Development and Implementation of a Variational Cloud Retrieval Scheme for the Measurements of the SURFRAD Observation System

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Steven Cooper, Joseph Michalksy,
Ellsworth G. Dutton, John Augustine, Gary Hodges

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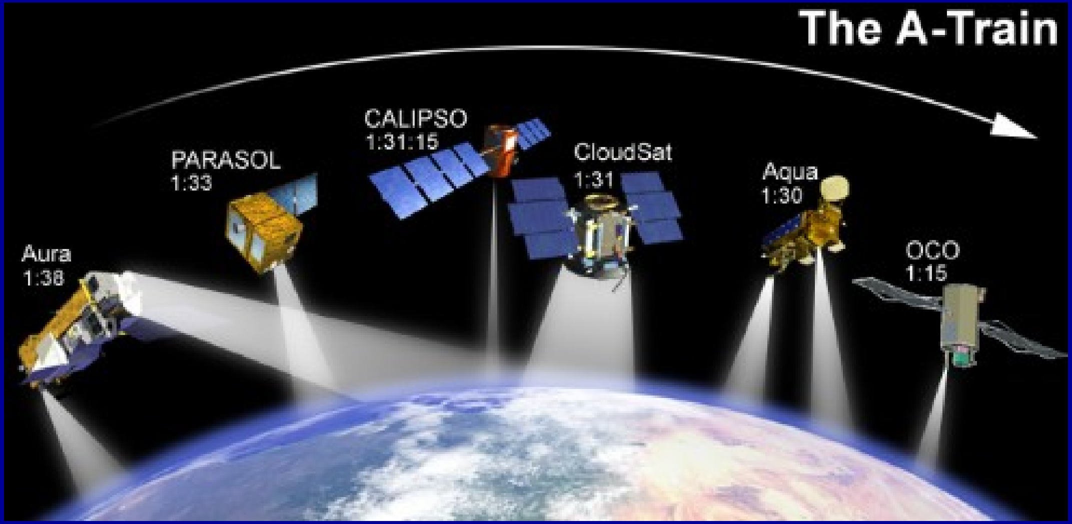
- GMD Radiation Group (G-RAD)

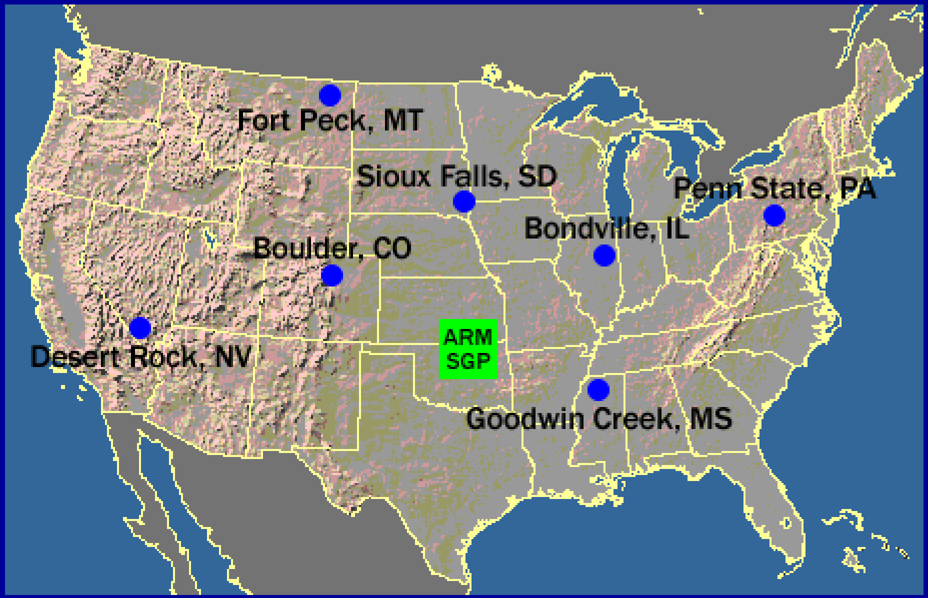
Motivation

Clouds play an important role in the regulation of climate

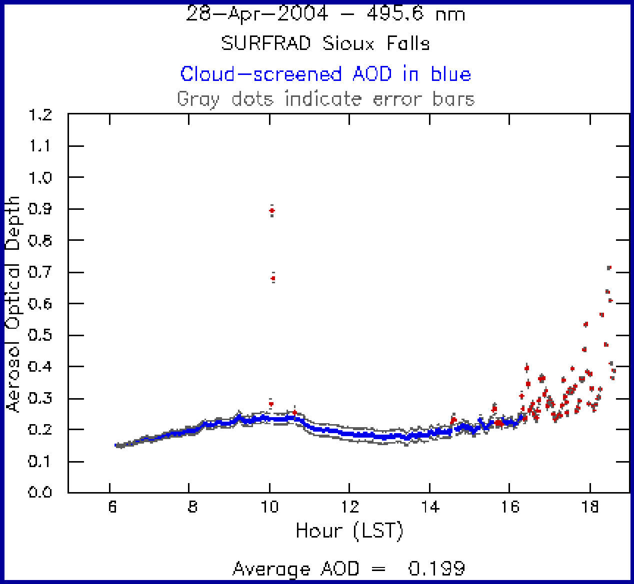


Satellite and ground-based retrieval perspectives

ESRL SURFRAD (Surface Radiation) Network



direct, diffuse, and global solar
infrared
upwelling solar
upwelling infrared
UVB
PAR
aerosol optical depth
cloud cover
temp, RH, pressure
wind



ESRL SURFRAD Cloud Retrievals

➢ Develop a Variational Cloud Retrieval Scheme for ESRL SURFRAD instrumentation

- Multi-Filter Rotating Shadowband Radiometer (MFRSR)-measures global and diffuse radiation at 415, 500, 615, 673, 870, and 940 nm

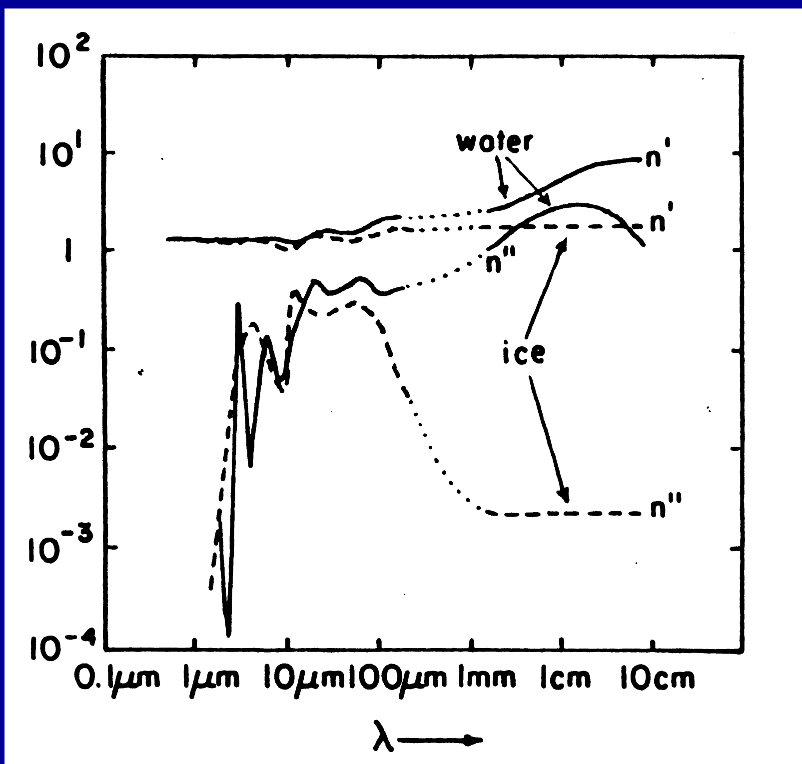
- Total Sky Imager

- Additional measurements?

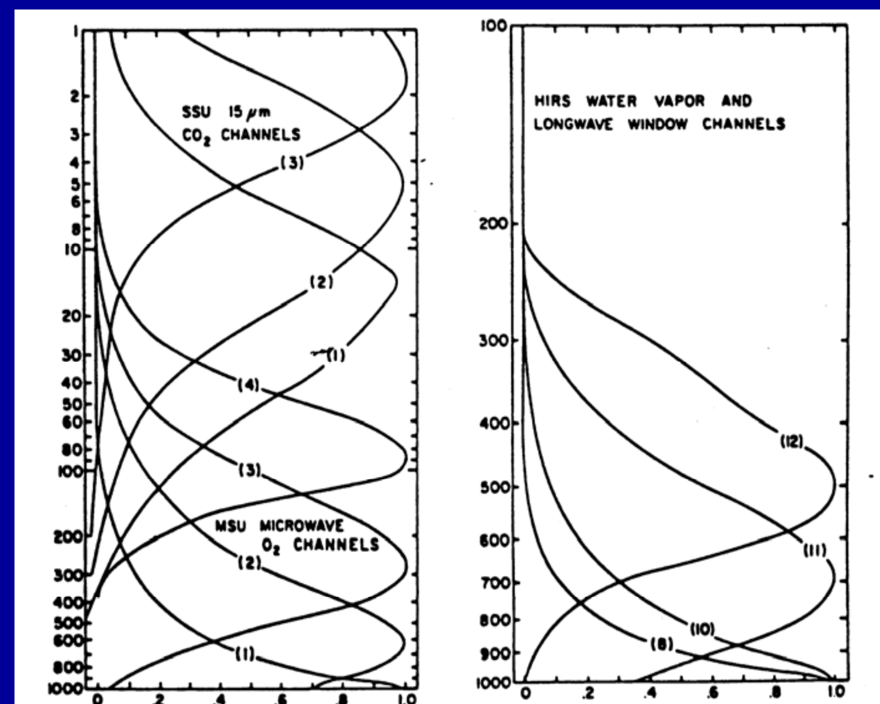
➢ Quantify expected retrieval performance (optical depth) given the inherent variability in the physics of the ground-based cloud retrieval problem

Physical Basis for Cloud Retrievals

- Cloud Particle Optical Properties (particle shape and refractive index)

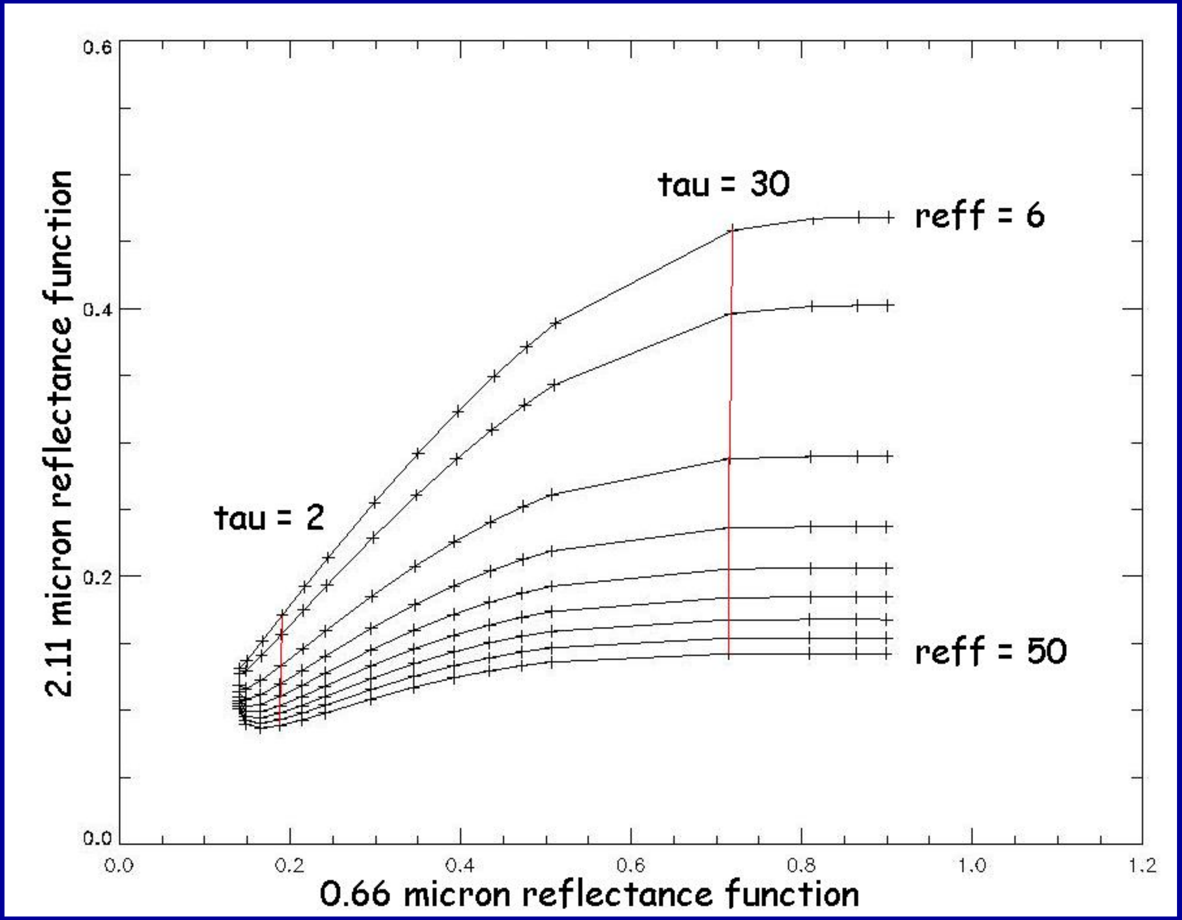


- Measurement weighting functions (temperature and gases profiles)

