Inversion of Microwave Measurements Impacted by Atmospheric Hydrometeors (Cloud, Rain, Ice) and Plans for Data Assimilation

Application to POES/MetOp AMSU-A/MHS, TRMM/TMI, DMSP SSMI/S, M-T/MADRAS & SAPHIR and NPP ATMS

S.-A. Boukabara[1], K. Garrett[2], F. Iturbide-Sanchez[3], L. Moy[3], C. Grassotti[3], W. Chen[2] and T. Clough[4]

18th International TOVS Study Conference
March 21-27, 2012

Toulouse, France

1. NOAA/NESDIS 2. Riverside Technology, Inc 3. I.M. Systems Group, 4. SRG Inc.

Contents

Introduction

- 1D-Variational approach to invert microwave sensors data
- Two modes of operation
  - 1DVAR Retrieval Mode (independent of NWP)
  - 1DVAR Assimilation Mode (relies on NWP forecast)
- Cost to extend algorithm to new sensors greatly reduced
- MiRS applies to imagers, sounders, combination
- MiRS uses the CRTM as forward operator (leverage)
- Applicable on all surfaces and in all-weather conditions
- Operational for N18,19,Metop-A and F16/F18 SSMI/S
- **On-going / Future:**
  - Extension to NPP/ATMS (in progress)
  - Extension operations to Metop-B (spring 2012)
  - Extension to Megha-Tropiques (MADRAS and SAPHIR) (on-going)
  - Get ready for the JPSS and GPM sensors (on-going for TRMM/TMI).

Mathematical Basis: Cost Function Minimization

- Cost Function to Minimize:

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

Jacobians & Radiance Simulation from Forward Operator: CRTM

- To find the optimal solution, solve for: $\frac{\partial J(X)}{\partial X}=J'(X)=0$
- Assuming Linearity $y(x)=y(x_0)+K[x-x_0]$
- This leads to iterative solution:

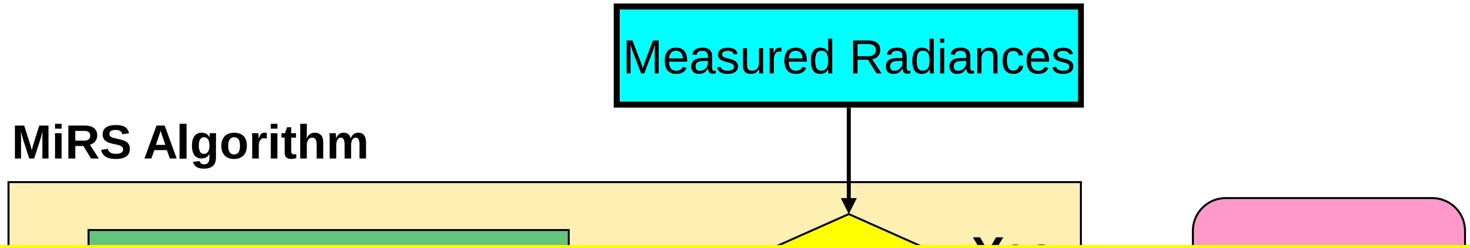
$$\Delta X_{n+1}=\left\{\left(B^{-1}+K_n^T E^{-1} K_n\right)^{-1} K_n^T E^{-1}\right\}\left[\left(Y^m-Y(X_n)\right)+K_n \Delta X_n\right]$$

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

More efficient (1 inversion)

Preferred when nChan << nParams (MW)

1D-Variational Retrieval/Assimilation



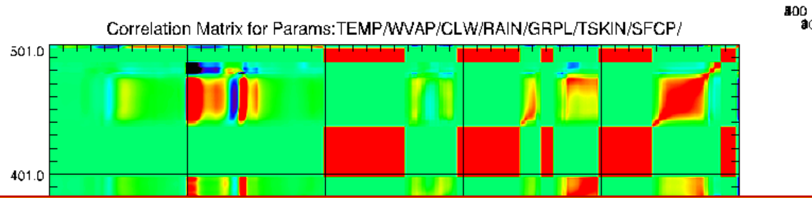
MiRS is a physical algorithm:

<u>All-parameters Solution (including hydrom.) constrained by:</u>

(1) Geophysical covariance,
(2) Fitting measurements,
(3) Physical Jacobians,
(4) Physical radiative transfer and
(5) Simultaneous retrieval of all parameters

Atmospheric Covariance Matrix

New **Atmospheric Background Covariance Matrix based on ECMWF 60, and WRF simulations over tropic oceans performed during SON season**



MiRS Rainfall rate = Fct (Hydrometeors: IWP, CLW, IWP)

Rain <u>Rate</u> can NOT be inverted per se without time-varying information

<u>Characteristics:</u>

- **A relationship between hydrometeors and rainfall rate is used as post-processing**
- **Sensor-Independent (easy to extend)**
- **WRF-based physics included (trained offline to relate RR from IWP, RWP, CLW)**

<u>Room for Improvement:</u>

- **Same function used (one for land one for ocean)**
- **Same covar/background used for all retrievals (flow-dependence should improve perfs)**

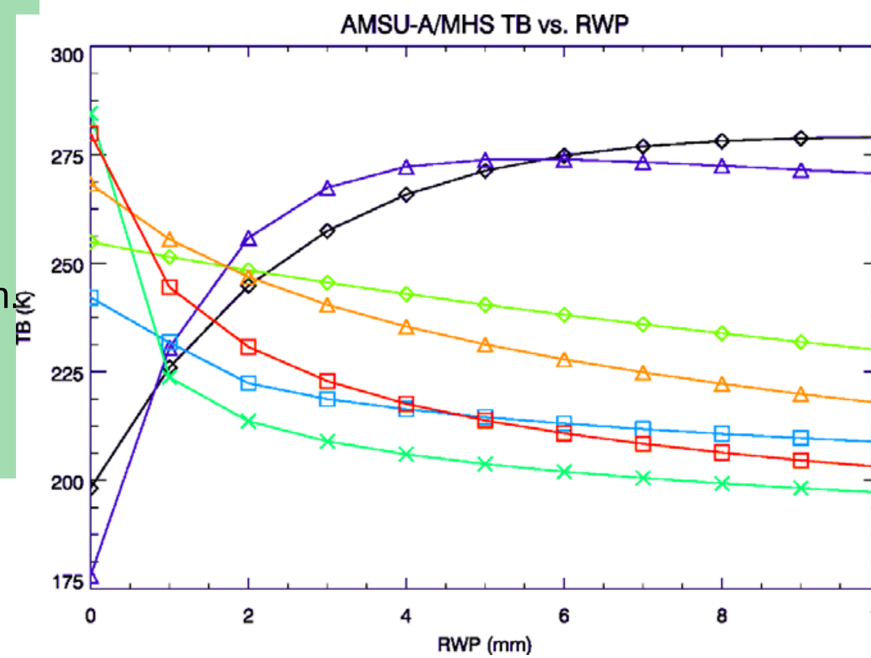
Temperature and Water Vapor from ECMWF 60

