>Surface Reflectance</th>
<th>Band Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>3.80–4.00</td>
<td>3.90</td>
<td>2</td>
<td>Surface and cloud, fog at night, fire, winds</td>
</tr>
<tr>
<td>8</td>
<td>5.77–6.6</td>
<td>6.19</td>
<td>2</td>
<td>High-level atmospheric water vapor, winds, rainfall</td>
</tr>
<tr>
<td>9</td>
<td>6.75–7.15</td>
<td>6.95</td>
<td>2</td>
<td>Midlevel atmospheric water vapor, winds, rainfall</td>
</tr>
<tr>
<td>10</td>
<td>7.24–7.44</td>
<td>7.34</td>
<td>2</td>
<td>Lower-level water vapor, winds, and SO$_2$</td>
</tr>
<tr>
<td>11</td>
<td>8.3–8.7</td>
<td>8.5</td>
<td>2</td>
<td>Total water for stability, cloud phase, dust, SO$_2$ rainfall</td>
</tr>
<tr>
<td>12</td>
<td>9.42–9.8</td>
<td>9.61</td>
<td>2</td>
<td>Total ozone, turbulence, and winds</td>
</tr>
<tr>
<td>13</td>
<td>10.1–10.6</td>
<td>10.35</td>
<td>2</td>
<td>Surface and cloud</td>
</tr>
<tr>
<td>14</td>
<td>10.8–11.6</td>
<td>11.2</td>
<td>2</td>
<td>Imagery, SST, clouds, rainfall</td>
</tr>
<tr>
<td>15</td>
<td>11.8–12.8</td>
<td>12.3</td>
<td>2</td>
<td>Total water, ash, and SST</td>
</tr>
<tr>
<td>16</td>
<td>13.0–13.6</td>
<td>13.3</td>
<td>2</td>
<td>Air temperature, cloud heights and amounts</td>
</tr>
</tbody>
</table>

Schmit et al. 2005, BAMS – Introducing the next generation of ABI on GOES-R
ABI has only 1 CO₂ band, so upper-level temperature will be degraded compared to the current sounder.
GOES-13 Sounder WFs

The GOES-N sounder has 5 CO₂ bands, and more SW bands than ABI.
Question

- Can ABI be used to continue the GOES Sounder legacy product before we have hyperspectral IR sounding system on GEO orbit?
Near global simulation on ABI, GOES Sounder and HES alone

- ABI alone
- GOES Sounder alone
- HES alone
RMS of Temperature

HES 10 km

ABI alone!

Retrieval Simulations
**Retrieval Simulations**

**ABI alone!**

- GOES-N
- ABI 5x5
- ABI + GOES-N
Regional simulation (using forecast information)
(update on 07 March 2007)

- Using time/space collocated RAOB/Forecast over CONUS
- HES end formulation assumption, GOES-13 (for current Sounder class), and ABI were used in simulation. PORD noise were used for HES and ABI,
- Total precipitable water (TPW) and Lifted Index (LI) are used for performance analysis
Lifted Index

Root Mean Square Error

- Forecast: 2.27
- ABI (5X5) + fcst: 2.19
- GOES 13 + fcst: 2.18
- HES + fcst: 1.78
Root Mean Square Error

- Forecast: 0.40
- ABI (5x5) + fcst: 0.32
- GOES 13 + fcst: 0.31
- HES + fcst: 0.16
Error Analysis

Temperature (left panel) and water vapor mixing ratio (right panel) background error covariance matrix from forecast model, B, and analysis error covariances matrix, A, with ABI, GOES-12 Sounder and HES final formulation.
Summary of Simulations

- ABI/SEVIRI alone temperature is degraded significantly from GOES Sounder alone, ABI alone moisture has comparable information of GOES Sounder alone.

- ABI/SEVIRI + forecast and GOES Sounder + forecast have similar precisions on temperature, moisture profiles, TPW, LI.

- Both GOES Sounder and ABI/SEVIRI has significant less temperature and moisture information than HES like hyperspectral IR sounder.
The ABI can provide *continuity* of current Sounder products

— Operational products —

<table>
<thead>
<tr>
<th>Product</th>
<th>Temporal /Latency</th>
<th>Spatial</th>
<th>Accuracy</th>
<th>Overall</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiiances</td>
<td>ABI ~ 20X faster</td>
<td>Comparable (when averaged)</td>
<td>Comparable</td>
<td>Comparable</td>
<td>Only 1 CO2 band on ABI (18 vs 10 IR)</td>
</tr>
<tr>
<td>TPW/LI Skin Temp</td>
<td>ABI ~ 20X faster</td>
<td>Comparable (when averaged)</td>
<td>Sounder more precise</td>
<td>Comparable</td>
<td></td>
</tr>
<tr>
<td>Profiles</td>
<td>ABI ~ 20X faster</td>
<td>Comparable (when averaged)</td>
<td>Sounder more precise</td>
<td>Comparable</td>
<td>Worse upper-level T and lower-level moisture</td>
</tr>
</tbody>
</table>