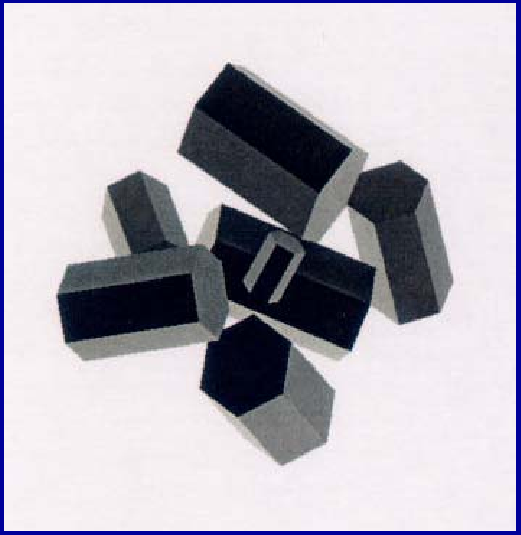


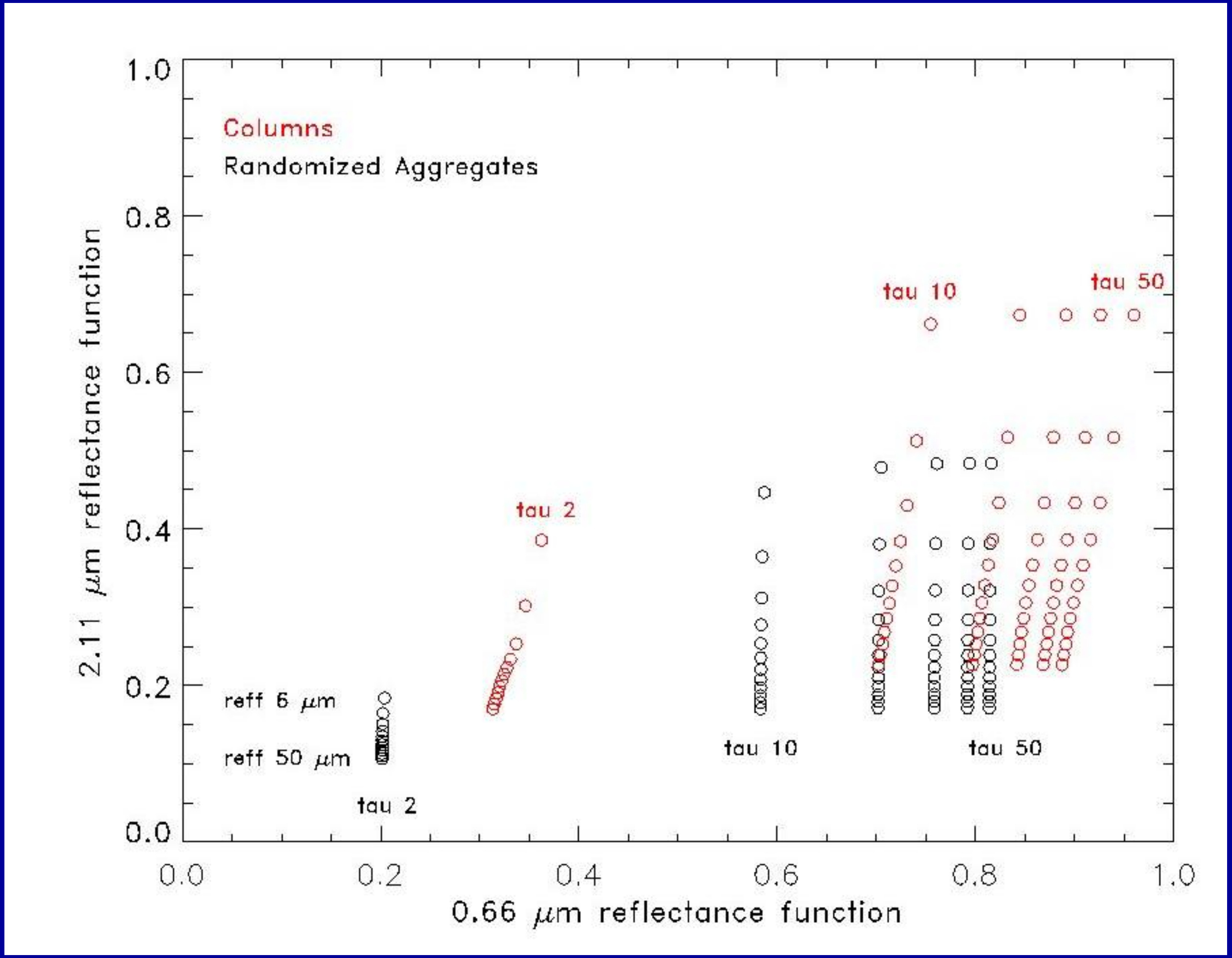
Nakajima and King Retrieval Scheme

- Non- absorbing visible channel provides optical depth, absorbing near- IR channel provides r_{eff}
- Sensitivity to large range of optical depths and effective radius
- Requires proper assumption of ice crystal habit



Nakajima and King Retrieval Scheme





Quantify Retrieval Uncertainties through Optimal- Estimation Framework

$$
\begin{aligned}
\Phi(\hat{\mathbf{x}}, \mathbf{y}, \mathbf{x}_a) &= (\mathbf{y} - F(\hat{\mathbf{x}}))^T \mathbf{S}_y^{-1} (\mathbf{y} - F(\hat{\mathbf{x}})) \\
&+ (\hat{\mathbf{x}} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\hat{\mathbf{x}} - \mathbf{x}_a)
\end{aligned}
$$

- Determine most likely estimate of cloud properties with associated uncertainties

- Weight confidence in measurement error, inversion uncertainties, and climatology (signal to noise)

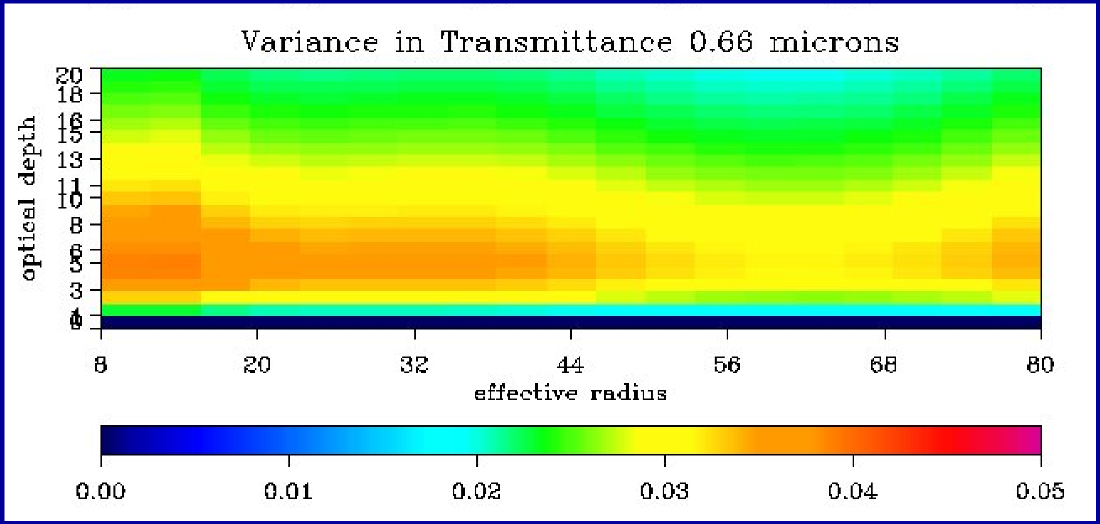
- Flexible retrieval framework allows measurements from multiple sensors

MFRSR Measurements and Uncertainties

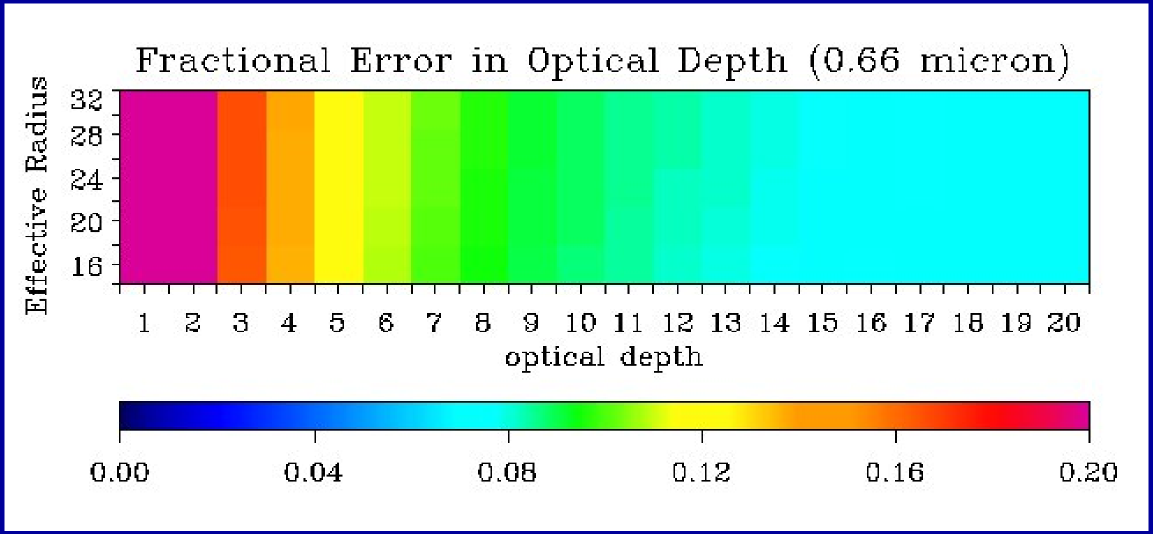
- Measures global and diffuse radiation at 415, 500, 615, 673, 870, and 940 nm

- Determine uncertainties in forward radiative transfer calculations due to assumptions of ice crystal habit, size distribution, and atmospheric profile

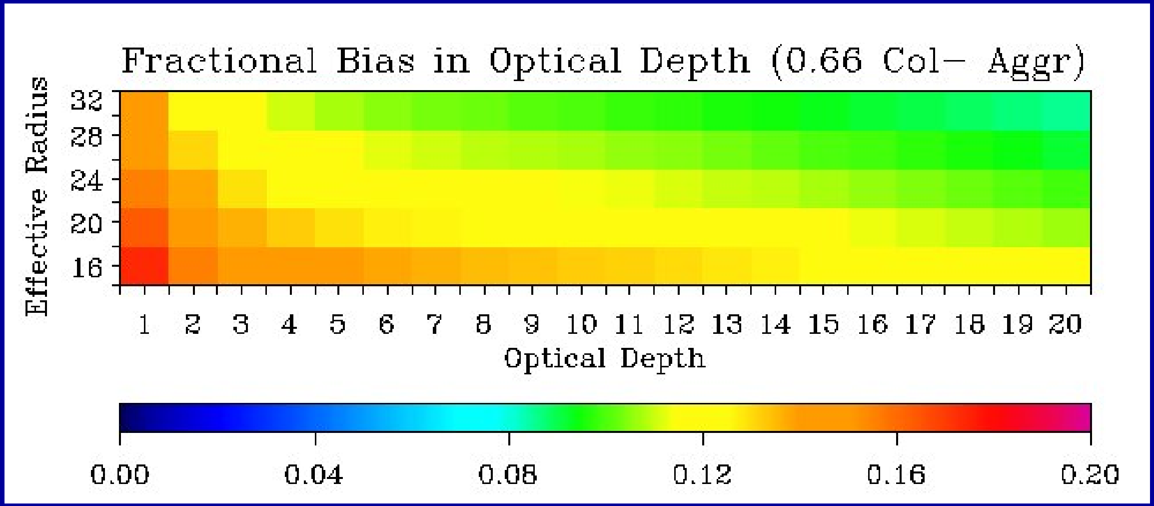
- RADIANT, correlated- K absorption, and modified delta-m scaling



Uncertainties in MFRSR Retrieved Cloud Optical Depth



- Uncertainties in retrieved optical depth roughly 10-20%



Retrieval Uncertainties

- Uncertainties in ground-based MFRSR retrieved cloud optical depth typically near 10-20%

- These uncertainties, however, are smaller than those from similar passive satellite observations, typically 20-30%

Cooper et al., 2007: ‘Performance assessment of a five-channel estimation-based ice cloud retrieval scheme for use over the global oceans’, JGR.