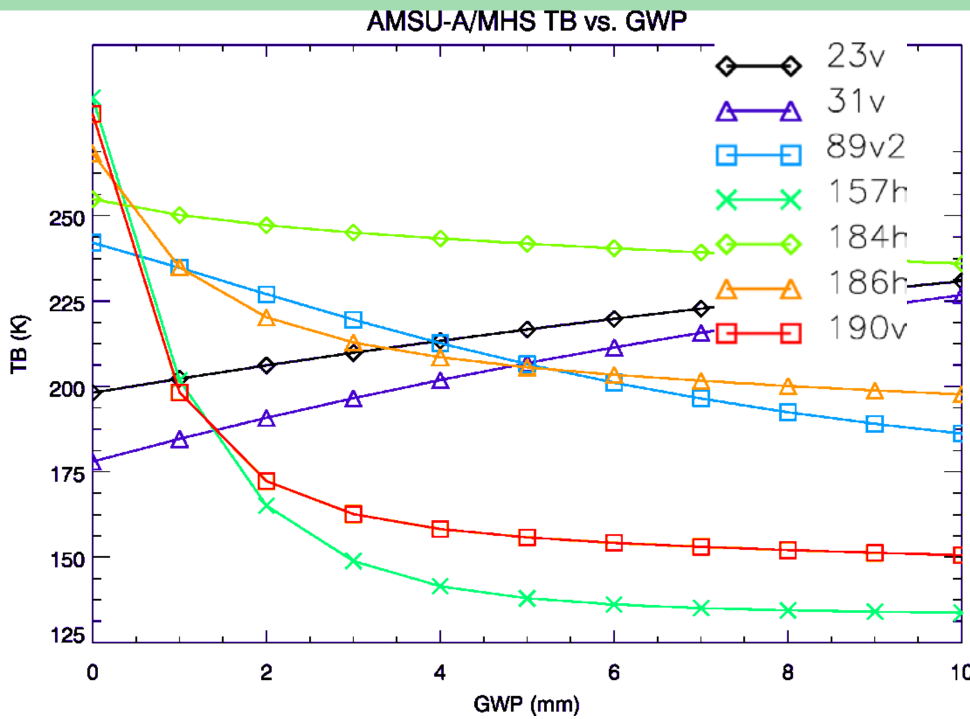
Cloud liquid, Rain and Ice water from WRF

Off-diagonal elements exist to constrain T, Q, Cloud, Rain and Ice variations within the minimization process

Non-Linearity Issue in Cloudy/Rainy TBs
(TB Variation as a Fct of hydrometeors)

- 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.
- Nothing, in theory, prevents us from including hydrometeors in the state vector, along with T, Q, Emissivity, Tskin

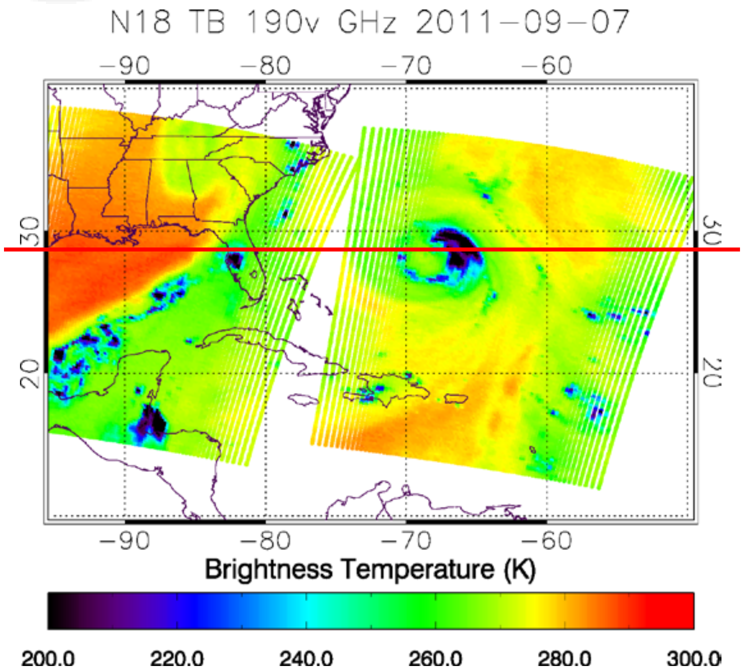




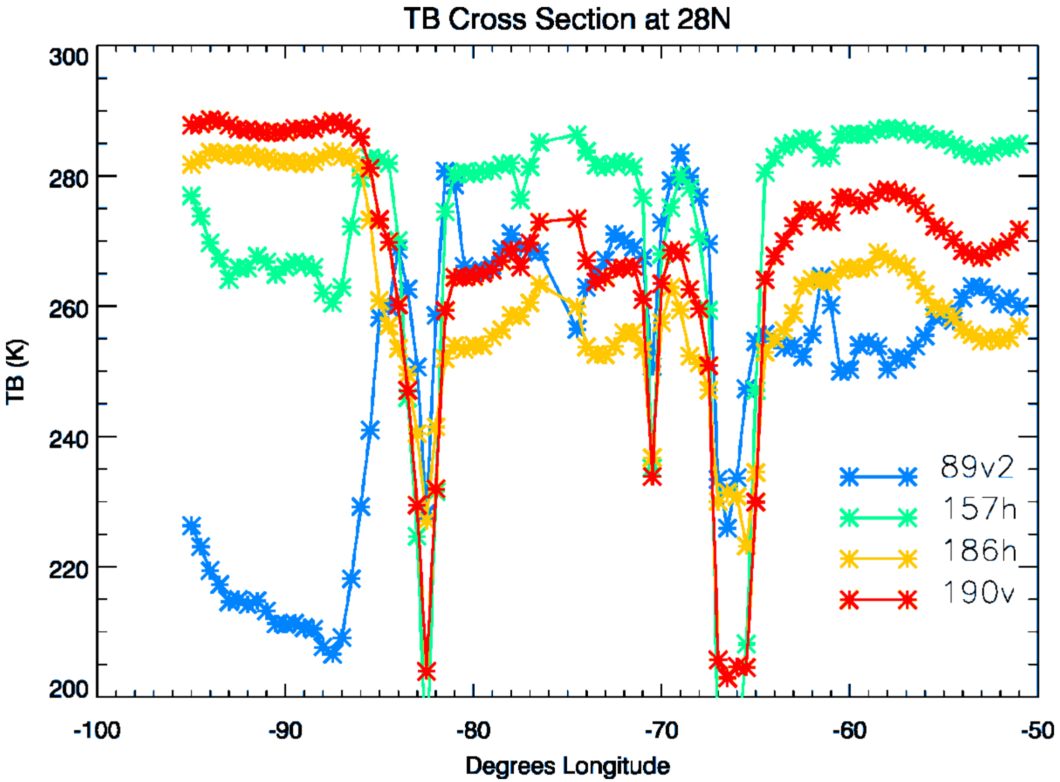
-TB variation vs. hydrometeors is non-linear but is locally linear, therefore compatible with variational inversion

-TB variation in time and space is highly non-linear and is discontinuous due to non-continuity variations of hydrometeors in time and space

