Variational Inversion of Hydrometeors Using Passive Microwave Sensors

-Application to AMSU/MHS, SSMIS and ATMS-

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1. Overview of MiRS Algorithm
2. Concept of Cloud/Precip-clearing
3. Performance Assessment
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1D-Variational Retrieval/Assimilation

MiRS Algorithm

Measured Radiances

Simulated Radiances

Comparison: Fit Within Noise Level?

Yes

No

Solution Reached

Initial State Vector

Forecast Field (1D-Assimilation Mode)

Geophysical Mean Background

Geophysical Covariance Matrix B

Measurement & RTM Uncertainty Matrix E

Geophysical Covariance Matrix B

Forward Operator (CRTM)

New State Vector

Update State Vector

Jacobians

No
Quality Control of MIRS Outputs

- **Convergence Metric:** $\varphi^2$

- **Uncertainty matrix $S$:**

$$S = B - B \times K^T \left( K \times B \times K^T + E \right)^{-1} \times K \times B$$

- **Contribution Functions $D$:** indicate amount of noise amplification happening for each parameter.

$$D = B \times K^T \left( K \times B \times K^T + E \right)^{-1} \times \left( Y(X) - K \times X \right)$$

- **Average kernel $A$:**

$$A = D \times K$$

- If close to zero, retrieval coming essentially from background
- If close to unity, retrieval coming from radiances: No artifacts from background
If $X$ is the set of parameters that impact the radiances $Y_m$, and $F$ the Fwd Operator

*If $F(X)$ Does not Fit $Y_m$ within Noise*

$X$ is not the solution

*F(X) Fits $Y_m$ within Noise levels*

$X$ is a solution

X is the solution

All parameters are retrieved simultaneously to fit all radiances together

Suggests it is not recommended to use independent algorithms for different parameters, since they don’t guarantee the fit to the radiances
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Sounding Retrieval:
- Temperature
- Moisture

To account for cloud, rain, ice, we add the following in the state vector:
- Cloud (non-precipitating)
- Liquid Precipitation
- Frozen precipitation

To handle surface-sensitive channels, we add the following in the state vector:
- Skin temperature
- Surface emissivity (proxy parameter for all surface parameters)

- Instead of guessing and then removing the impact of cloud and rain and ice on TBs (very hard), MiRS approach is to account for cloud, rain and ice within its state vector.
- It is highly non-linear way of using cloud/rain/ice-impacted radiances.
Instead of guessing impact of cloud and rain and ice on TBs (very hard), MiRS approach is to account for cloud, rain and ice within its state vector.

Advantages:
- It is highly non-linear way of using cloud/rain/ice-impacted radiances
- Does not rely on cloud or rain uniform distribution
- Does not rely on cloud resolving models (added uncertainty, need to linearize, speed cost, etc)

Disadvantage:
- Results depend on assumptions made in RT (particle size, distribution, etc)
- Greater reliance on a robust, valid covariance matrix (flow dependent matrix becomes necessary: see poster by K. Garrett).

Is the retrieval stable?
- EOF decomposition for all profiles (T, Q, C, R, I) and emissivity vector.

Is the solution physically consistent? (between T, Q, C, R and I)
- Cov Matrix constraint
- Physical Retrieval & RT constraints
- Convergence (fitting Ym)
- Jacobians to determine signals
Convergence is reached everywhere: all surfaces, all weather conditions including precipitating, icy conditions.

A radiometric solution (whole state vector) is found even when precip/ice present. With CRTM physical constraints.

$$\phi^2 = (\gamma_m - \gamma(X))^T E^{-1} (\gamma_m - \gamma(X))$$

**Previous version**
(non convergence when precip/ice present)

**Current version**
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Hydrometeors Inversion Approach

MIRS Core Products (from 1DVAR)

CLW, IWP and RWP

MIRS Rainfall Rate Algorithm

\[ RR = a_1 \text{CLW} + a_2 \text{RWP} + a_3 \text{IWP} \]

Sensor-independent Function which allows expanding to all sensors easily (pending 1DVAR core products)

Hydrometeors are hard to validate. RR is easier to assess (wrt ground-based radar, gauges). Assessing RR is an indirect validation of IWP, CLW, RWP.

MIRS Rainfall Rate (mm/hr)
Rainfall Rate Assessment

**MiRS Monthly composite (Metop-A)**

- **1DVAR**

**MSPPS Monthly composite (Metop-A)**

- **Heritage algorithm: based on physical regression**

**Significant reduction in Rain false alarm using MiRS, at surface transitions and edges**
MiRS RR part of IPWG Intercomparison (N. America, S. America and Australia sites)

No discontinuity at coasts (MiRS applies to both land and ocean)

Verification statistics for 20090723  n=15707  Verif. grid=0.25° Units=mm/d

<table>
<thead>
<tr>
<th>MIRS_INTG</th>
<th>Analysed MIRS_INTG</th>
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<tbody>
<tr>
<td>&lt;1</td>
<td>10390 689</td>
</tr>
<tr>
<td>≥1</td>
<td>3228 1400</td>
</tr>
</tbody>
</table>

- # gridpoints raining: 4628 2089
- Average rain: 3.0 1.7
- Conditional rain: 10.0 12.4
- Rain volume (mm*km²*10⁶): 33.1 19.5
- Maximum rain: 69.5 85.4

No data:
- <1
- 1-2
- 2-5
- 5-10
- 10-20
- 20-50
- 50-100
- 100-150
- 150-200

Image taken from IPWG web site: credit to Daniel Villa
Upper Limit set by the Rain Gauge to Rain Radar Comparison
Qualitative check of the Cloudy/Rainy radiance handling

Cross-sections of both TRMM and MiRS products at 25 degrees North

Notes:
- Generally, consistent features between TRMM and MiRS (except for expected shift)

- Ice is found on top of liquid rain

- Transition between frozen and liquid is delineated by the freezing level determined from the temperature profile.