Cooper et al., 2006: ‘Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part II: Ice Clouds’, JAM.

L.’Ecuyer et al., 2006: ‘Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part I: Water Clouds’, JAM.

Cooper et al., 2003: ‘The Impact of Explicit Cloud Boundary Information on Ice Cloud Microphysical Property Retrievals from Infrared Radiances’, JGR.

- MFRSR hemispheric FOV smoothes effect of particle shape

Research Conclusions- Goals

- Rigorous uncertainty analysis (signal to noise) suggests potential utility of MFRSR cloud retrievals

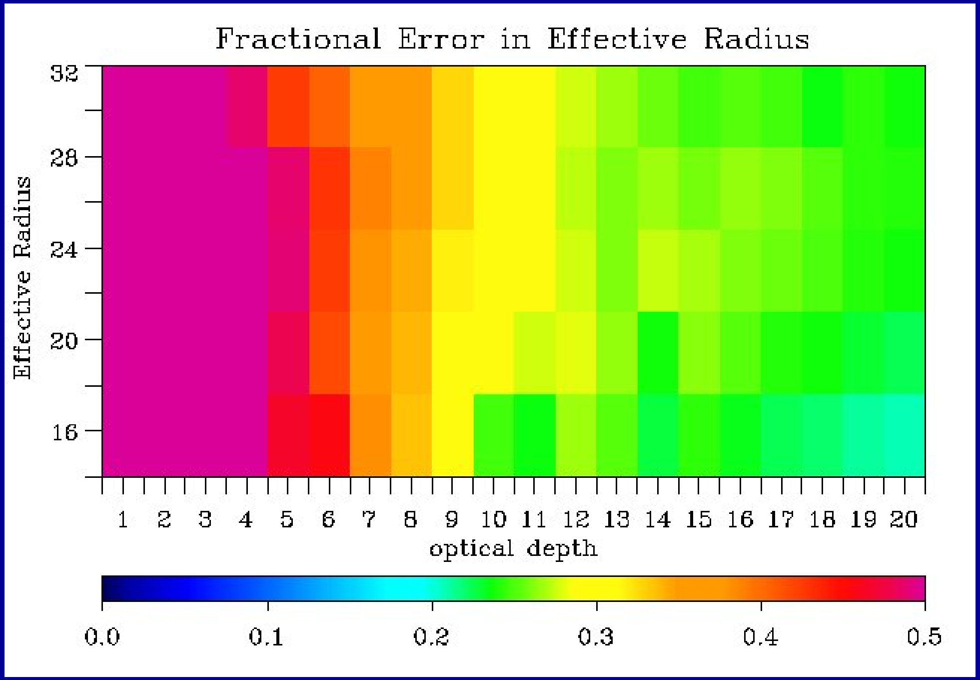
- Perform retrievals for ESRL SURFRAD Table Mountain site where have implemented a downward MFR to constrain surface albedo

- Climatology or validation of satellite missions

Possible SURFRAD Improvements

- Quantify impacts of adding additional measurements such as absorbing near infrared, 1.6 or 2.1 microns

- See different part of cloud compared to satellite



- Also examine the effects of adding other measurements such as microwave radiometer, cloud boundary information, etc.

Cooper, Steven J., T. L.'Ecuyer, P. Gabriel, and G. Stephens, 'Performance assessment of a five-channel estimation-based ice cloud retrieval scheme for use over the global oceans', *J. Geophys Res,* **112**, D04207, doi:10.1029/2006JD007122, 2007.

Cooper, Steven J., T. L.'Ecuyer, P. Gabriel, A. Baran, and G. Stephens, 'Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part II: Ice Clouds," Journal of Applied Meteorology and Climatology, **45**, No. 1, 42–62, 2006.

L.'Ecuyer, T., P. Gabriel, K. Leesman, **S. Cooper**, and G. Stephens, 'Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part I: Water Clouds," *Journal of Applied Meteorology and Climatology*, **45**, No. 1, 20-41, 2006.

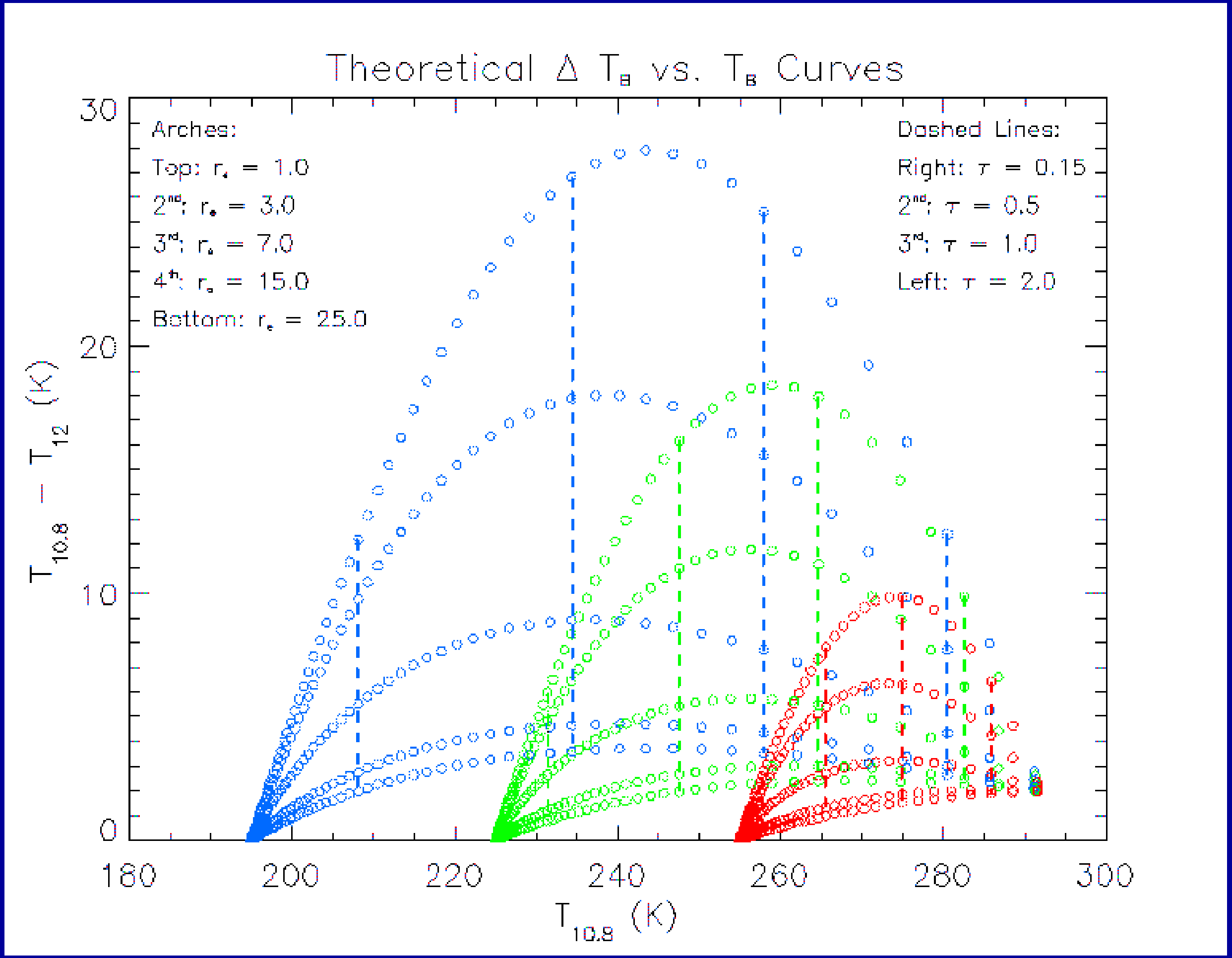
Cooper, Steven J., Tristan S. L'Ecuyer, and Graeme L. Stephens, "The Impact of Explicit Cloud Boundary Information on Ice Cloud Microphysical Property Retrievals from Infrared Radiances", *Journal of Geophysical Research*, 108(D3), 4107, doi:10.1029/2002JD002611, 2003.

Example Passive Ice Cloud Retrieval Schemes

Platt et al. (1980)	10, 12 μm
Szejwach (1982)	6.5, 11.5
Prabhakara (1988)	10.6, 12.8
Nakajima and King (1990)	0.65, 2.13
Liou et al. (1990)	6.5, 10.6
Stone et al. (1990)	3.7, 10.9, 12.7
Wielicki et al. (1990)	0.83, 1.65, 2.21
Ou et al. (1995)	3.7, 10.9
Arking and Childs (1985)	0.65, 3.7, 11.0
Twomey and Cocks (1989)	0.75, 1.0, 1.2, 1.6, 2.25
Gao and Kaufman (1995)	0.65, 1.37
Smith et al. (1996)	3.9, 10.7, 12.0
CSU (2004)	0.65, 2.13, 4.05, 11.0, 13.3