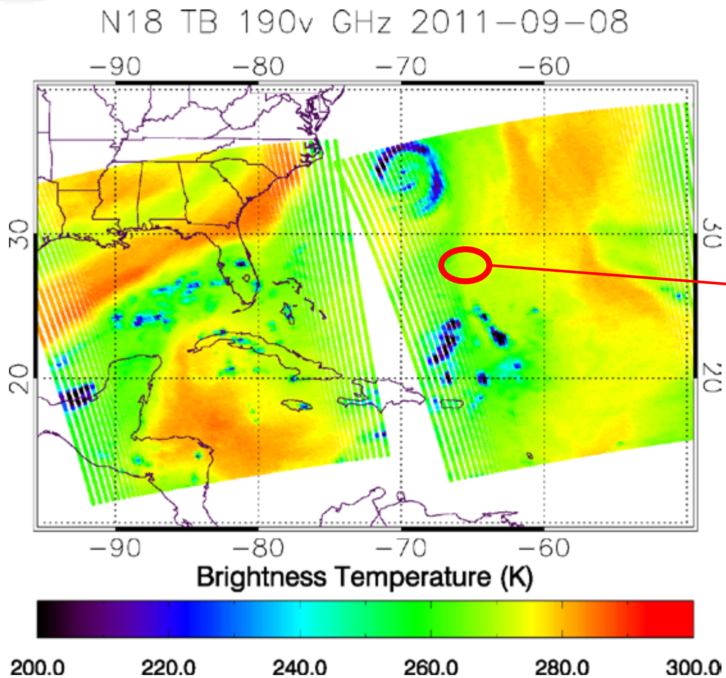
Non-Linearity Issue in Cloudy/Rainy TBs
(TB Variation as a Fct of X-Y)

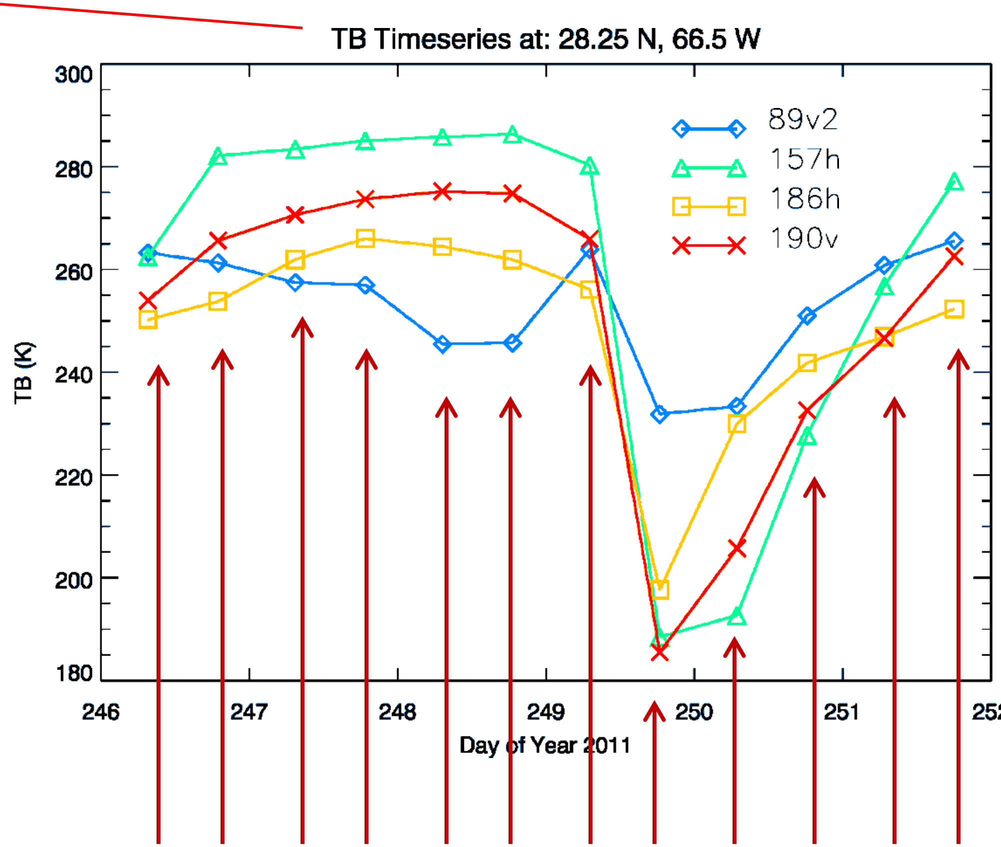


Cross section at 28 N follows red curve for 190 GHz.



Non-Linearity Issue in Cloudy/Rainy TBs
(TB Variation as a Fct of Time)



