Introducing NOAA’s Microwave Integrated Retrieval System (MIRS)

S-A. Boukabara, F. Weng, R. Ferraro, L. Zhao, Q. Liu, B. Yan, A. Li, W. Chen, N. Sun, H. Meng, T. Kleespies, C. Kongoli, Y. Han, P. Van Delst, J. Zhao and C. Dean

NOAA/NESDIS
Camp Springs, Maryland, USA

15th International TOVS Study Conference (ITSC-15), Maratea, Italy, October 9th 2006
Contents

1. Overview
2. Algorithm Scientific Basis
3. Performance Evaluation
4. Summary & Online Access
Stated Goals of MIRS

- Algorithm for sounding, imaging, or combination thereof
- Applicable to all Microwave Sensors
- Extend over non-oceanic surfaces & in all-weather conditions
- Operate independently from NWP model forecasts

Benefits

- Reduction of Time/Cost to Adapt to New Sensors
- Reduction of Time/Cost to Transition to Operations
- Improvements in Severe Weather Forecasts
- Better Climate Data Records
MIRS Concept

- Variational Retrieval (1DVAR)
- Algorithm valid in all-weather conditions, over all-surface types
- Cloud & Precip profiles retrieval (no cloud top, thickness, etc)
- Sensor-independent
- Flexibility and Robustness
- CRTM as forward operator, validity-> clear, cloudy and precip conditions
- Emissivity spectrum is part of the retrieved state vector
- EOF decomposition
- Highly Modular Design
- Modeling & Instrumental Errors are input to algorithm

Selection of Channels to use, parameters to retrieve
Contents

1. Overview
2. Algorithm Scientific Basis
3. Performance Evaluation
4. Summary & Online Access
Cost Function Minimization

Cost Function to Minimize:

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

To find the optimal solution, solve for:

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

Assuming Linearity

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

This leads to iterative solution:

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

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

More efficient (1 inversion)

Preferred when \( n_{\text{Chan}} \ll n_{\text{Params}} \) (MW)
Quality Control of MIRS Outputs

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

- **Uncertainty matrix $S$:**
  \[
  S = B - B \times K^T (K \times B \times K^T + E)^{-1} \times K \times B
  \]

- **Contribution Functions $D$:** indicate amount of noise amplification happening for each parameter.
  \[
  D = B \times K^T \left( K \times B \times K^T + E \right)^{-1} \times \left( Y(X) - K \times X \right)_0
  \]

- **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
System Design & Architecture

Heritage Algorithms

- NOAA-18/METOP
  - MSPPS
  - Locally Developed Algorithms for:
    - Temperature Profile
    - Water Vapor Profile
    - Emissivity Spectrum

- DMSP SSMI/S
  - FNMOC Operational Algs
  - Locally Developed Algorithms for:
    - Temperature Profile
    - Water Vapor Profile
    - Emissivity Spectrum

- WINDSAT
  - Combination of:
    - Existing Published Algorithms
    - Complemented by
    - Locally Developed Statistical Algorithms

EDRs

Other MW sensors

- MSPPS
- WINDSAT
Ready-To-Invert Radiances

**Vertical Integration and Post-Processing**

**Advanced Algorithm Outputs**
- Temp. Profile
- Humidity Profile
- Liq. Amount Prof
- Ice. Amount Prof
- Rain Amount Prof
- Emissivity Spectrum
- Skin Temperature

**Core Products**
- TPW
- RWP
- IWP
- CLW

**Core Products**
- Snow Pack Properties
- Land Moisture/Wetness
- Rain Rate
- Snow Fall Rate
- Wind Speed/Vector
- Cloud Top
- Cloud Thickness
- Cloud phase
- Etc.
Contents