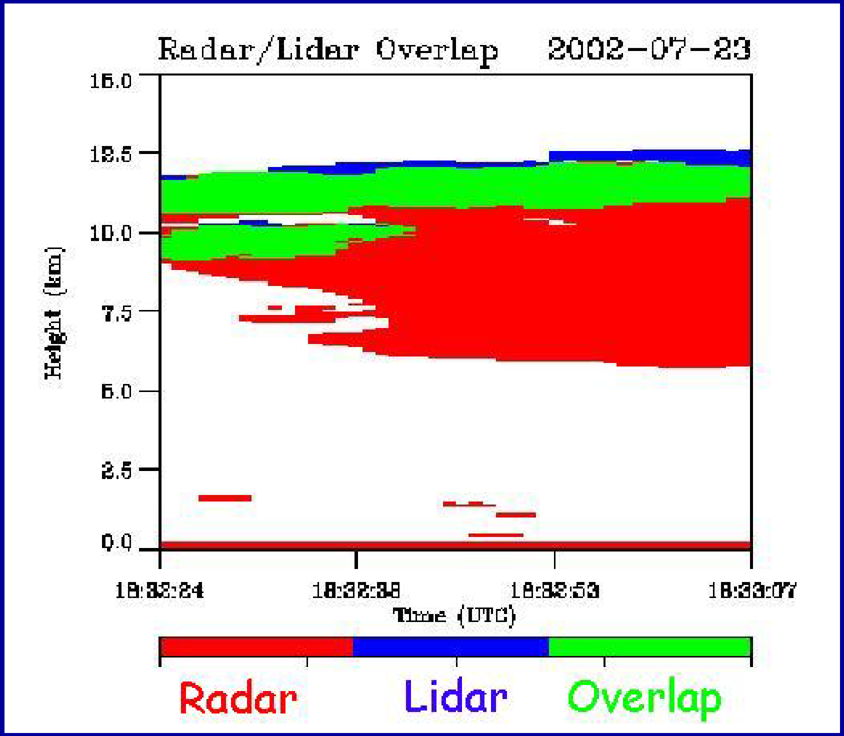
Split- Window Retrieval Scheme

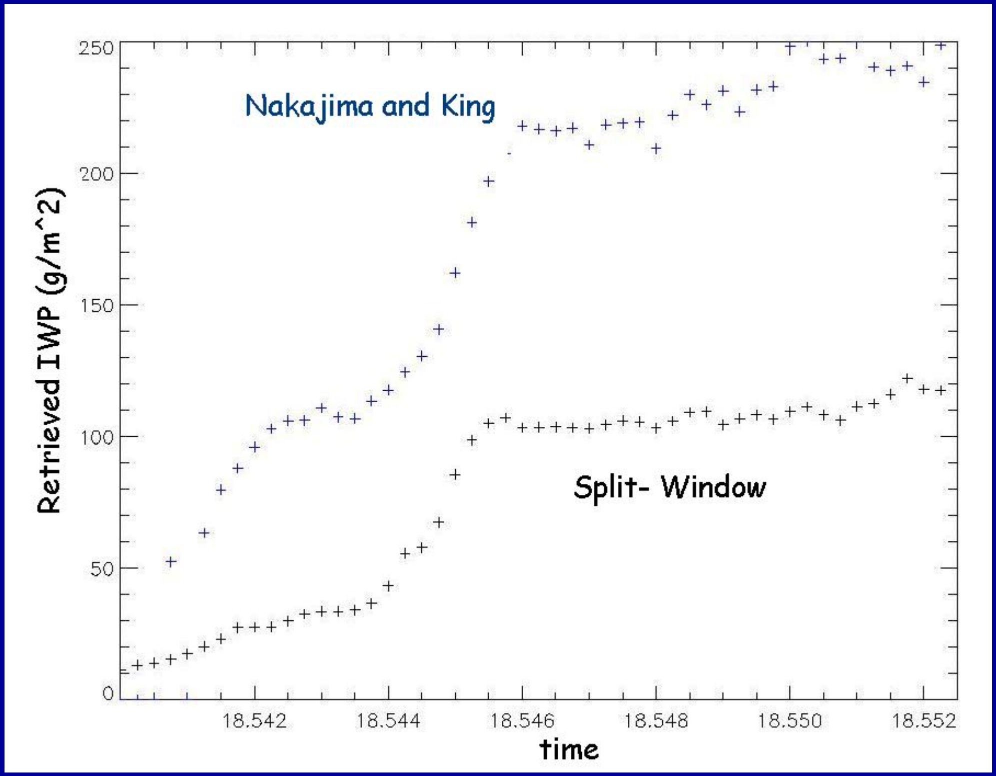
- Based upon spectral variation of absorption by ice cloud particles across the window region
- Sensitivity to limited range of retrieved cloud properties
- Requires accurate cloud boundary information



Retrieval Scheme Discontinuities

Consistency between retrieval schemes and across different measurement campaigns is desirable





Re-Examination of the Ice Cloud Problem

In this work, we will rigorously assess the implications of these generally neglected inversion uncertainties on the global retrieval of ice cloud properties given the practical constraint of our current observational platforms

1. Implement an advanced version of the split- window technique as an illustrative example to quantify the importance of inversion uncertainties on the overall retrieval of cloud properties

2. Objectively select the optimal combination of measurements (visible, near- infrared, and infrared) for an ice cloud retrieval scheme constrained by CloudSat cloud boundary information

3. Quantify retrieval performance through application to both synthetic studies and real- world data

Publications

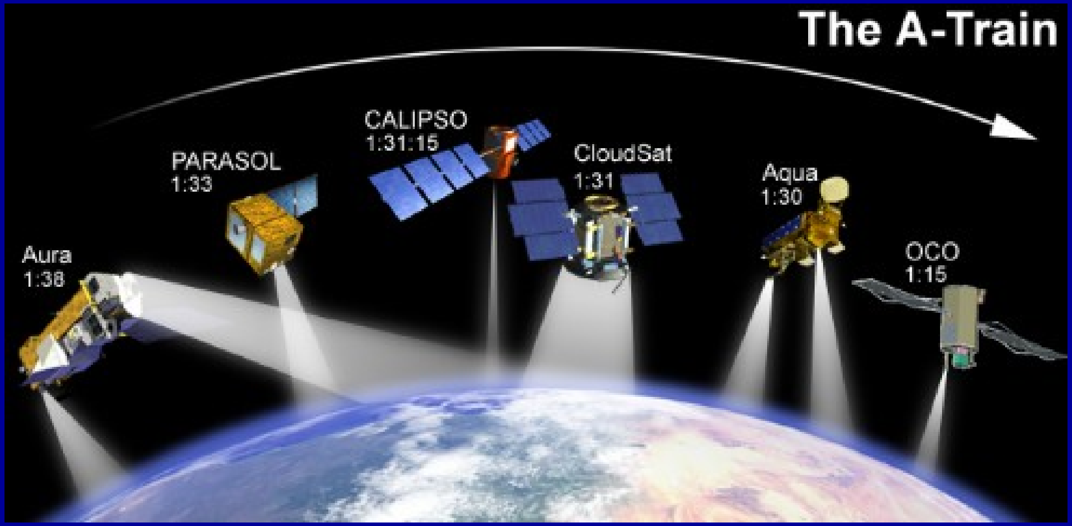
1. **Cooper, Steven J.,** T. L.'Ecuyer, P. Gabriel, and G. Stephens, 'Performance assessment of a five-channel estimation-based ice cloud retrieval scheme for use over the global oceans', in publication *J. Geophys Res,* **112**, D04207, doi:10.1029/2006JD007122, 2007.

2. **Cooper, Steven J**., T. L.'Ecuyer, P. Gabriel, A. Baran, and G. Stephens, 'Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part II: Ice Clouds," Journal of Applied Meteorology and Climatology, **45**, No. 1, 42–62, 2006.

3. L.'Ecuyer, T., P. Gabriel, K. Leesman, **S. Cooper**, and G. Stephens, 'Objective Assessment of the Information Content of Visible and Infrared Radiance Measurements for Cloud Microphysical Property Retrievals over the Global Oceans. Part I: Water Clouds," *Journal of Applied Meteorology and Climatology*, **45**, No. 1, 20-41, 2006.

4. **Cooper, Steven J**., Tristan S. L'Ecuyer, and Graeme L. Stephens, "The Impact of Explicit Cloud Boundary Information on Ice Cloud Microphysical Property Retrievals from Infrared Radiances", *Journal of Geophysical Research*, 108(D3), 4107, doi:10.1029/2002JD002611, 2003.

- Studies will be based upon the instrumentation of the NASA Afternoon A-Train constellation of satellites



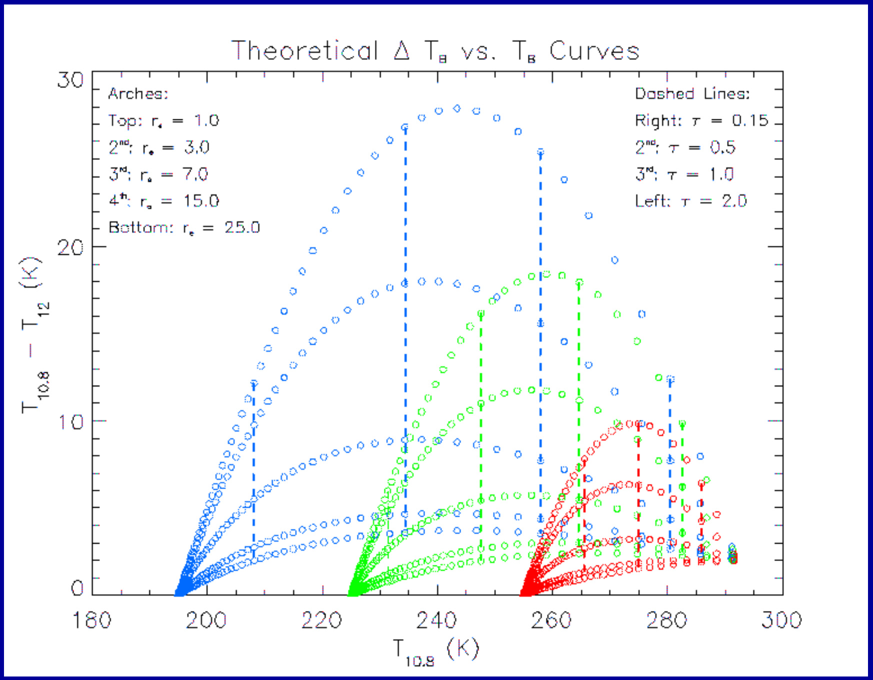
- Optimal- estimation retrieval framework is used to incorporate uncertainty estimates into retrieval scheme and to provide error-diagnostics on retrieved cloud properties

- Recent advances in the understanding of optical properties for a variety of realistic ice crystals allow estimates of inversion uncertainties due to habit (Baran, 2002; Yang, 2001; Yang 2003)

Split- Window Study

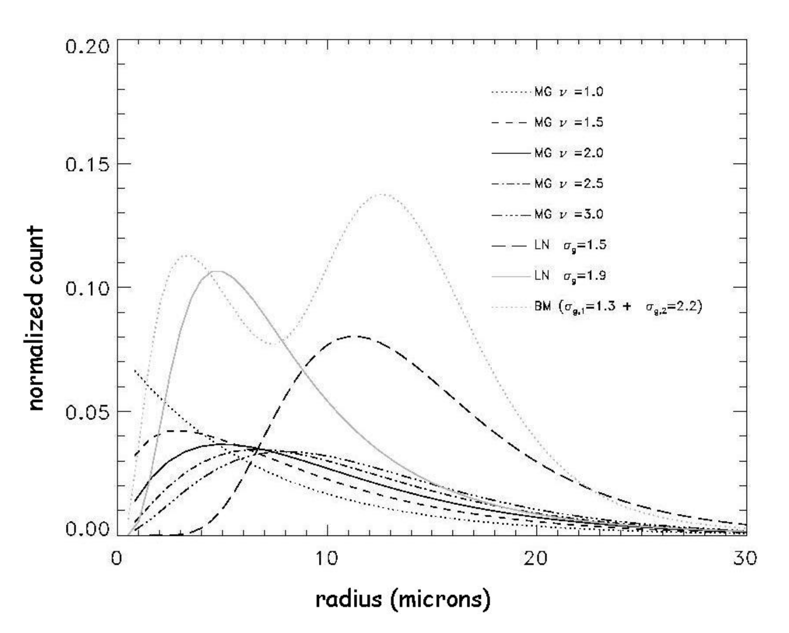
- Split- window study used to illustrate importance of inversion uncertainties on retrieval performance, also describes nighttime physics (published in *JGR*- Cooper et al., 2003)

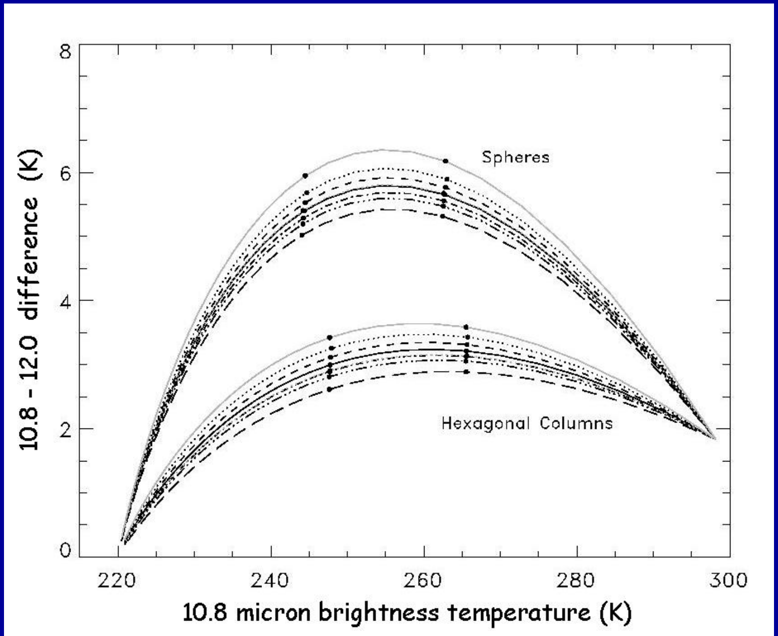
- Optimal- estimation framework allows for consideration of uncertainties and incorporation of CloudSat cloud boundary information as constraint