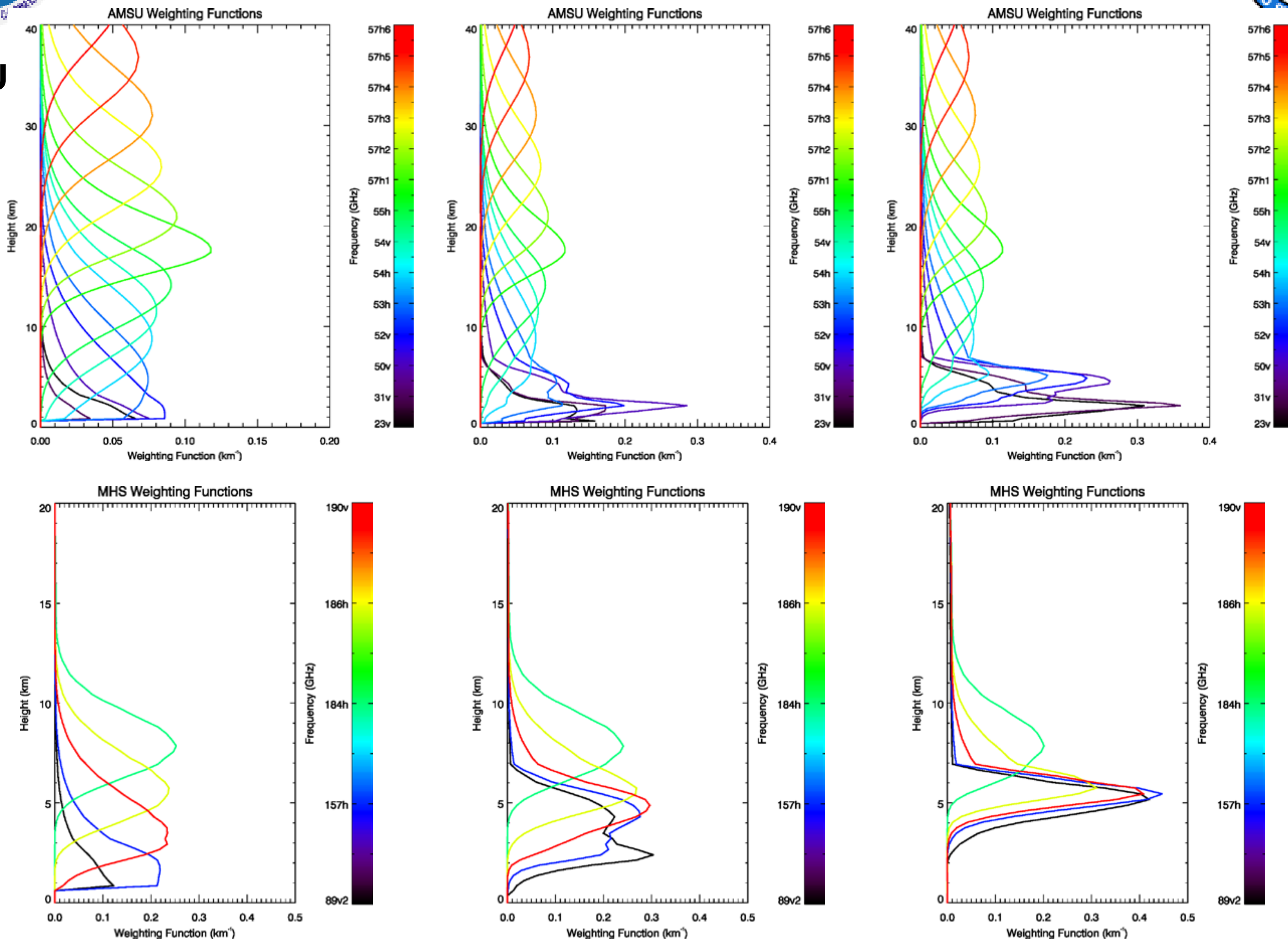


Information Content in Rain

(Both imaging and sounding channels)

AMSU

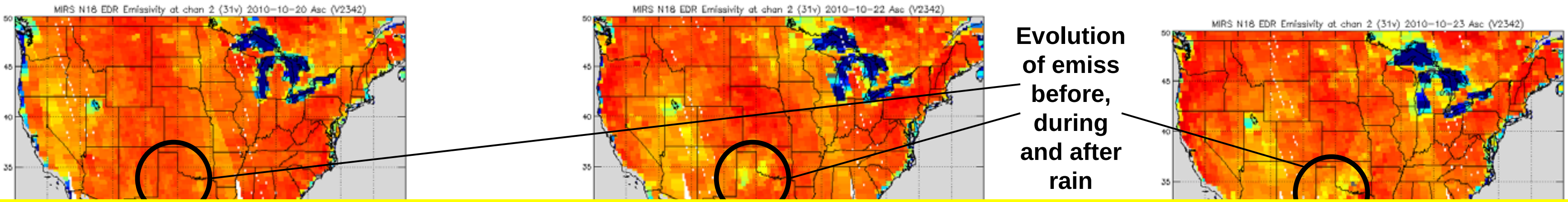
MHS



Clear Sky **2 mm RWP** **10 mm RWP**

Proper handling of Surface signal

MiRS N18 retrieved emissivity at 31 GHz ascending node



-Most channels sensitive to surface rainfall are also sensitive to surface.

-The emissivity varies greatly and at short temporal scales when precipitation occurs.

-Signal in TB is therefore a mixture of rain and emissivity signals (depending on the intensity of the precip)

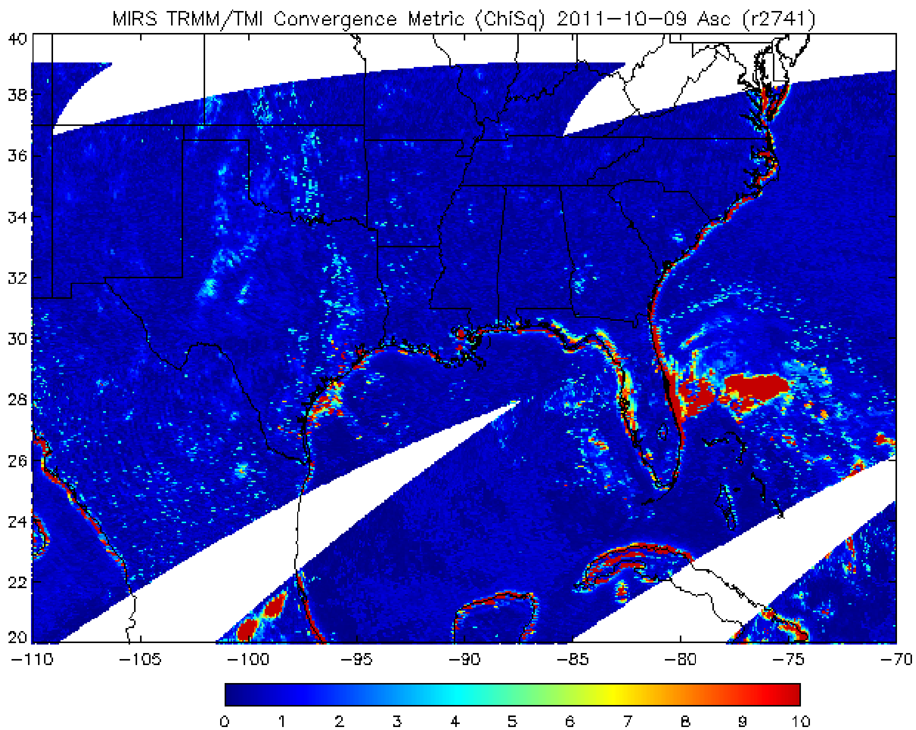
<u>This suggests:</u>

(1) Not using fixed atlases for emissivity

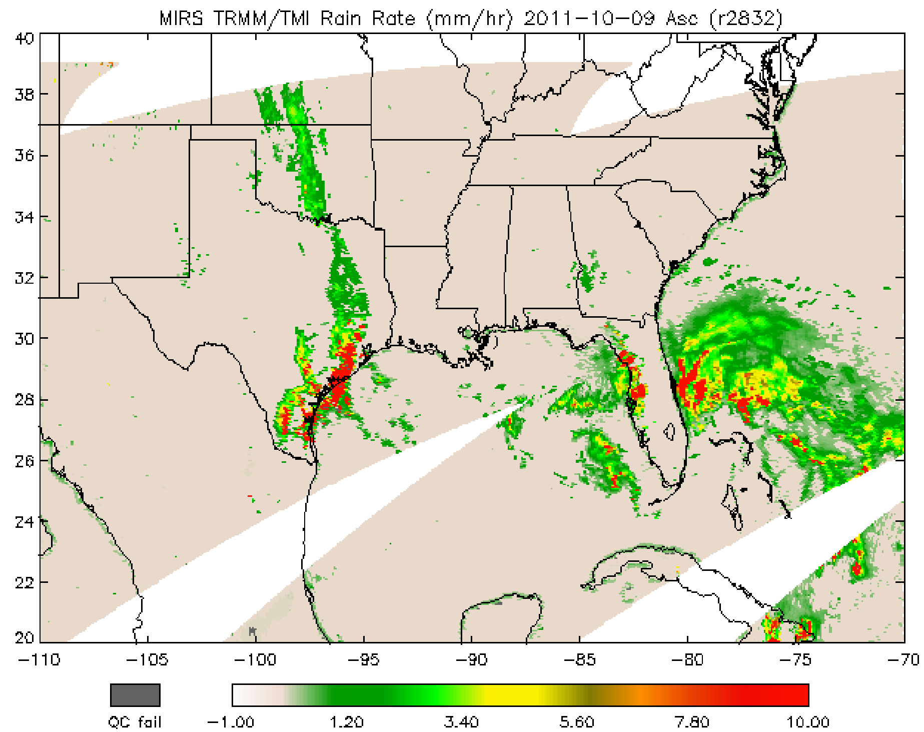
(2) Dynamically vary the emissivity along with rain, ice,cld