1. Overview
2. Algorithm Scientific Basis
3. Performance Evaluation
4. Summary & Online Access
Performance Evaluation

Validation

1. Imaging (TPW)
2. Profiling (T,Q)
3. Over Land (TPW)
4. Hurricane Conditions
QC of the Validation Set

Error increases with increasing time separation

![Graph showing the relationship between standard deviation of TPW Diff and abs value time difference.](image)
Improvement Assessment (*wrt Heritage*)

MSPPS: NOAA’s operational system responsible for deriving microwave products

<table>
<thead>
<tr>
<th></th>
<th>MSPPS (bias)</th>
<th>MIRS (Bias)</th>
<th>MSPPS (Std)</th>
<th>MIRS (Std)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N15</td>
<td>1.87</td>
<td>0.49</td>
<td>4.57</td>
<td>3.85</td>
<td>16%</td>
</tr>
<tr>
<td>N16</td>
<td>1.31</td>
<td>-1.10</td>
<td>4.22</td>
<td>3.85</td>
<td>9%</td>
</tr>
<tr>
<td>N17</td>
<td>2.51</td>
<td>-0.2</td>
<td>4.26</td>
<td>3.30</td>
<td>23%</td>
</tr>
</tbody>
</table>

- Average TPW Standard Deviation Improvement is 16% over ocean
- Better scan angle handling
- Independence from NWP forecast outputs
- Capability extended over land
Performance Evaluation

- Temperature & Humidity profiles using N15,16,17,18
- Comparison with radiosondes (statistical)

Validation

1. Imaging (TPW)
2. Profiling (T,Q)
3. Over Land (TPW)
Raob Profiles with at least 30 levels used. Ocean cases only. Retrievals up to 0.05 mbars. Assessment only up to 300 mbars.

These are real data performances (stratified by sensor)

Results shown here are cloudy (up to 0.15 mm from MIRS retrieval)

Independent from NWP forecast information, including surface pressure

Improvements in progress (scan-dependent covariance Matrix, air-mass pre-classification, etc)
Importance of the Evaluation Set

Focus of current efforts:

- Air-mass preclassification of the background
- Improvement expected from first guess

Caution must be exercised when comparing performances of algorithms on different sets. Types of sets are critical (tropical, polar, clear, cloudy, etc. and their relative percentage in the set).
Performance Evaluation

- TPW retrieval extended over land
- Comparison with GDAS analyses
- Comparison with Radiosondes over land
- Sanity Check of MIRS Emissivity Over Land
Microwave TPW Extended over Land

snow-covered surfaces need better handling

GDAS Analysis

Retrieval over sea-ice and most land areas capturing same features as GDAS

MIRS Retrieval
Validation of TPW Retrieval over Land

- ~4000 NCD IGRA points collocated with NOAA-18 radiances
- Only convergent points over land used
- Only points within 0.5 degrees and within 1 hour used
- Cloudy points included, up to 0.15 mm

- Bias: -1.13 mm
- Std Dev: 4.09 mm
- Corr. Factor: 0.86
- #Points: 4293
Same MIRS code used for retrieval over land and ocean.

MIRS-retrieved Emissivity @ Channel 2 F: 31.40GHz Pol:V+H  2006 JulDay: 32

River/Coast signature
Global Temperature Profiling

No Scan-Dependence in retrieval
Smooth Transition Land/Ocean

QC-failure is based on convergence:
Focus of on-going work

Similar Features Captured
Performance Evaluation

- Temperature profiling in active regions (using NOAA-18 sounders)
Challenges of Profiling in Active Areas

Case of July 8th 2005

Zoom in space (over theHurricane 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]  
Water Vapor [g/Kg]  

DeltaQ = 4g/Kg  
DeltaT = 3K
N-18 Profiling In Active Areas

700 mb

0.2 Hrs 2.6 Kms

700 mb

0.30 Hrs 11.1 Kms

700 mb

0.7 Hrs 4.2 Kms

Deg C

Retrieval

GDAS

DropSonde

Profile of DS Distance Departure
Contents

1. Overview
2. Algorithm Scientific Basis
3. Performance Evaluation
4. Summary & Online Access
MIRS is applied to a number of microwave sensors, each time gaining robustness and improving validation for future new sensors.