Estimation of S_y Matrix

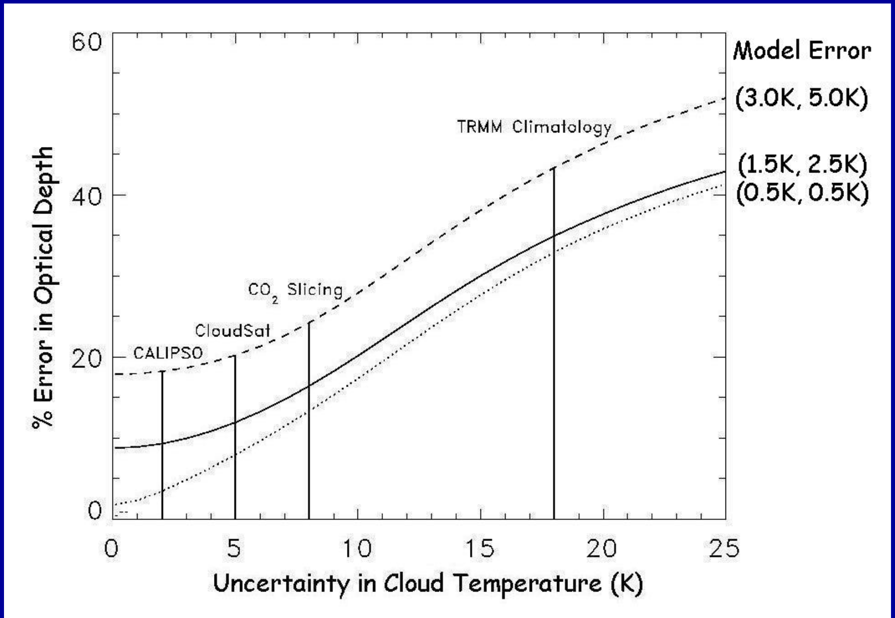
Assumptions of size distribution and ice crystal habit affect radiative transfer calculations

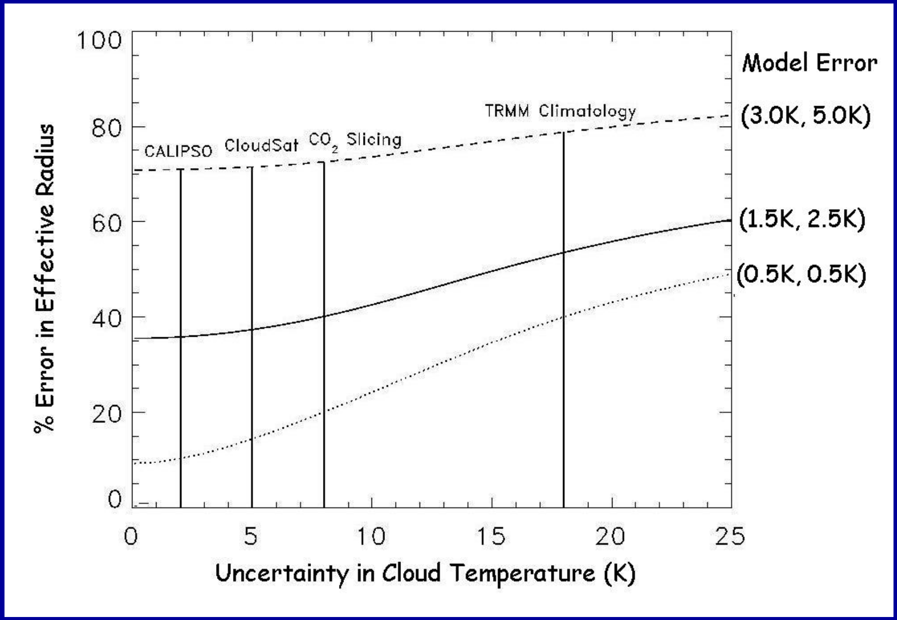




Split- Window Retrieval Results

Retrieved optical depth and effective radius are dependent upon uncertainties in both the cloud temperature (i.e. observation system) and the forward model assumptions such as ice crystal habit





MODIS + CloudSat Retrieval

- Apply methodologies from the split- window study to all MODIS cloud channels given CloudSat constraint
- The optimal combination of channels will be objectively selected through a formal information content analysis based on signal to noise considerations (ratio of sensitivity to uncertainty)
- Over ocean surface for overhead sun and nadir observation angles

0.64 µm
0.85 µm
0.93 µm
1.24 µm
1.37 µm
1.64 µm
2.13 µm
3.75 µm
4.05 µm
6.70 µm
8.55 µm
11.0 µm
12.0 µm
13.3 µm
13.6 µm
13.9 µm
14.2 µm

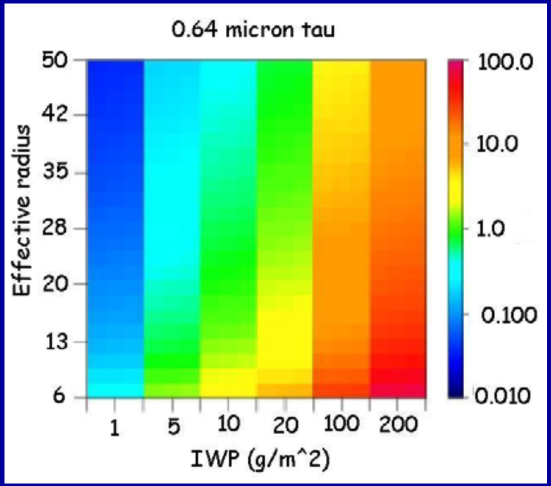
Channel Selection via Information Content

Information content approach (Shannon and Weaver, 1949: Rodgers, 2000; and L'Ecuyer, 2004) based on the reduction of entropy between *a priori* and retrieval probability distribution functions

$$H = S(P_1) - S(P_2)$$

$$H = \frac{1}{2} log_2 \left| \mathbf{S_a} \left(\mathbf{K}^{\mathbf{T}} \mathbf{S_y}^{-1} \mathbf{K} + \mathbf{S_a}^{-1} \right) \right|$$

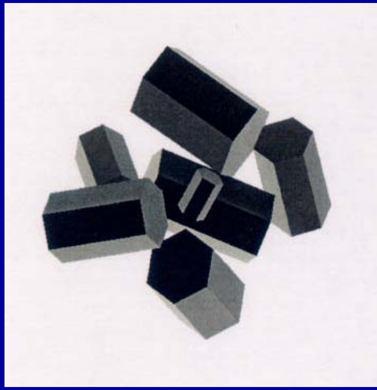
Sensitivities (K) and uncertainties (S_Y) were determined across the expected climatological range of ice cloud properties



Sensitivity Studies- Forward Model

- A 48- stream adding and doubling forward model was built to determine the change in satellite- viewed radiance with small changes in cloud retrievables

- Randomly- oriented randomized hexagonal ice aggregates (Baran, 2001) arranged in a modified gamma distribution with variance parameter equal to 2



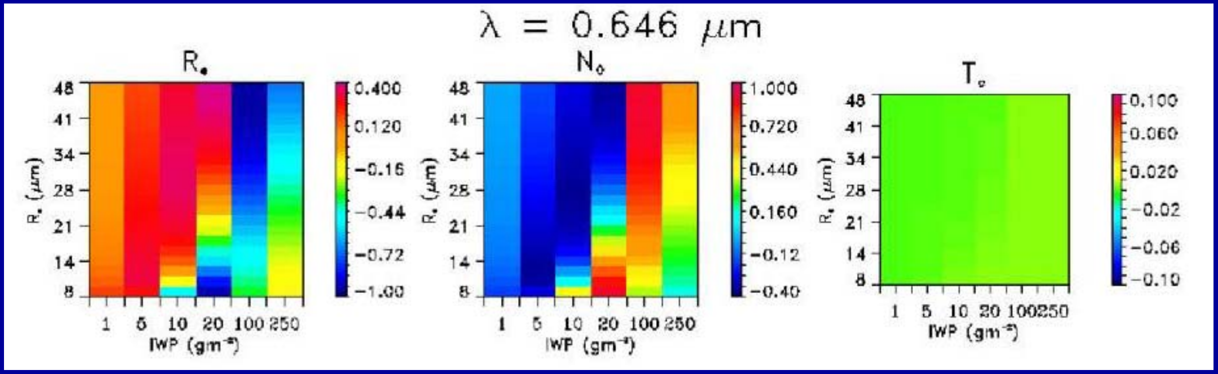
- Atmospheric absorption modeled by correlated- k distributions (Kratz, 1995) for the MODIS wavelengths

- Modified delta- M scaling technique (Mitrescu, 2003) used to handle complex phase functions while maintaining computational efficiency

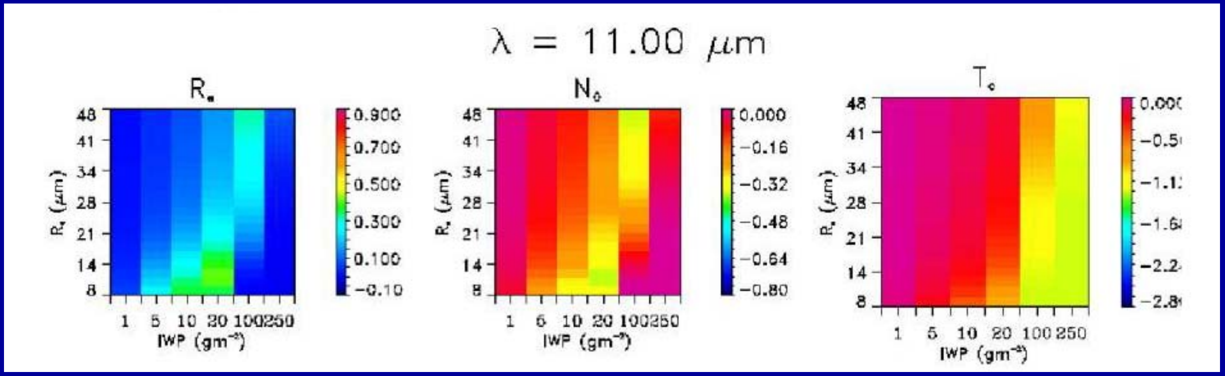
Sample Sensitivity Calculations (Determine K)

Studies defined in terms of IWP, effective radius, and cloud temperature

0.64 μm channel sensitive to IWP and r_{eff} but not cloud temperature

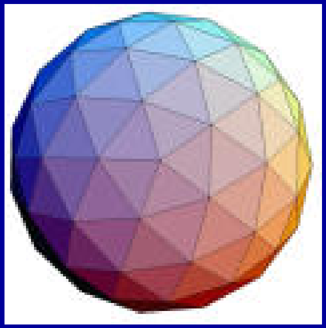


11.0 μm channel sensitive to IWP, r_{eff} and cloud temperature but only for moderately thick clouds



Uncertainty Analysis (Determine S_y)

- Different forward model assumptions will yield different radiative transfer results, each of the following assumptions were examined



Ice crystal habit: columns, bullets, plates, droxtals, dendrites and rough and smooth aggregates

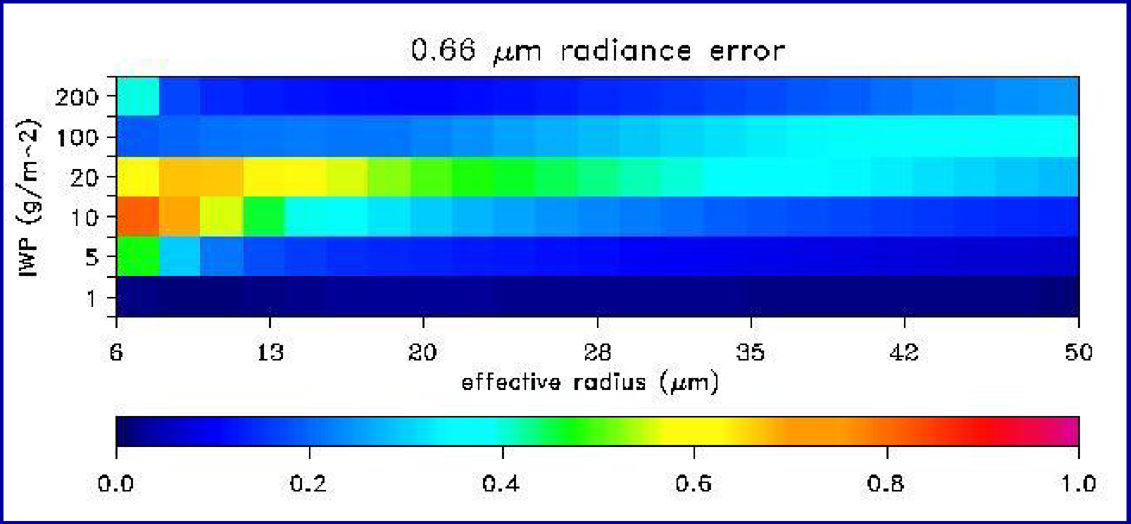
Ice particle size distribution: lognormal and modified gamma with different variance parameter