CP

Example: MiRS Rainfall Rate from TMI data
Comparison to official TMI/GPROF 2A12



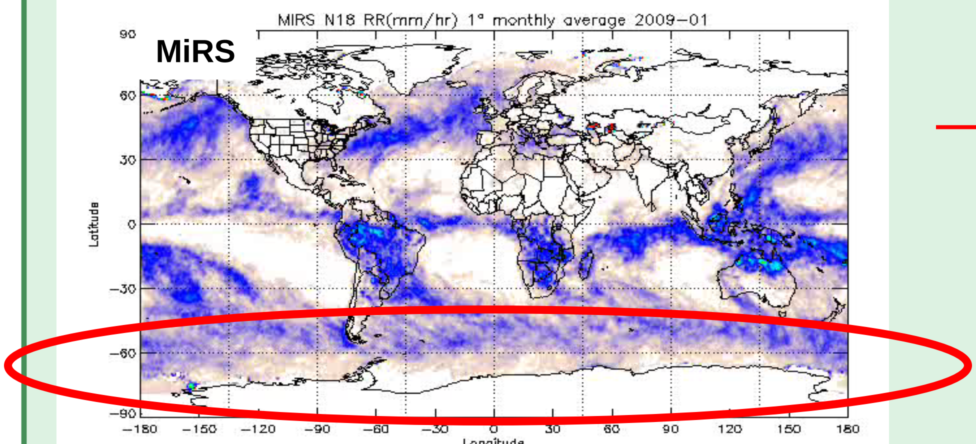
TRMM-2A12 Rainfall Rate (GPROF)



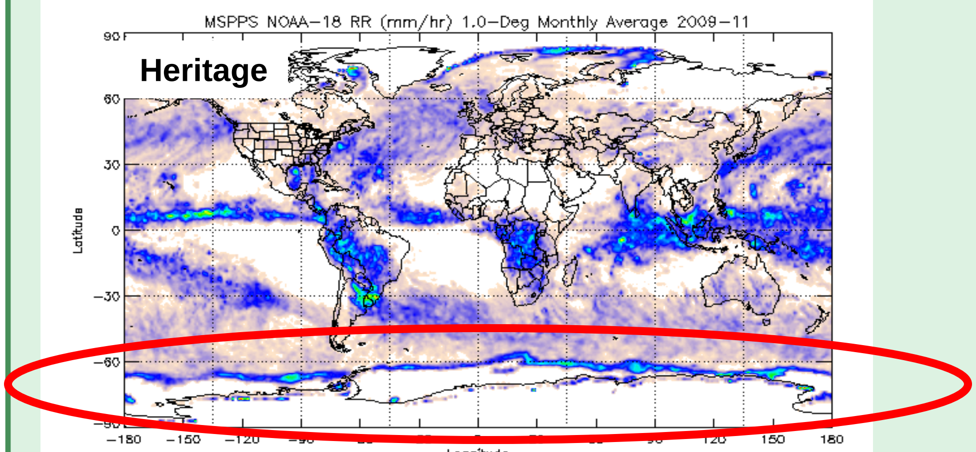
MiRS TRMM/TMI RR

MiRS Testbed: Climatology & Vertical Structure

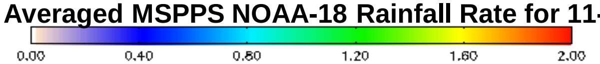
Rainfall Climatologies



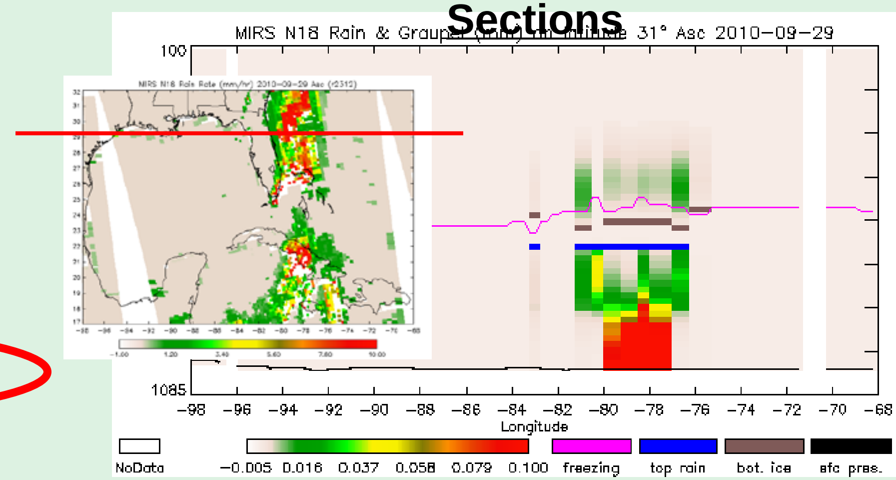
Monthly Averaged MiRS NOAA-18 Rainfall Rate for 2009



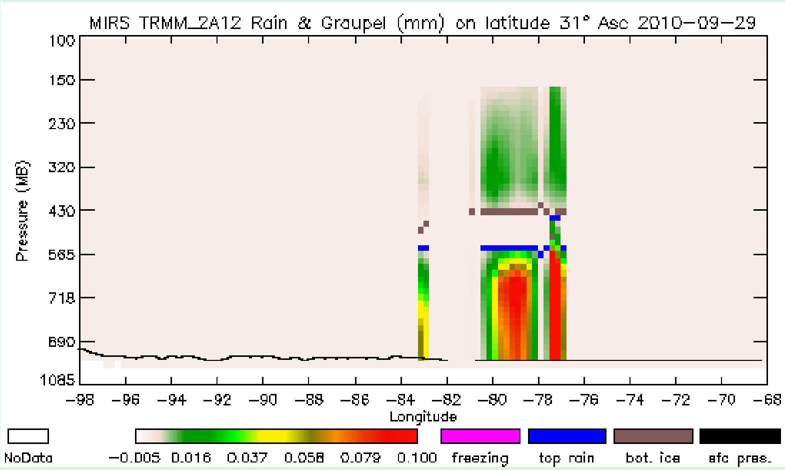
Monthly Averaged MSPPS NOAA-18 Rainfall Rate for 11-2009