- **DMSP SSMIS**
  - Applied Daily

- **POES N18**
  - Applied occasionally

- **CORIOLIS WINDSAT**
  - Tested in Simulation

- **NPP/NPOESS ATMS, MIS**

Cumulative Validation & Consolidation of MIRS
Online Access

Online Scrolling Menus

Microwave Integrated Retrieval System

Home  Overview  Sensor  Algorithm  Testbed  Monitoring  Validation  Document  Download

Geophysical Monitoring  Product
Radiometric Monitoring  Geophysical Performance
Telemetry Calibration Parameters
Products Performance Monitoring – Functionalities (cont’d)

MIRS Products Monitoring

Panel 1
- Sensor: NOAA-18 AMSU-A/MHS
- Product: Ch. Square
- Region: Globe
- 2005, Sep, 23

Panel 2
- Sensor: NOAA-18 AMSU-A/MHS
- Product: TPW
- Region: Globe
- 2005, Sep, 23
Thank You!

Questions?
BACKUP SLIDES
Main Goal in ANY Retrieval System is to find a vector $X$ with a maximum probability of being the source responsible for the measurements vector $Y$.

In plain words:

Mathematically:

$$P(Y) = P(Y|X) \times P(X) = P(X|Y) \times P(Y)$$

Bayes' Theorem (of Joint probabilities):

$$P(X|Y^m) = \frac{P(Y^m|X) \times P(X)}{P(Y^m)} = 1$$
Mathematically:

\[
\text{Maximizing} \quad P(X \mid Y^m) = \exp\left(-\frac{1}{2}(X - X_0)^T B^{-1} (X - X_0)\right) \times \exp\left(-\frac{1}{2}(Y^m - Y(X))^T E^{-1} (Y^m - Y(X))\right)
\]

Is Equivalent to Minimizing

\[
- \ln \left( P(X \mid Y^m) \right)
\]

Which amounts to Minimizing \( J(X) \) – also called COST FUNCTION –

Same cost Function used in 1DVAR Data Assimilation System

\[
J(X) = \left[\frac{1}{2}(X - X_0)^T B^{-1} (X - X_0)\right] + \left[\frac{1}{2}(Y^m - Y(X))^T E^{-1} (Y^m - Y(X))\right]
\]
System Design & Architecture

Radiometric Bias

Ready-To-Invert Radiances

Heritage Algorithms

Advanced Retrieval (1DVAR)

Vertical Integration & Post-processing

MIRS Products

1st Guess

selection

EDRs

NWP Ext. Data

External Data & Tools

Legend

Products To Inversion

Monitored

In Geoph. Monit.

RTM Uncert. Matrx

NEDT Matrx
System Design & Architecture

Raw Measurements
Level 1B Tbs

Radiance Processing & Radiometric Bias Monitoring

Radiometric Bias

NEDT Matrix E

Geophysical Bias

Inversion Process

EDRs

Comparison

External Data & Tools

Ready-To-Invert Radiances

RTM Uncert. Matrix F

NWP Ext. Data

In-Situ Data
Nominal approach: Simultaneous Retrieval

**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.
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.
Retrieval in Reduced Space (EOF Decomposition)

- 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

\[ \Theta = L^T \times B \times L \]

- Diagonal Matrix
  (used in reduced space retrieval)
- Transf. Matrix
  (computed offline)
- Covariance matrix
  (geophysical space)
Retrieval in Logarithm Space

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

Applied to WV, Cloud and precip

\[
J_1 = \frac{\partial R}{\partial \log(x)} = \frac{\partial R}{\partial x} \times \frac{\partial x}{\partial \log(x)} = J \times x
\]
Use of Multiple Microwave Sensors:
- AMSU A/B (or MHS) onboard NOAA-15-16-17-18
- WINDSAT onboard CORIOLIS
- SSMI/S onboard DMSP F-16