Atmosphere temperature and relative humidity profiles

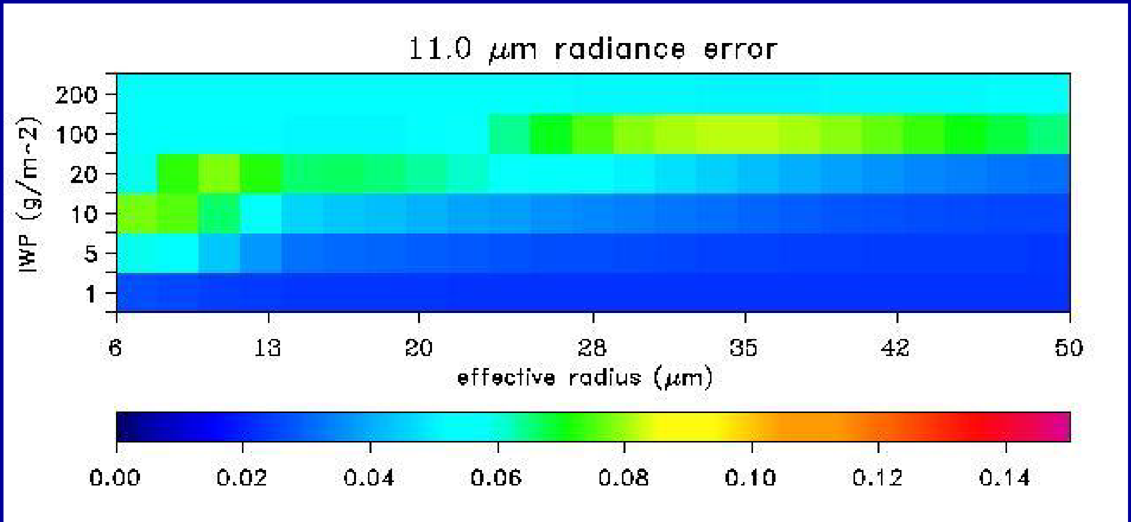
- Total uncertainty is the square of the sum of the squares

Sample Uncertainty Calculations

Uncertainties in visible radiances are large and state- dependent, dominated by habit effects



Uncertainties in infrared radiances are much smaller than those in the visible, consisting of a combination of temperature, relative humidity, and habit effects



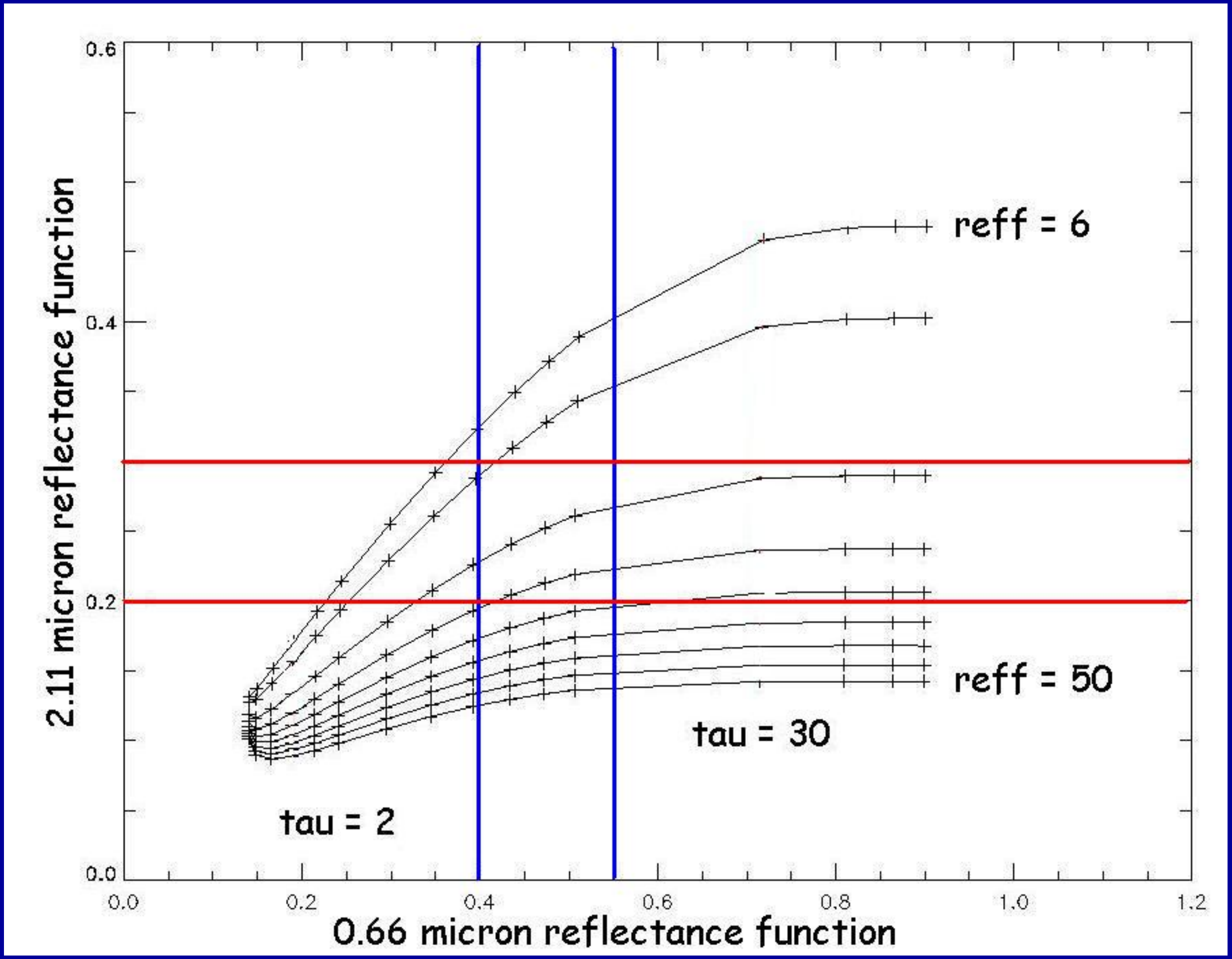
Physical Interpretation of Information

$$H = \frac{1}{2} log_2 \left| \mathbf{S_a} \left(\mathbf{K^T S_y^{-1} K} + \mathbf{S_a^{-1}} \right) \right|$$

The measurements with the most information are those that minimize the retrieval space relative to the a priori space