- For continuity only

*ABI better than N Sounder*

*ABI comparable to N Sounder*

*ABI worse than N Sounder, but acceptable*

*ABI worse than N Sounder, unacceptable*

(Slide from Tim Schmit)
Much improved spatial coverage (and hence total product latency) with ABI over the current Sounder

Current GOES Sounder coverage in **one hour**

ABI in **5 minutes**

**Cloud Top Pressure**
Improved spatial resolution with ABI over the current Sounder
Lifted Index simulations using GOES sounder

LI from Current GOES Sounder (GOES Sounder and forecast)

LI from “ABI” from GOES Sounder (via channel selection) and forecast

LI first guess (from forecast)
Algorithm development/improvement

- Noise filtering for radiances – spatially and temporally
- Handling surface emissivities
- Physical inverse of radiances
- Using time continuity
CIMSS Legacy Atmospheric Profile
Processing Overview

- Radiance measurements (Level 1B)
- Background profiles and error covariance matrix
- Forecast Error Co-var
- Leo data (optional) Forecast Surface T/q
- Global training and emissivity database
- Profiles and Radiance match up data

Best first guess

Optimal RTA bias estimate

Optimal Inverse Algorithm

Profiles surface properties

Best validation (RAOB, MW, GPS, analysis, etc.)

QA

Level 2 products

Spatial Filtering Temporal Filtering

Optimal Radiances
Example of GOES-13 band 7 radiances: before detriping (upper left), after destriping (upper right), and the differences (lower left)
Noise filtering – inverted cone idea from Paul Menzel

- Weighted averaging
- Closer FOVs have more weights
- Averaging area increases for channels peaking in the upper atmosphere
How to evaluate the results

- Compare the filtered and unfiltered
  - The difference image should have a spatially evenly distributed noise pattern
  - The difference should have a zero mean and comparable STD as the instrument’s noise specifications
- Noise is better viewed on channel difference (close channels only) image, so after the filtering
  - The gradient of signals should be preserved
  - The random noise should be reduced
Channel 1 (14.72 µm)

Ch 1 radiance (mW/(m²•sr•cm⁻¹)) before filtering

Ch 1 radiance (mW/(m²•sr•cm⁻¹)) after filtering

Difference (mW/(m²•sr•cm⁻¹)) (after - before)

Histogram of difference

GOES-12 Sounder

2007114
00 UTC
mean: 0.0015079
std: 0.74145
NEDR: 0.77
Channel 2 (14.34 µm)

Ch 2 radiance (mW/(m²•sr•cm⁻¹)) before filtering

Ch 2 radiance (mW/(m²•sr•cm⁻¹)) after filtering

Difference (mW/(m²•sr•cm⁻¹)) (after - before)

Histogram of difference

2007114
00 UTC
mean: -0.015539
std: 0.58819
NEDR: 0.61

GOES-12 Sounder
Channel 3 (14.08 μm)

Ch 3 radiance (mW/(m²•sr•cm⁻¹)) before filtering

Ch 3 radiance (mW/(m²•sr•cm⁻¹)) after filtering

Difference (mW/(m²•sr•cm⁻¹)) (after - before)

Histogram of difference

2007114
00 UTC
mean: -0.0077469
std: 0.30899
NEDR: 0.45

GOES-12 Sounder
Channel 12 (6.52 μm)

Ch 12 radiance (mW/(m²•sr•cm⁻¹) before filtering

Ch 12 radiance (mW/(m²•sr•cm⁻¹) after filtering

Difference (mW/(m²•sr•cm⁻¹) (after - before)

Histogram of difference

2007114
00 UTC
mean: -0.0022455
std: 0.095731
NEDR:0.11

GOES-12 Sounder
Channel 1 – Channel 2

Ch1 - Ch2 (mW/(m²•sr•cm⁻¹)) before filtering

Ch1 - Ch2 (mW/(m²•sr•cm⁻¹)) after filtering
Channel 2 – Channel 3

Ch2 - Ch3 (mW/(m²•sr•cm⁻¹)) before filtering

Ch2 - Ch3 (mW/(m²•sr•cm⁻¹)) after filtering
Physical module Flow Chart

Start

Input
BT, forecast
Surface analysis
parameters

Regression
(T,W,O,Ts,emis.)

Next iteration

Error matrix, EOF file for T(p) and q(p)

Forward model calculation

Jacobian calculation

$\delta R = R_m - R_c$

Decrease gamma
Increase gamma

Inversion calculation
Update profiles

Fail < \( f_m \)
Check Iteration < \( I_m \)
\( \delta R > \delta R_c \)

no

yes

no

yes

(Exit physical module)

Return updated T,W,O,Ts,emis.