- Moisture increases in and around the rain event

- Suggests that these products are reasonably constrained within physical inversion
MiRS is a generic retrieval/assimilation system (N18, N19, Metop-A, DMSP F16/18 SSMIS). Being extended to NPP/ATMS, TRMM/TMI and GPM/Mega-Tropiques.

- All parameters impacting TBs are retrieved simultaneously: sounding, emissivity, skin temperature, cloud, rain, ice, allowing point-to-point variation of emissivity over land.
- Final solution fits measurements (a necessary requirement).
- Inclusion of hydrometeors in retrieval allows processing cloud/rain –impacted radiances. Non-linear cloud-precip clearing.
- Physical Constraints are included through Covariance.
- Assessment of hydrometeors performed using RR as proxy.
- Results show that MiRS RR is consistent with established algorithms perfs, with the added value of a physically consistent solution.
BACKUP SECTION
Cost Function Minimization

Cost Function to Minimize:

\[ J = \frac{1}{2} (X - X_0)^T B^{-1} (X - X_0) \]

To find the optimal solution, solve for:

\[ \frac{\partial J}{\partial X} = J' (X) = 0 \]

Assuming Linearity

\[ y (x) = y (x_0) + K [x - x_0] \]

This leads to iterative solution:

\[ \Delta X_{n+1} = \left[ B^{-1} + K_n T E^{-1} K_n \right]^{-1} \left[ Y_m - Y (x_n) + K_n \Delta X_n \right] \]

More efficient (1 inversion)

Preferred when nChan << nParams (MW)
Covariances using Rainy atmospheric profiles only, rather than a Global climatology, had a significant impact on performances. In the cases examined, the use of a covariance matrix specific to precipitating conditions helps to overcome the loss of radiometric signal in the MiRS physical retrieval.
MiRS General Overview

Vertical Integration and Post-Processing

1DVAR Outputs
- Temp. Profile
- Humidity Profile
- Liq. Amount Prof
- Ice. Amount Prof
- Rain Amount Prof
- Emissivity Spectrum
- Skin Temperature

Core Products

Vertical Integration

Post Processing (Algorithms)

TPW
RWP
IWP
CLW

- Sea Ice Concentration
- Snow Water Equivalent
- Snow Pack Properties
- Land Moisture/Wetness
- Rain Rate
- Snow Fall Rate
- Wind Speed/Vector
- Cloud Top
- Cloud Thickness
- Cloud phase
Similar to handling cloud and hydrometeors, MiRS approach to account for surface-sensitivity of channels is by accounting for emissivity vector within state vector.

Advantages:
- Extend retrieval to all surfaces (only difference is background covariance and mean used).  
  Example: TPW over land.
- Generating an emissivity vector product, clear from atmospheric effects (used for a more accurate estimate of surface parameters)
- Consistent treatment of all parameters globally (same methodology).  
  Example: RR is retrieved over ocean and land using the same code.
- Greater physical distinction between Tskin and Emissivity (based on physical Jacobians and different spectral signatures)
- Allows a point to point variation of emissivity (useful for coasts, after rain, etc)

Disadvantages:
- Great emphasis must be given to the balance between different parameters (so that emissivity does not become a sink hole for variability due to other parameters such as cloud: hard)
- Great constraint is put on the accuracy of emissivity
The PDF of X is assumed **Gaussian**

Operator Y able to simulate measurements-like radiances

Errors of the model and the instrumental noise combined are assumed (1) **non-biased** and (2) **Normally** distributed.

Forward model assumed **locally linear** at each iteration.
All retrieval is done in EOF space, which allows:
- Retrieval of profiles (T, Q, RR, etc): using a limited number of EOFs
- More stable inversion: smaller matrix but also quasi-diagonal
- Time saving: smaller matrix to invert

Mathematical Basis:
- EOF decomposition (or Eigenvalue Decomposition)
  - By projecting back and forth Cov Matrix, Jacobians and X
Retrieval in Logarithm Space

Advantages:
1. Distributions made more Gaussian
2. No risk of having unphysical negative values

Applied to WV, Cloud and precip

\[ J = \frac{\partial R}{\partial \log(x)} = \frac{\partial R}{\partial x} \times \frac{\partial x}{\partial \log(x)} = J \times x \]
Challenges of Profiling in Active Areas

Case of July 8th 2005

Zoom in space (over the Hurricane Eye) and Time (within 2 hours)

MHS footprint size at nadir is 15 Kms. But at this angles range (around 28°), the MHS footprint is around 30 Kms.

All these 4 Dropsondes were dropped within 45 minutes and are located within 10 kms from each other.

Temperature [K]

DeltaT=3K

Water Vapor [g/Kg]

DeltaQ=4g/Kg

[Graphs and maps showing temperature and water vapor data]
TPW Global Coverage

MiRS TPW Retrieval (zoom over CONUS)

Very similar features to GDAS

Smooth transition over coasts
No Discontinuities at Coast

Validation over Australia

Rain Gauge

Courtesy of Elizabeth E. Ebert, Bureau of Meteorology, Australia
International TOVS Study Conference, 17th, ITSC-17, Monterey, CA, 14-20 April 2010.
Madison, WI, University of Wisconsin-Madison, Space Science and Engineering Center,
Cooperative Institute for Meteorological Satellite Studies, 2011.