Two Types of Validation, depending on parameter
- Quantitative Validation
  - NWP Data (GDAS)
  - Heritage Algorithms (MSPPS)
  - Conventional Radiosondes (from NCEP and from NCDC)
  - GPS-DropSondes
- Qualitative Validation
  - Science Constraints in Retrieval System
  - Capture of known meteorological phenomena

Metrics:
- Standard statistical metrics Bias/RMS/StdV/Correlation
- Case By Case Evaluation (especially for active areas)
## TPW Comparison MIRS vs MSPPS

<table>
<thead>
<tr>
<th>MIRS TPW [mm]</th>
<th>MSPPS TPW [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>m...</td>
<td>m...</td>
</tr>
<tr>
<td>m...</td>
<td>m...</td>
</tr>
<tr>
<td>m...</td>
<td>m...</td>
</tr>
<tr>
<td>m...</td>
<td>m...</td>
</tr>
<tr>
<td>m...</td>
<td>m...</td>
</tr>
</tbody>
</table>

- **MSPPS TPW used as reference**
- **MIRS retrieves the humidity profile. The TPW is integrated in post-processing stage.**
- **MSPPS relies on NWP forecast for both SST and Wind (emissivity).**
- **MIRS is independent of NWP data (even from surface pressure).**
FNMOC Operational Algorithm

SSMIS Retrieved Cloud Liquid Water Path over Ocean
2006-05-29

MIRS Algorithm

MIRS SSMIS EDR Cloud Liquid Water Path over Ocean
2006-05-29

MIRS is more sensitive to small values
(due to use of higher frequency channels)

Retrieval using DMSP F16 SSMI/S
### In-Situ Global Distribution

<table>
<thead>
<tr>
<th>Source</th>
<th>Period</th>
<th>Coverage</th>
<th># of Points</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>POES NOAA15</td>
<td>NCEP</td>
<td>Ocean</td>
<td>1255</td>
<td>Liu &amp; Weng 2004</td>
</tr>
<tr>
<td>POES NOAA16</td>
<td>NCEP</td>
<td>Ocean</td>
<td>1655</td>
<td>Liu &amp; Weng 2004</td>
</tr>
<tr>
<td>POES NOAA17</td>
<td>NCEP</td>
<td>Ocean</td>
<td>1522</td>
<td>Liu &amp; Weng 2004</td>
</tr>
<tr>
<td>POES NOAA18</td>
<td>NCDC-IGRA</td>
<td>Land</td>
<td>~8,000</td>
<td>Durre et al. 2006</td>
</tr>
</tbody>
</table>

**Dataset used for both TPW and Profiling Validation**
Retrieval Bias vs. Viewing Angles

Match-up TPW from radiosondes and AMSU retrieval in 2002. Bias variation to viewing angles. Bias = radiosonde – AMSU
Emissivity Qualitative Validation

Emissivity Difference @ 31 GHz

- Use of GDAS (T,Q,Tskin) as 1st guess & Back move

Two conditions:

\[ \Gamma \neq 0 \]

\[ \Gamma_{T_s - T} \neq 0 \]
Global Humidity Profiling

No Scan-dependence noticed: Angle dependence properly accounted for
Effect of using scattering RTM on convergence
Skin temperature retrieval using WINDSAT in eye of hurricane
Temperature profiling in active regions (using NOAA-18 sounders)
WINDSAT Retrieval (Chi Square)

- Rain Model OFF
- Rain Model ON

Retrieval using Windsat data (sdr68)
Spatial resolution of 6.8 GHz (50 kms)
But with a lot of oversampling
During Hurricane Dennis on July 6th 2005, WINDSAT Data captured Skin Temperature Cooling inside Eye of Hurricane

MIRS SST Retrieval Using WINDSAT (Fq 6 to 37 GHz)

Dennis Hurricane Track, Courtesy of National Hurricane Center