Output

End

(To physical module)
Algorithm Development Strategy

- **Use spatial continuities (users decide)**
  - For ABI
    - 2 km product
  - For SEVIRI
    - 3 km product
  - For GOES Sounder
    - 10 km product

- **Using forecast information (interpolated spatially, temporally, vertically)**
  - Request forecast output at least every 3 hours, hourly data is the goal.
  - The grid size of forecast should be 10 km if possible

- **Use two-step approach**
  - Statistical retrieval that requires a nearly global representative training data set
  - Physical retrieval takes into account the IR emissivities, surface pressure
    - Pre-determined emissivities
    - Surface pressure from forecast

- **Quality Control**
  - Generate QA index during both statistical and physical procedures
    - Residual Index (RI)
    - Convergence Index (CI)
    - Cloud Contamination Index (CCI)
    - Estimated Error (EE)
    - Quality Indicator (QI) derived from above parameters
Questions Remain

• How to better use of temporal continuity?

• Improving emissivity prior information, adjusting emissivity in physical approach? Study shows that adjustment on emissivities in hyperspectral sounding retrieval is reliable (Li et al. 2007 - GRL), but for broad bands?
Algorithm Development Strategy

**Validation:**

- **Truth data**
  - Rawinsondes
  - Ground based microwave radiometer water vapor measurements
  - GPS water vapor measurement

- **Algorithm Test plan**
  - Develop analyses using truth data above on proxy/simulated cases discussed previously to perform verification/validation

- **Error Estimation**
  - Based on our heritage approaches of validating sounding products

- **Model impact**
  - Assimilate product in regional model for impact (this is suggested, need additional resource for this task)
Validation and Applications

- Validation of GOES sounding product
- Applications of GOES Sounder products on convective storm cases
Current GOES Sounder retrievals gives reasonable accuracy when compared with microwave radiometer TPW measurements. The new algorithm improves the legacy product.

**Validation with ARM site measurements**

- **Legacy retrieval**
- **Regression**
- **Forecast**

**Current GOES Sounder retrievals**

- Bias: -0.4553
- RMSE: 2.7959

- Bias: -0.66769
- RMSE: 2.6129

- Bias: 0.36334
- RMSE: 2.2055

- Bias: -0.24617
- RMSE: 2.2472

**New RTVL (reg guess)**

**New RTVL (fcst guess)**
Temperature & Moisture Profiles

- **Physical Retrieval** (Ma et al, 1999)
  - Short-term (< 12 hrs) GFS model forecasts provide first guess
  - Hourly surface observations, NCEP SST analysis provide boundary conditions
  - Computed at 40 levels
  - Pixel level retrievals

- **Distributed to AWIPS, NCEP**

- **Operational Applications**
  - **Nowcasting**
    - Aids in monitoring of vertical structure of temperature and moisture of the atmosphere
    - Fills in gaps between conventional observations
    - Convective potential and morphology
    - Situational awareness in pre-convective environments for potential watch/warning scenarios
The lifted index (LI)

- The LI, a measurement of atmospheric instability

- positive $\rightarrow$ a stable atmosphere

- $[0\ -3] \rightarrow$ marginally unstable

- $[-3\ -6] \rightarrow$ moderately unstable

- $[-6\ -9] \rightarrow$ very unstable

- $\leq -9 \rightarrow$ extreme instability

- Best chances of a severe thunderstorm $\leq -6$. 

Diagram showing atmospheric conditions and thresholds for LI values.
EXCESSIVE RAINFALL POTENTIAL OUTLOOK
HYDROMETEOROLOGICAL PREDICTION CENTER...NWS...CAMP SPRINGS MD

GOES SOUNDER DATA SHOWS Precipitable Water from the Sounder (PWS) SOUTH OF THE OUTFLOW BOUNDARY ARE IN THE 1.60 TO 1.70 INCH RANGE. THE SOUNDER DATA ALSO INDICATES THAT THE AIRMASS TO THE WEST ACROSS IL IS CONTINUING TO DESTABILIZE. ALL THE ABOVE ARGUE FOR THE POTENTIAL FOR ISOLATED 3 TO 5 INCH RAINFALL BEFORE THE SYSTEM STARTS SHIFTING EWD.