Hydrometeor Profiles/Vertical Cross Sections



MiRS Hydrometeor Profiles

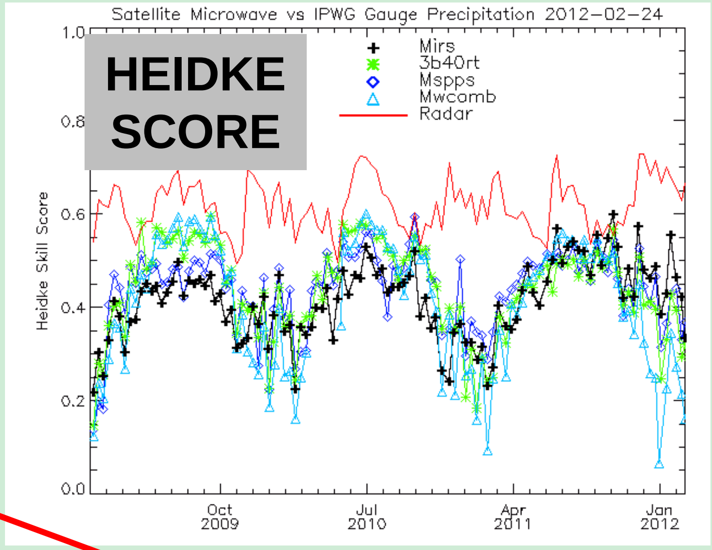


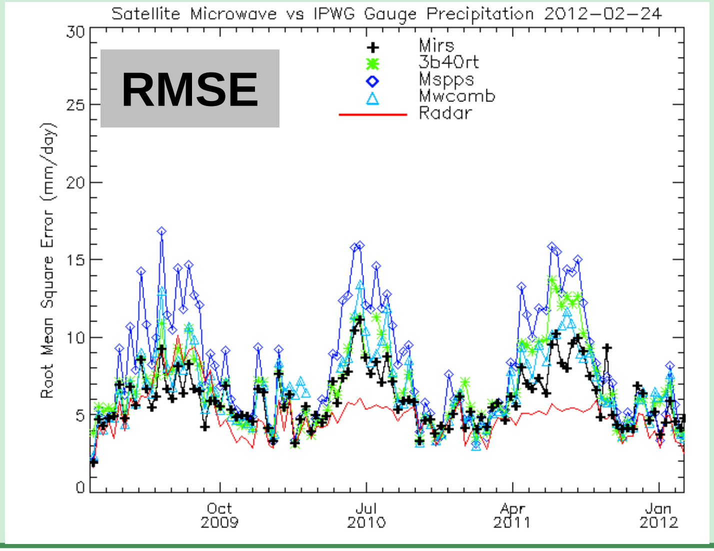
TRMM 2A12 Hydrometeor Profiles

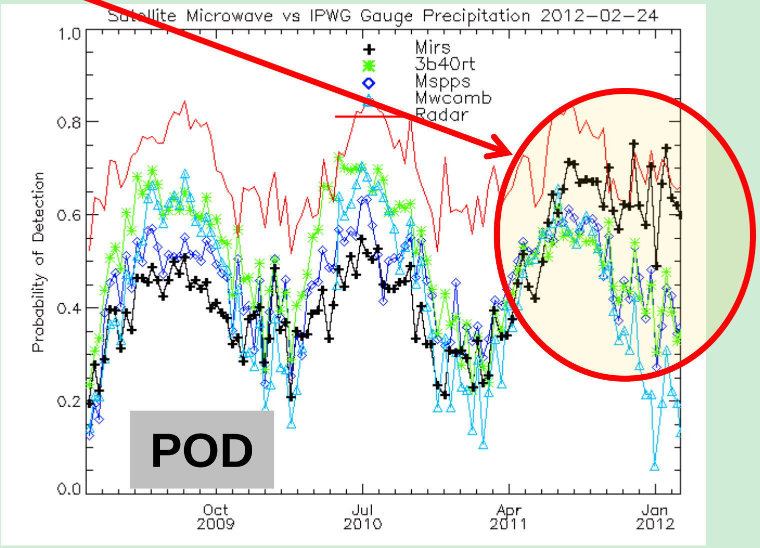
Independent Validation (IPWG)

Caution: algorithms perfs depend on how many sensors are used

- Monitor a running time series of statistics relative to rain gauges
- Intercomparison with other PE algorithms and radar
- MiRS composite uses Metop-A, N18, F16
- Tightening of RTM uncertainty in June 2011 improves POD & Heidke







Data Assimilation Applications

- Efforts are on going to:
  - Use 1DVAR as a pre-processor to NWP for quality control purposes (Kevin Garrett's presentation)
  - Implement dynamically-retrieved emissivity in the NWP first guess/background (to allow further assimilation of surface –sensitive channels)
  - Assess assimilating sounding products in cloudy/rainy conditions

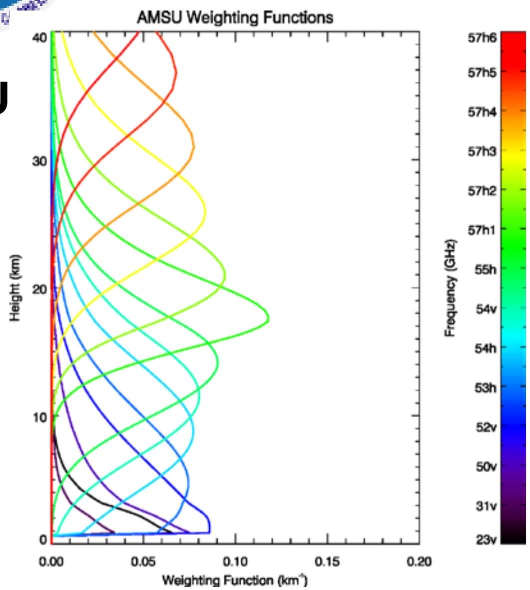
Summary & Conclusion

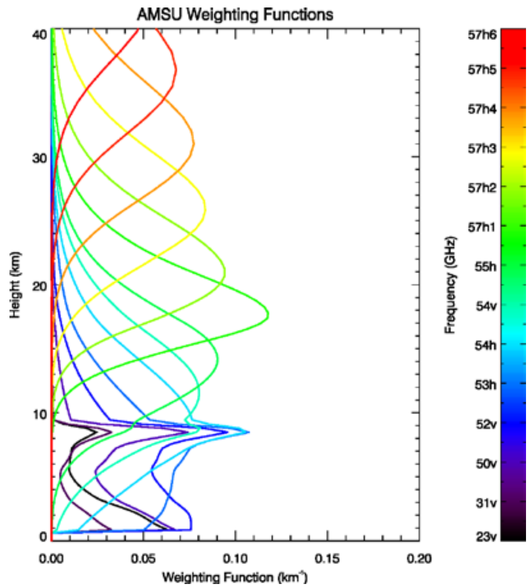
- MiRS is a generic retrieval/assimilation system (N18, DMSP, NPP, etc).
- Handling cloud/rainy –radiances by varying hydrometeors.
- Sfc rainfall rate is derived using IWP, RWP, CLW inputs
- Handling surface-sensitive channels (important for hydrometeors and rainfall rate estimation) by varying emissivity
- RR Assessment suggests approach provides reasonable results (Compared to Radar, gauges, other algorithms)
  - Importance of RTM uncertainty:~0.5 K in high-freq channels.
- Local linearity satisfied in 1DVAR, when hydrometeors are added. Jacobians are derived like other parameters.
- Avoiding cloud-resolving models in the VAR systems (1D, 3/4DVAR assimilation schemes) avoids challenges altogether:
- 1DVAR+ 3/4DVAR assimilation is one appealing way to treat hydrometeor-impacted measurements (in data assimilation)
- Current efforts to assess1DVAR preprocessing in an NWP
- For more information about the MiRS project, visit: mirs.nesdis.noaa.gov