S_a state defined with σ of

200 g/m2 for IWP
25 μm for radius
1.5 K for cloud temperature



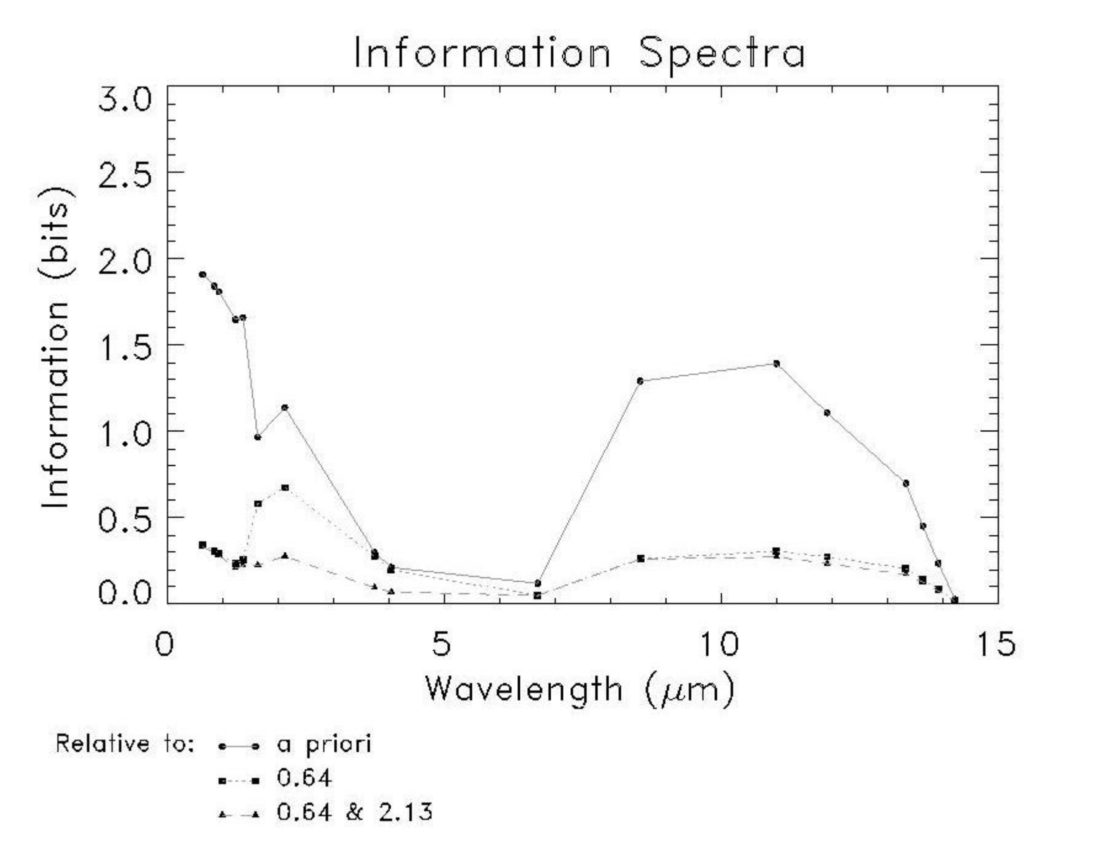
Information Content Results

Thick cloud case, tau = 11.0

IWP = 100 g/m^2
r_{eff} = 16 μm
cloud height = 9 km

↓

0.64 μm and 2.13 μm maximize information, i.e. Nakajima and King



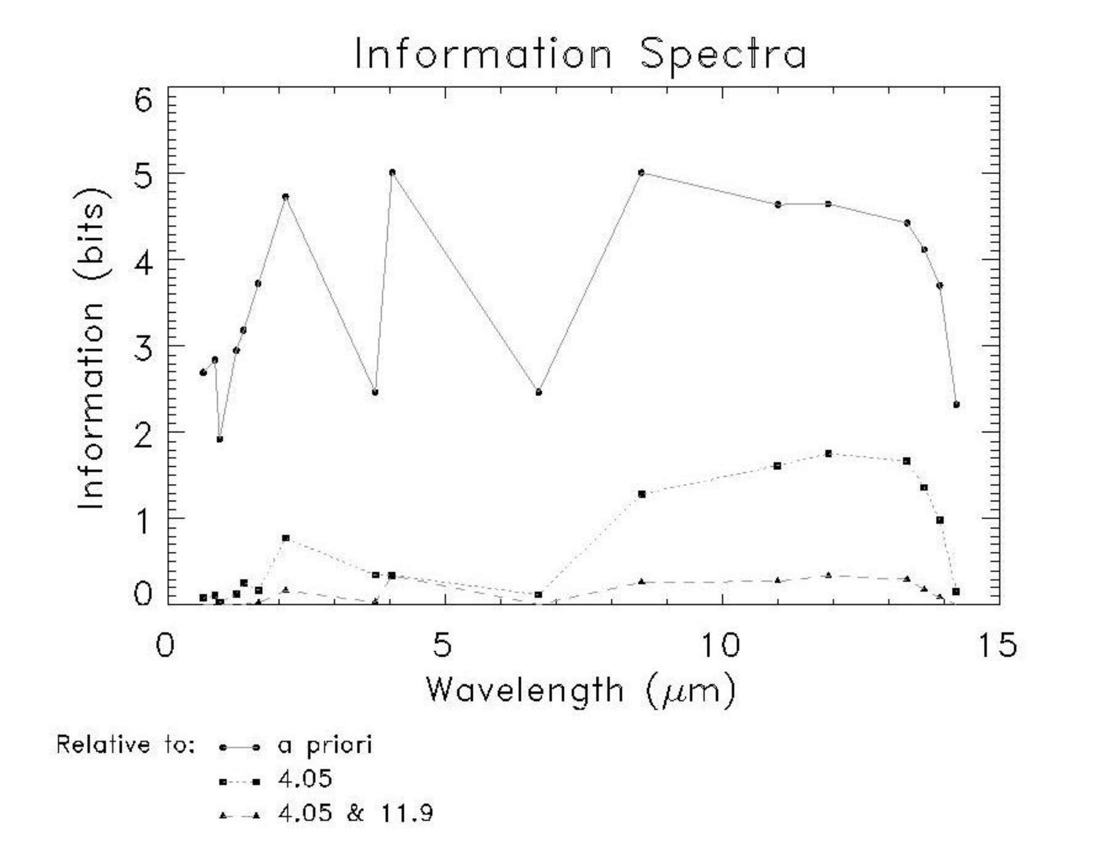
Information Content Results

<u>Thin cloud case, tau = 1.1</u>

IWP = 10 g/m^2
r_{eff} = 16 μm
cloud height = 9 km

↓

4.05 μm and 11.9 μm maximize information, i.e. split- window



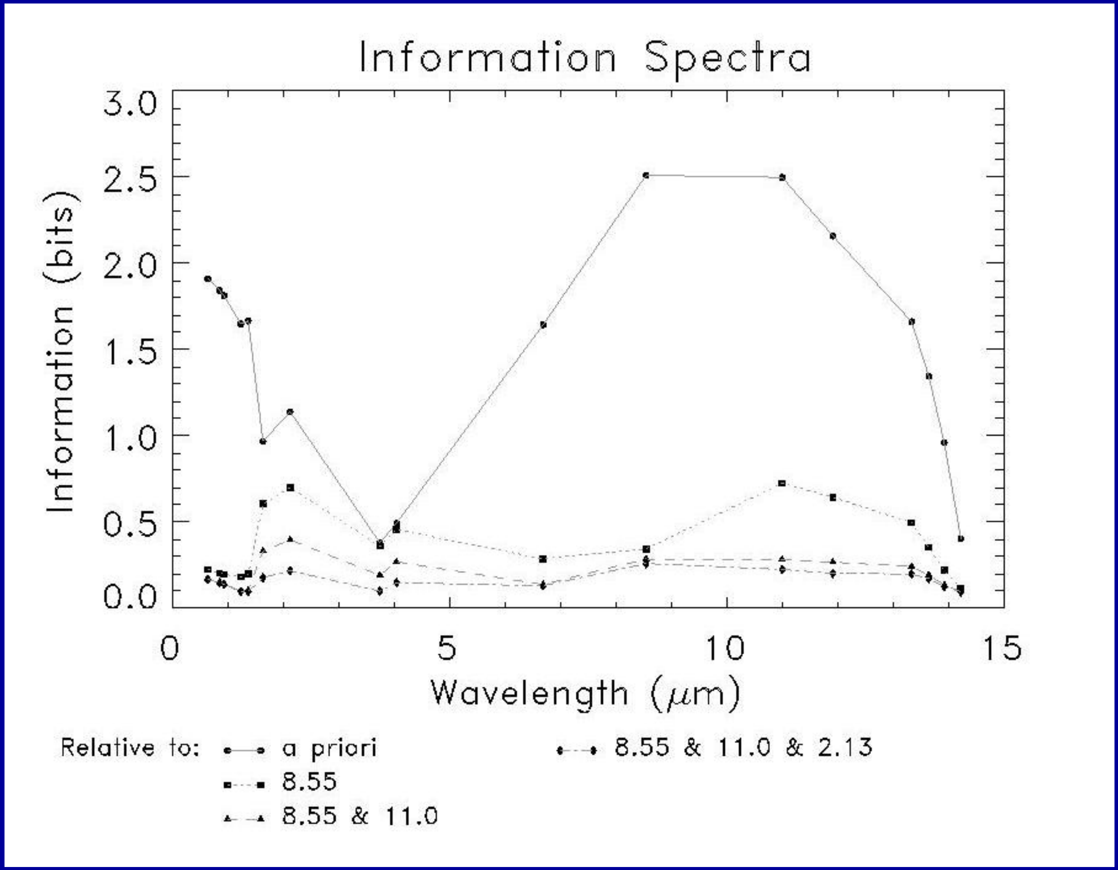
Information Content Results

High cloud case, tau = 11.0

IWP = 100 g/m^2
r_{eff} = 16 µm
cloud height = 14 km

↓

8.55, 11.0, and 2.13 µm
maximize information,
i.e. split- window + near- IR



State- Dependence of Channel Selection

Exact combination of channels that maximizes retrieval information is often ambiguous

Vis Conservative Scattering (dark blue)

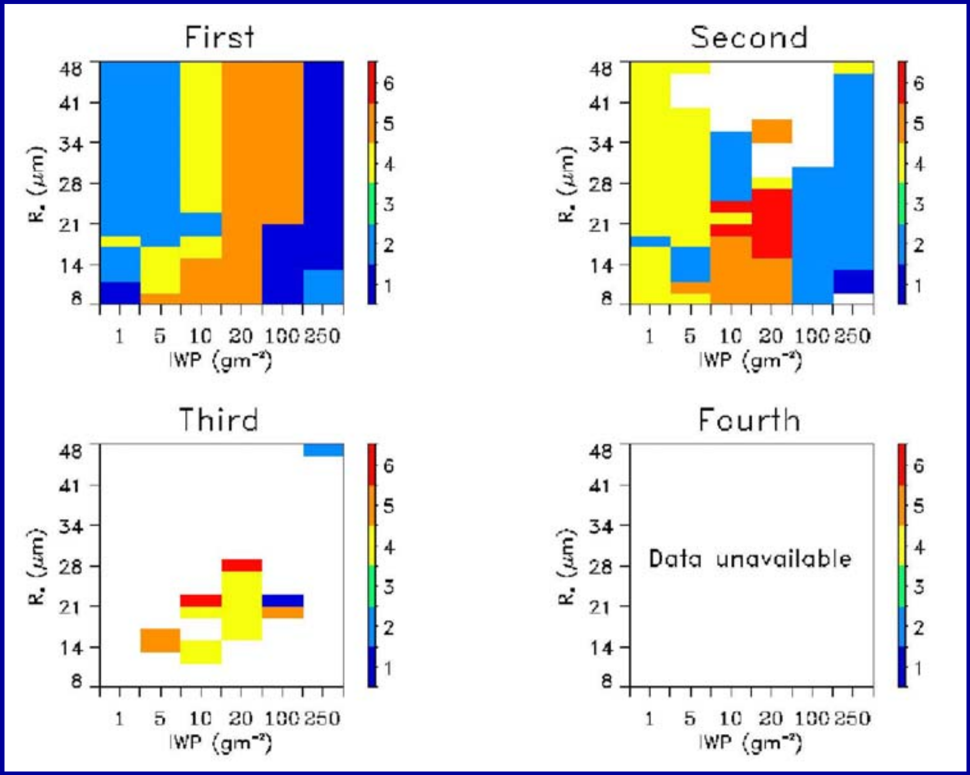
Near-IR Non- Conservative Scattering

SW-IR (3.75 µm and 4.05 µm)

Water Vapor

Infrared Window

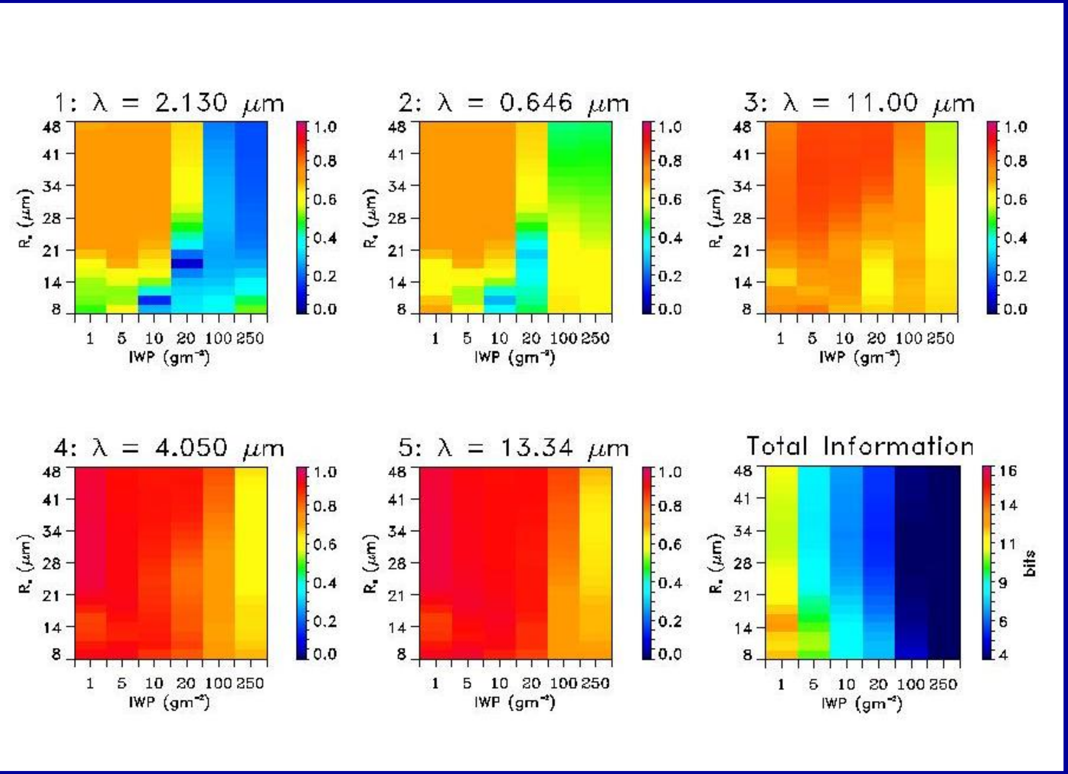
CO_2 Slicing Channels



Implications for Global Retrieval Approach

Traditional bi- spectral schemes cannot always ensure an accurate retrieval for all states of the atmosphere

We therefore propose a five- channel optimal- estimation based retrieval scheme that incorporates information from all spectral regions, error- weighted as a function of atmospheric state



Performance of Five- Channel Scheme

- Results of the five- channel retrieval scheme will be compared to those of the traditional bi- spectral approaches

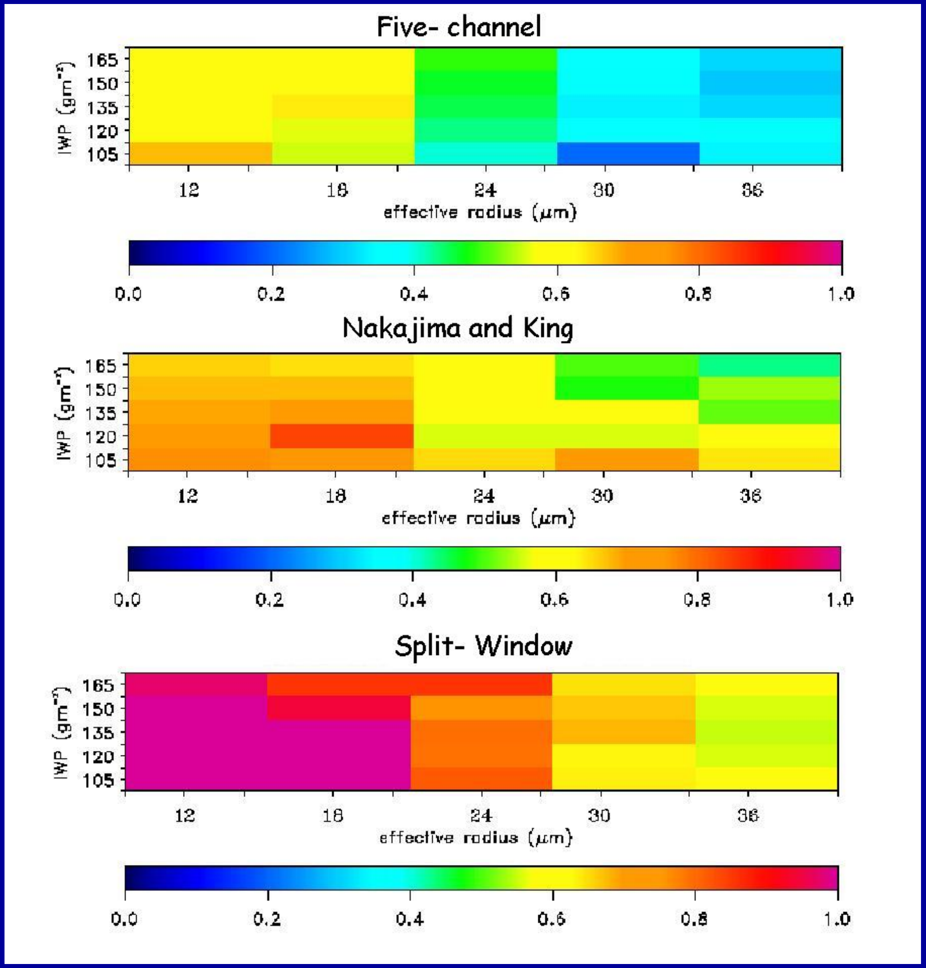
- Synthetic studies are controlled experiments that estimate expected retrieval uncertainties given our best estimate of measurement and forward model errors