Janesville, WI received 4 inches of rain; Sullivan, WI had 3 inches.
Super Cell

Air mass tracking 22 UTC, 13 April 2006

Clustering using 15 Sounder radiances

GOES Sounder retrieved RH

Potentially convective unstable
Air mass tracking  00 UTC, 14 April 2006

Super Cell
Dry air
Conditionally Unstable

Clustering using 15 Sounder radiances

GOES Sounder retrieved RH

Air mass classification 20060414 00 UTC

Dry
wet
Super Cell

BT(K) of 11 um 20060414 00 UTC

Pressure(hPa)
Relative Humidity(%)
Air mass tracking 03 UTC, 14 April 2006
Forecast LI

22 UTC on 24 April 2007

GOES Sounder LI

Tornado that killed 10 and injured 120 persons in the Eagle Pass, Texas area
Large instabilities will initialize the supercell. It is also reasonable to assume instabilities under these clouds are large.
20 UTC
24 April 2007

Case 1, a tornadic supercell
Eagle Pass, Texas

Increased areas of large instabilities.
Supercell formed. Large instabilities from the south support the supercell.

Case 1, a tornadic supercell
Eagle Pass, Texas
Supercell kept growing. Large instabilities from the south still support the supercell.

This small area of extremely large instabilities will trigger another convective storm.

Watch out for this increasing instabilities here.

Case 1, a tornadic supercell
Eagle Pass, Texas

22 UTC
24 April 2007

Tornado that killed 10 and injured 120 persons in the Eagle Pass, Texas area
Supercell kept growing. Large instabilities from the south still support the supercell.

The second convective storm formed to the north of the supercell.

Instabilities kept growing here.
Supercell kept growing. Large instabilities from the south still support the supercell.

The second convective storm grew quickly with the support from the large instabilities.

Instabilities kept growing here.

Case 1, a tornadic supercell
Eagle Pass, Texas

00 UTC
25 April 2007
Supercell kept growing. Large instabilities from the south still support the supercell.

Without constant moisture supply, the instabilities stopped increasing. The convective storm died out.

Instabilities kept growing here.
The area of large instabilities was decreasing. The supercell began dying out.

The second storm was history.

The third convective storm formed with the supply of large instabilities.
No instabilities support the supercell. The supercell was history.

Increased area of instabilities kept the third convective storm growing quickly.
Increased area of instabilities kept the third convective storm growing quickly. It was reasonable to assume large instabilities under the clouds within this area.
A lot of areas were covered by clouds. And the storm kept growing.
A lot of areas were covered by clouds. And the storm still kept growing.
A lot of areas were covered by clouds. And the storm still kept growing.
A lot of areas were covered by clouds. The area of large instabilities began decreasing. The storm began dying out.

Case 1, a tornadic supercell
Eagle Pass, Texas

08 UTC
25 April 2007
Case 1, a tornadic supercell
Eagle Pass, Texas

These instabilities were too far away from the storm. The storm kept dying out.
All storms were gone!!!

10 UTC
25 April 2007

Case 1, a tornadic supercell
Eagle Pass, Texas
Total Precipitable Water
Cloud-Top Height
Surface Skin Temperature
Lifted Index from T/° soundings in clear skies
## Legacy products and operational applications

<table>
<thead>
<tr>
<th><strong>GOES Sounder/ABI Profile Related Legacy Products</strong></th>
<th><strong>Operational Use within NWS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer &amp; Total Precipitable Water</td>
<td><strong>Assimilation</strong> into NCEP operational regional &amp; global NWP models; <strong>display and animation</strong> within NWS AWIPS for use by forecasters at NWS WFOs &amp; National Centers in forecasting precipitation and severe weather</td>
</tr>
<tr>
<td>Surface skin temperature</td>
<td><strong>Image display and animation</strong> within NWS AWIPS for use by forecasters at NWS WFOs</td>
</tr>
<tr>
<td>Profiles of temp &amp; moisture</td>
<td><strong>Skew-T diagram display</strong> within NWS AWIPS for use by forecasters at NWS WFOs in forecasting precipitation and severe weather</td>
</tr>
<tr>
<td>Atmospheric stability indices</td>
<td><strong>Image display and animation</strong> within NWS AWIPS for use by forecasters at NWS WFOs in forecasting precipitation and severe weather</td>
</tr>
</tbody>
</table>
NWS 1999 Survey: GOES Sounder Atmospheric Instability

NWS Forecaster responses (summer 1999) to:

“Rate the usefulness of LI, CAPE & CINH (changes in time / axes / gradients in the hourly product) for location/timing of thunderstorms.”

There were 248 valid weather cases.
- Significant Positive Impact (30%)
- Slight Positive Impact (49%)
- No Discernible Impact (19%)
- Slight Negative Impact (2%)
- Significant Negative Impact (0)
Selected References

Summary

• Same improved algorithm can be used for SEVIRI, ABI and GOES Sounder
• Forecast and its error covariance matrix are needed as background information. This is essential for SEVIRI and ABI since only a few “sounding” bands are available
• Handling surface emissivities is very important in sounding process
• Radiance noise filtering is very useful for quality retrievals
• Time continuity should be taken into account in the process, this area needs further investigation
• Geostationary sounding product is very useful for severe storm nowcast