BACKUP SLIDES

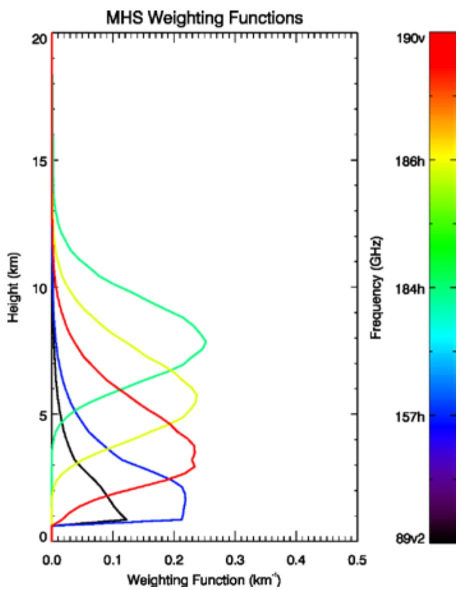
Information Content in Ice

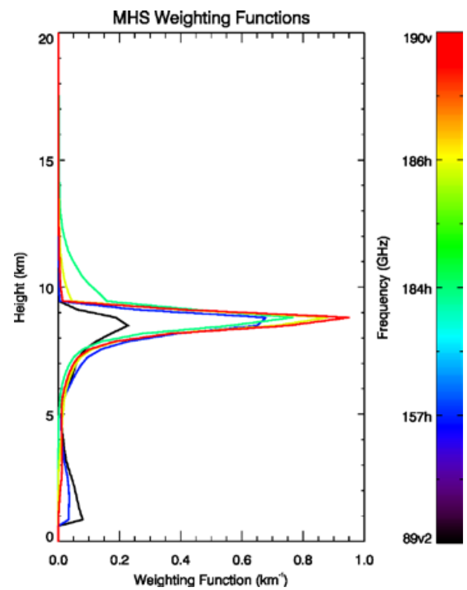
AMSU





MHS





Clear Sky **2 mm IWP**

All-Weather and All-Surfaces

Sounding Retrieval:

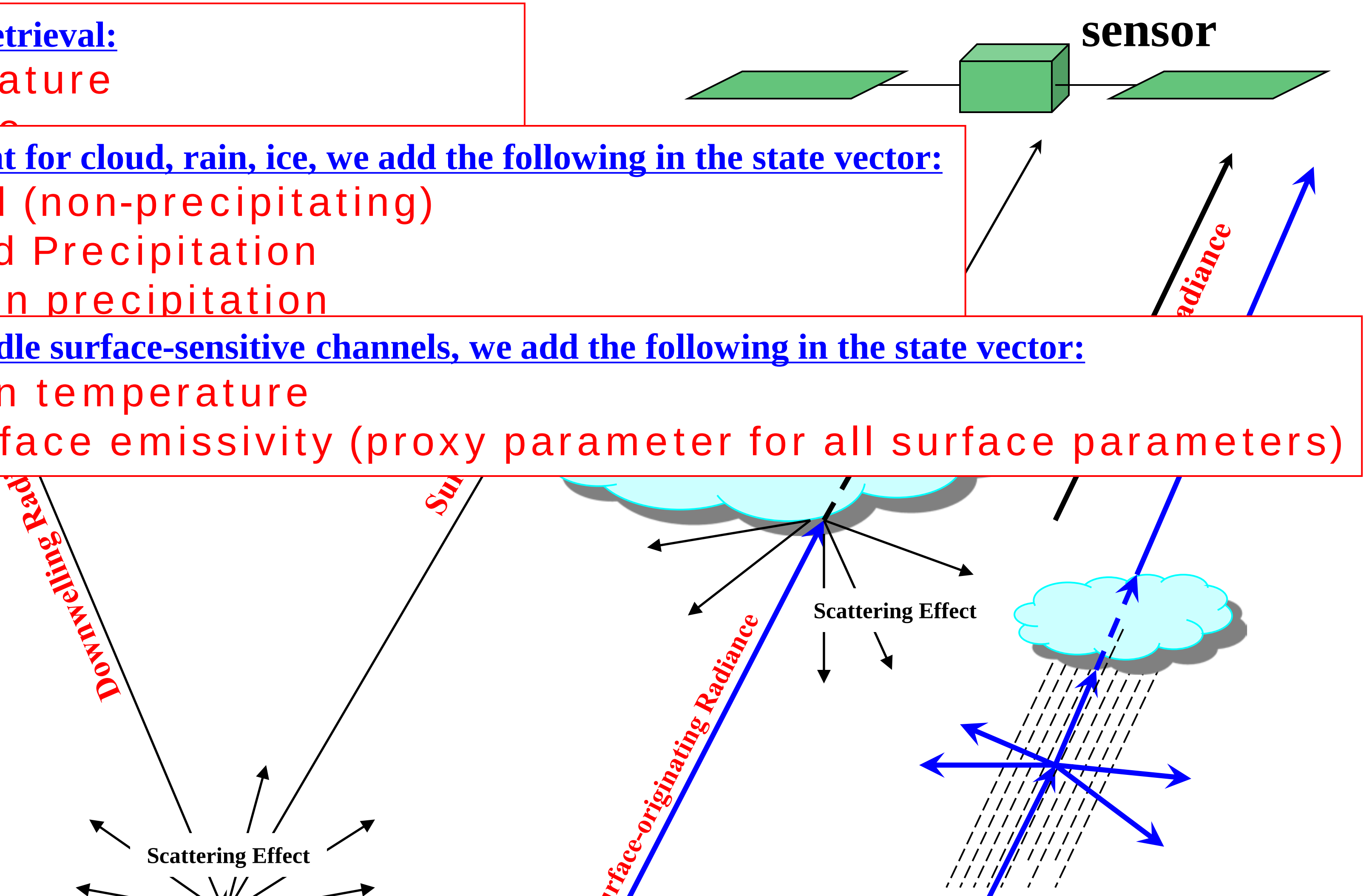
- Temperature
- Moisture

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)