- Application to real world CRYSTAL-FACE data offers insights into the operational utility of such an approach

Synthetic Results

Retrieval uncertainties were evaluated in terms of the optimal-estimation framework for both bias and random error

- Five- channel scheme better than bi- spectral techniques for all states for both IWP and reff
- Biases are non- negligible
- Random errors are large and state- dependent with typical values near 30 - 40 %



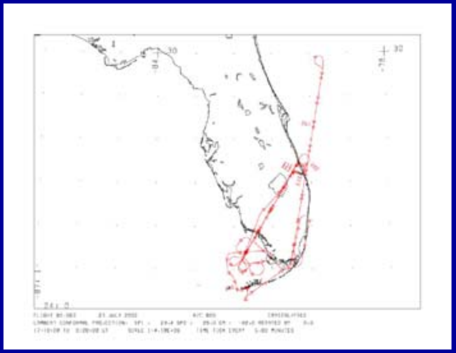
Synthetic Results- The Big Picture

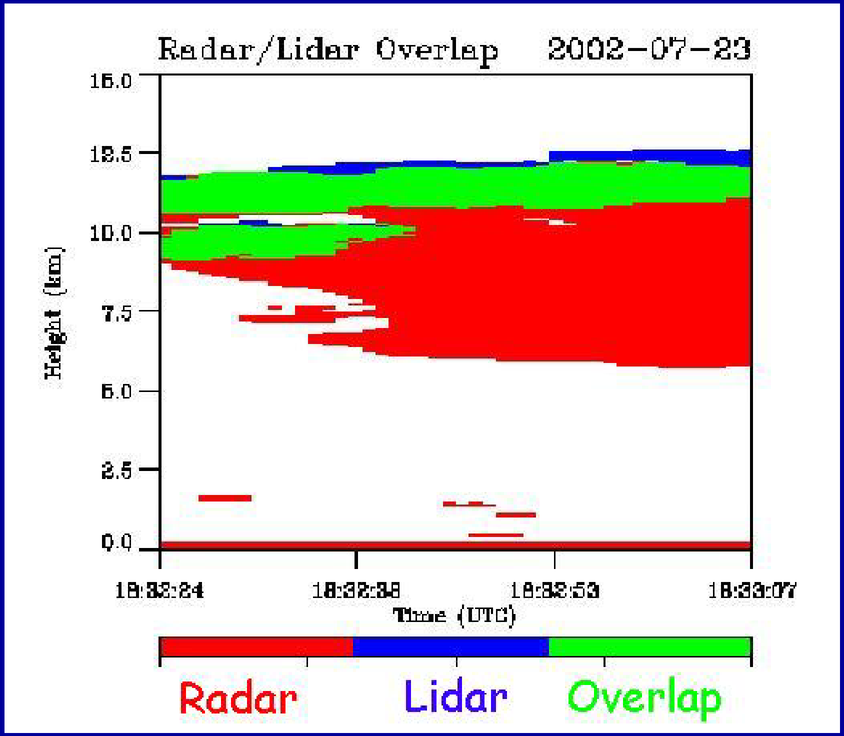
- Selection of non- representative cloud optical properties for inversion will result in a retrieval bias for global applications

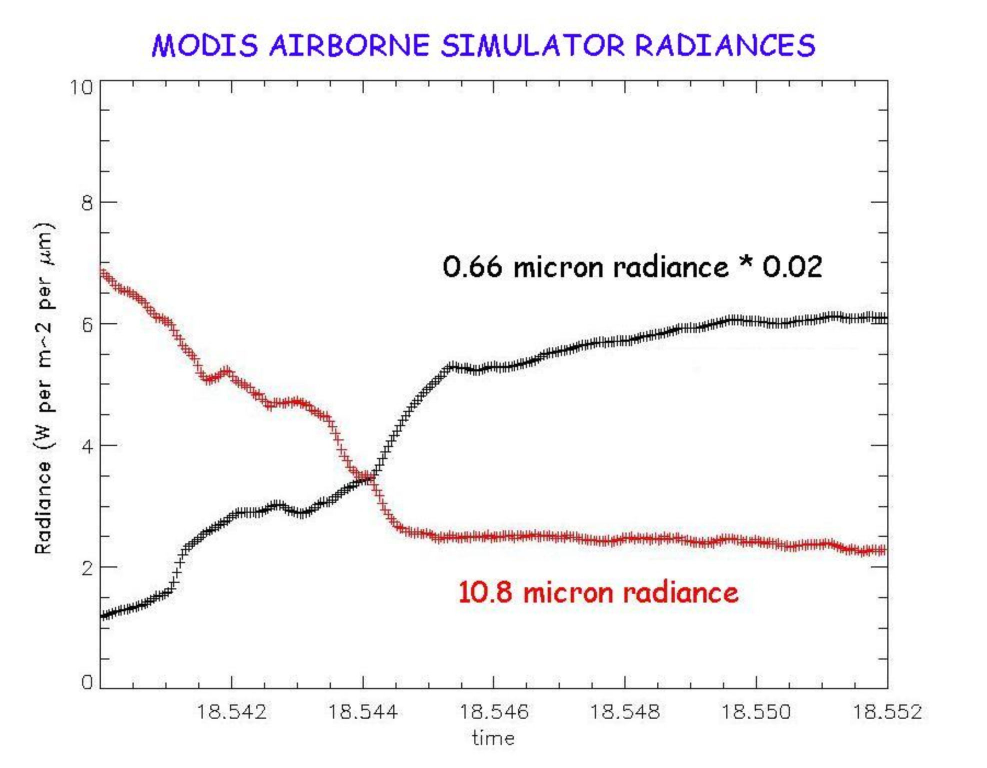
- Large retrieval uncertainties for advanced MODIS and CloudSat scheme raise concerns on the validity of absolute numbers or trends found in existing cloud climate products

- Inversion uncertainties need to be reduced before we can achieve accurate retrievals of ice cloud properties

CRYSTAL- FACE
Thin Cirrus Cloud Case

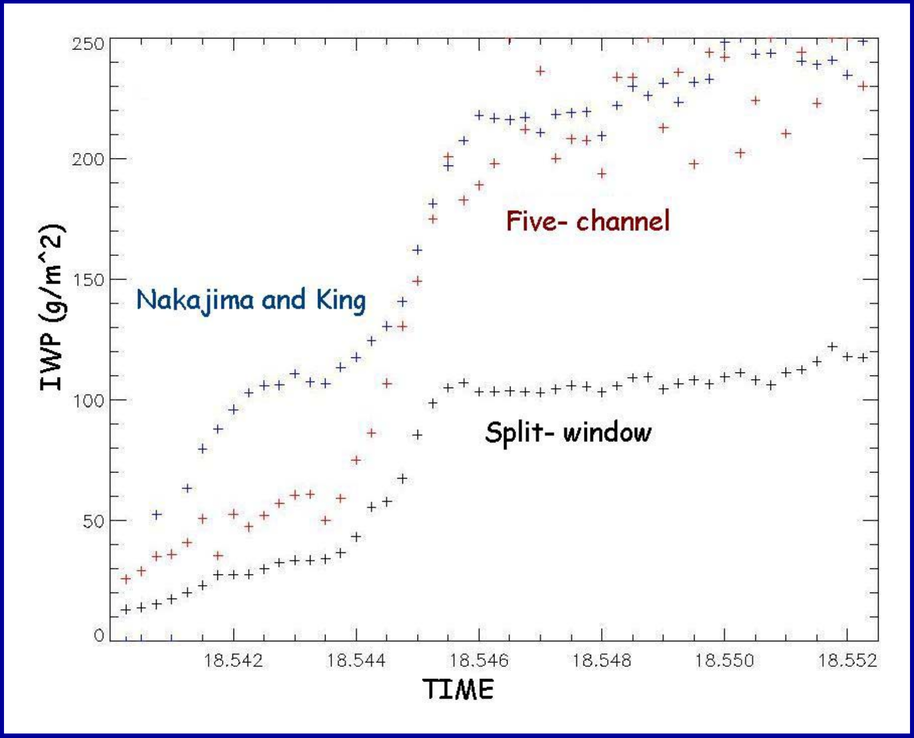


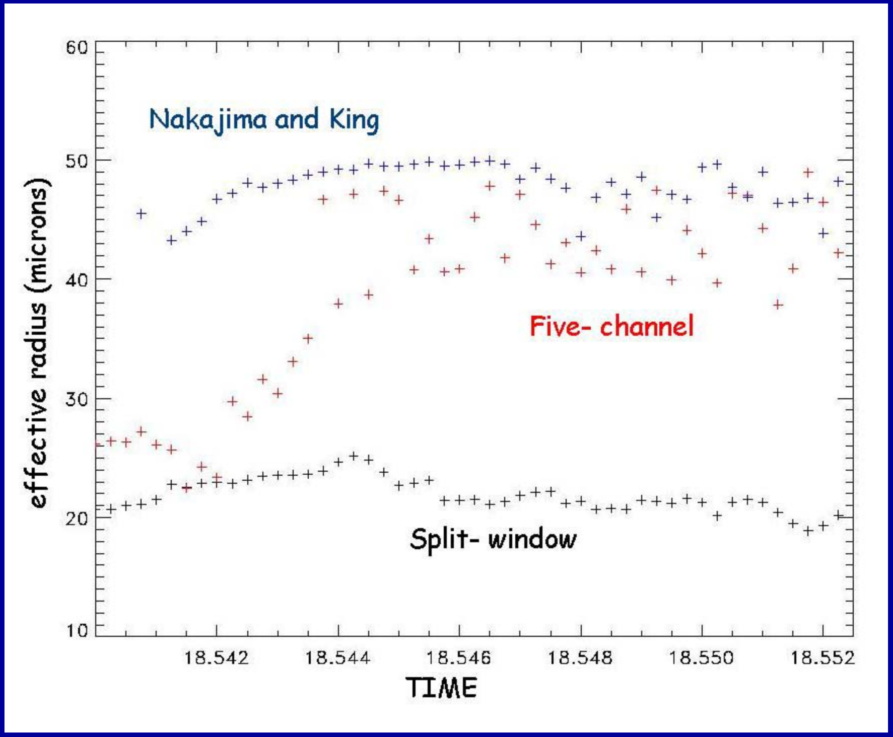




CRYSTAL- FACE Retrieval Results

Five- channel scheme behaves as a combination of the bi-spectral techniques





Operational Difficulties

- Five- channel and Nakajima and King retrieval schemes failed to converge for some of thin segments of the cloud when using ‘realistic’ measurement and forward model covariance estimates → surface albedo

- More channels in a retrieval scheme gives more chances for the violation of uncertainty estimates → surface, 3-D effects, and multi- layer clouds

- Selection of the initial guess influences estimate of cloud properties, possibly use CloudSat CPR reflectivities

- Computational expense

Conclusions

- The optimal- combination of measurements for an ice cloud microphysical property retrieval scheme is state- dependent
- An error- weighted five channel retrieval approach consisting of channels from each the visible, near- infrared, and infrared spectral regions ensures high information content regardless of the state of the atmosphere
- Uncertainties in retrieved ice cloud properties are large, implying caution in the strict use of existing cloud products
- The methodologies presented here can easily be extended to other research problems and should be implemented in the future design of satellite- based instrumentation

Future Work

- Development of operational retrieval as an experimental product for the CloudSat mission
- Apply information content methodologies presented here to the more complex multi- layer cloud problem
- Incorporate uncertainty estimates into a data- assimilation context
- Improvements in theory, in- situ measurements, and instrumentation to reduce inversion uncertainties
  $\rightarrow$ ice crystal habit