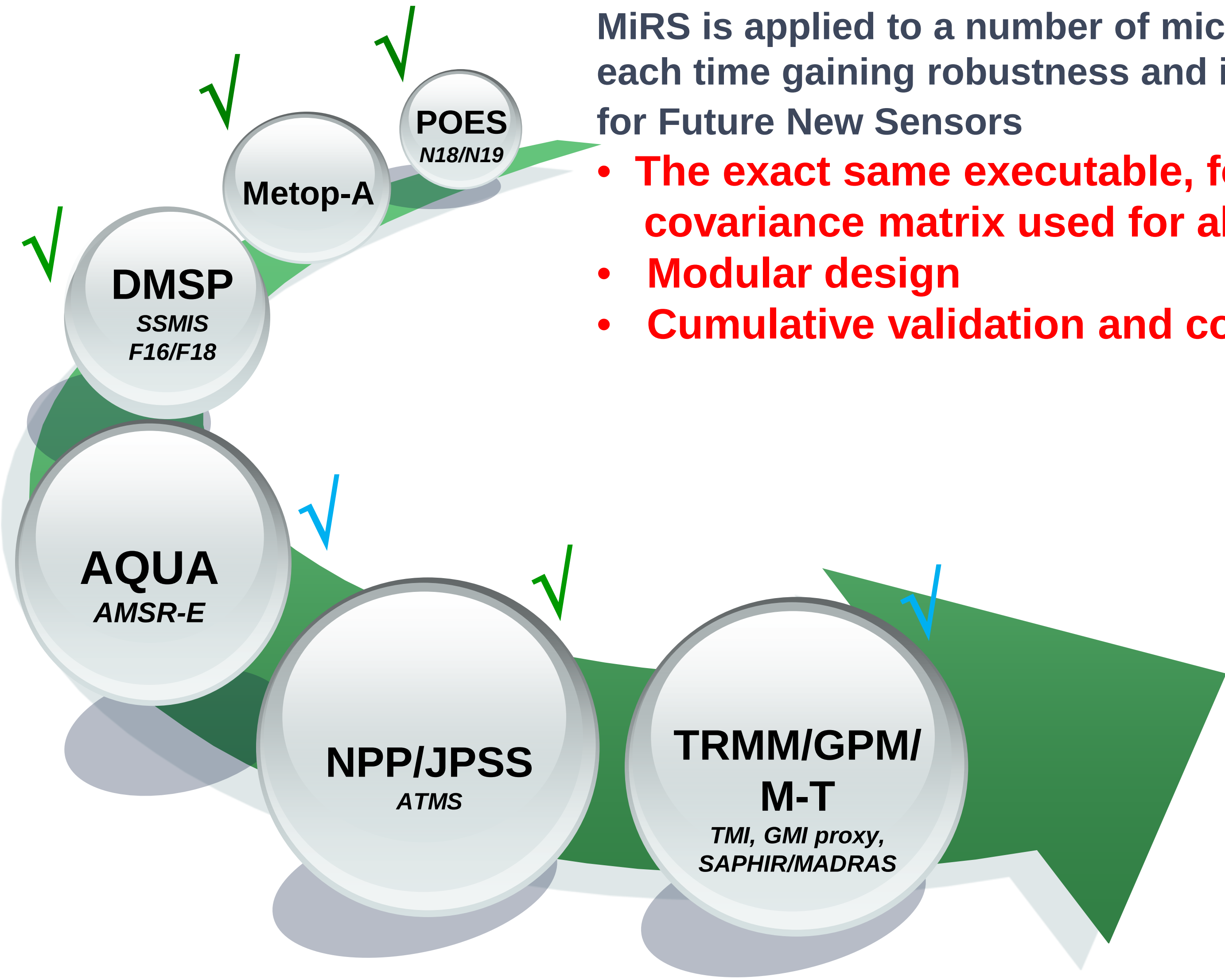


- ❖ **Instead of guessing and then removing the impact of cloud and rain and ice on TBs (difficult), MiRS approach is to account for cloud, rain and ice within its state vector.**
- ❖ **It is highly non-linear way of using cloud/rain/ice-impacted radiances.**

Current & Planned Capabilities

MiRS is applied to a number of microwave sensors, each time gaining robustness and improving validation for Future New Sensors

- **The exact same executable, forward operator, covariance matrix used for all sensors**
- **Modular design**
- **Cumulative validation and consolidation of MiRS**



√: Applied Operationally

√: Applied Routinely

√: Tested in Simulation

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 Matrx, Jacobians and X

$$\Phi = L^T \times B \times L$$

Diagonal Matrix *(used in reduced space retrieval)*

Transf. Matrx *(computed offline)*

Covariance matrix *(geophysical space)*

Parameters Retrieved Simultaneously *(Including Hydrometeors)*

If X is the set of parameters that impact the radiances Ym, and F the Fwd Operator

Necessary Condition (but not sufficient)

If F(X) <u>Does not</u> Fit Y^m within Noise

X is <u>not</u> the solution

F(X) <u>Fits</u> Y^m within Noise levels

X is <u>a</u> solution

X is <u>the</u> solution

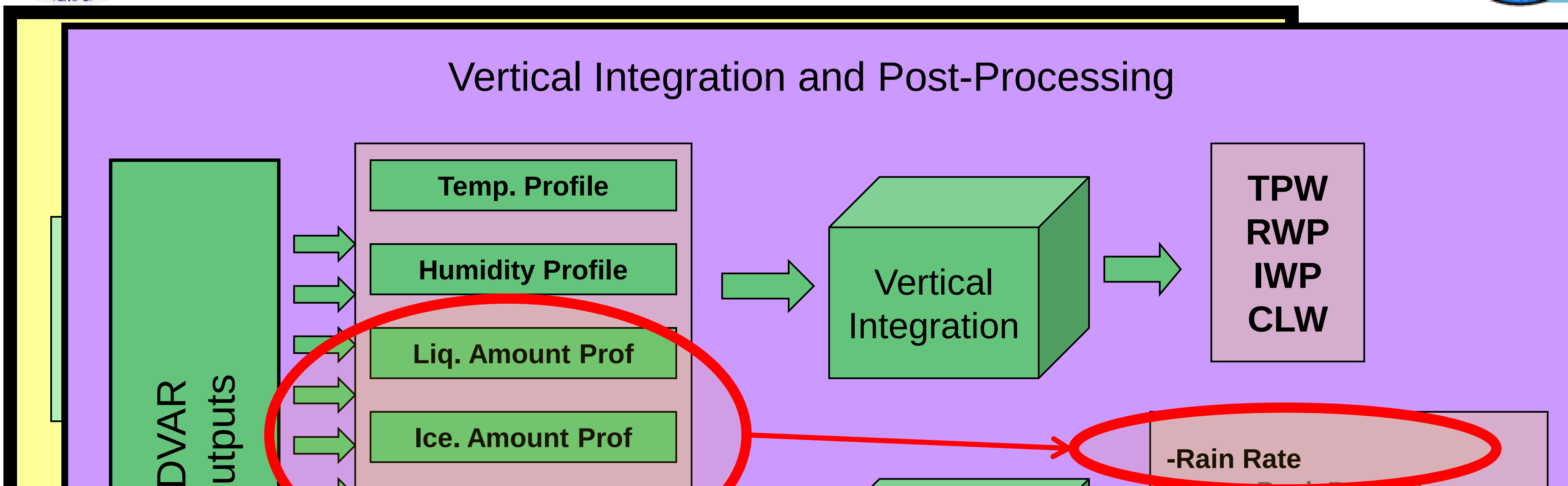
All parameters (including hydrometeors) are retrieved simultaneously to fit all radiances together

Suggests it is <u>not</u> recommended to use independent algorithms for different parameters, since they don't guarantee the fit to the radiances

CRTM as the Radiative Transfer & Jacobian Operator

- A validated, externally maintained forward operator
- Leverage (~4 FT working on CRTM at JCSDA plus a number of on-going funded projects with academia, industry to upgrade CRTM) .
- Have access to a model capable of producing not only radiances but also Jacobians
- Long-term benefit: stay up to science art by benefiting from advances in CRTM modeling capabilities:
  - Radiative & Multiple scattering solution
  - Ice and rain optical properties
  - Atmospheric absorption
  - Surface emissivity handling (and reflectivity)

MiRS Overview & Rain Rate Approach



MiRS Rainfall rate = Fct (Hydrometeors: IWP, CLW, IWP)

Rain Rate can NOT be inverted per se without time-varying information

Characteristics:
- A relationship between hydrometeors and rainfall rate is used as post-processing
- Sensor-Independent (easy to extend)
- WRF-based physics included (trained offline to relate RR from IWP, RWP, CLW)

Room for Improvement:
- Same function used (one for land one for ocean)
- Same covar/background used for all retrievals (flow-dependence should improve perfs)