Remote *Sounding* with Advanced Infrared and Microwave Instruments

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GOES-R Algorithm Working Group – Co-chair of Sounder Team

NOAA/NESDIS representative to IGCO

Monday July 23, 2007

Workshop on Applications of Remotely Sensed Observations in Satellite Data Assimilation

Sounding Theory Notes for the discussion today is on-line

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ftp site: ftp://ftp.orbit.nesdis.noaa.gov/pub/smcd/spb/cbarnet/

..or.. ftp ftp.orbit.nesdis.noaa.gov, cd pub/smcd/spb/cbarnet

Sounding NOTES, used in teaching UMBC PHYS-741: Remote Sounding and UMBC PHYS-640: Computational Physics (w/section on Apodization)

~/reference/rs_notes.pdf

~/reference/phys640_s04.pdf

These are *living* notes, or maybe a scrapbook – they are not textbooks.

For an excellent text book on the topic of remote sounding is:

Rodgers, C.D. 2000. Inverse methods for atmospheric sounding: Theory and practice. World Scientific Publishing 238 pgs

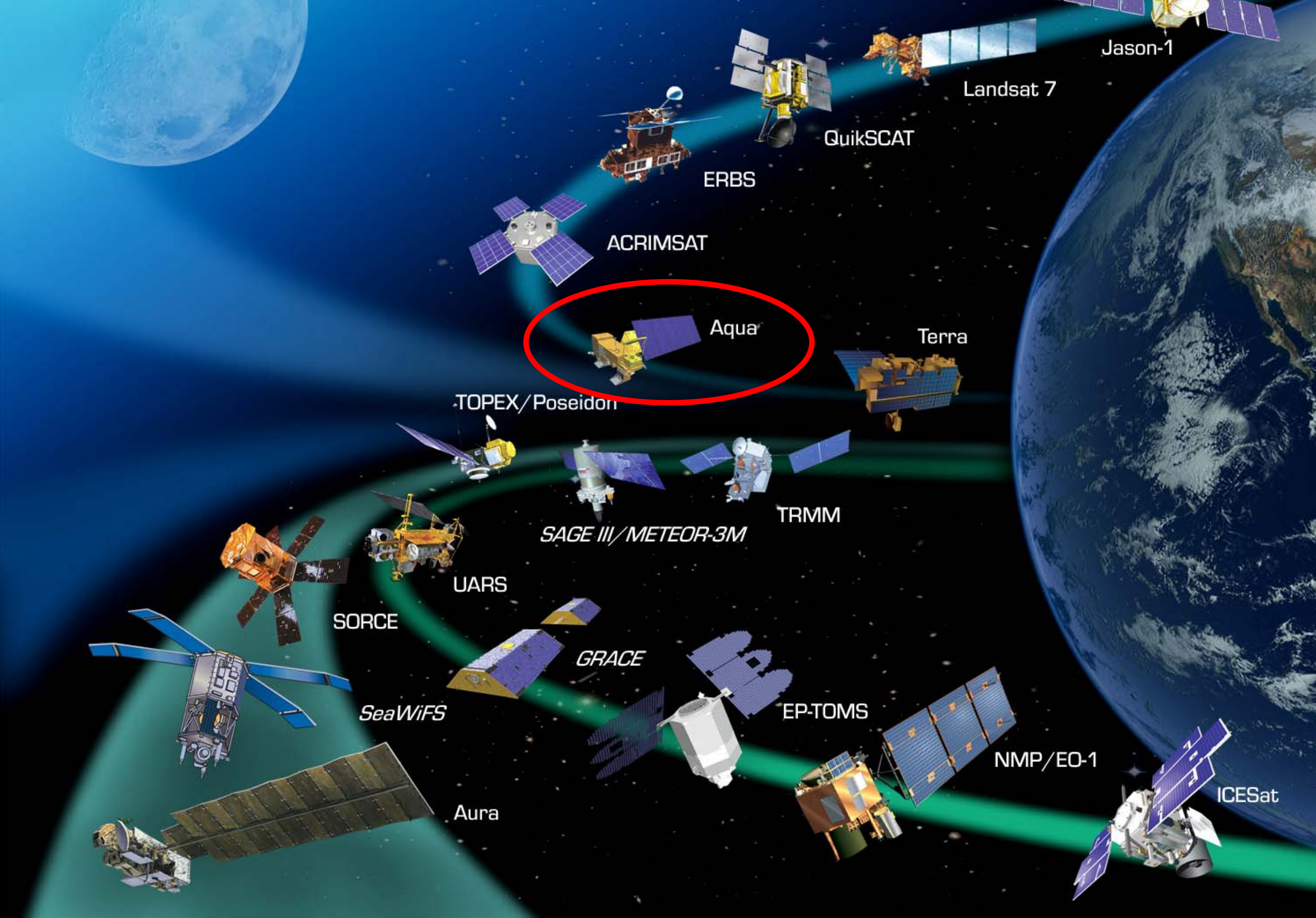
Acronyms

- Infrared Instruments
  - AIRS = Atmospheric Infrared Sounder
  - IASI = Infrared Atmospheric Sounding Interferometer
  - CrIS = Cross-track Infrared Sounder
  - HES = Hyperspectral Environmental Suite
- Microwave Instruments
  - AMSU = Advanced Microwave Sounding Unit
  - HSB = Humidity Sounder Brazil
  - MHS = Microwave Humidity Sensor
  - ATMS = Advanced Technology Microwave Sounder
  - AMSR = Advanced Microwave Scanning Radiometer
- Imaging Instruments
  - MODIS = MODerate resolution Imaging Spectroradiometer
  - AVHRR = Advanced Very High Resolution Radiometer
  - VIIRS = Visible/IR Imaging Radiometer Suite
  - ABI = Advanced Baseline Imager
- Other
  - CALIPSO = Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
  - EUMETSAT = EUropean organization for exploitation of METeorological SATellites
  - GOES = Geostationary Environmental Operational Satellite
  - IGCO = International Global Carbon Observation (theme within IGOS)
  - IGOS = Integrated Global Observing System
  - IPCC = Inter-government Panel on Climate Change
  - METOP = METeorological Observing Platform
  - NESDIS = National Environmental Satellite, Data, and Information Service
  - NPOESS = National Polar-orbiting Operational Environmental Satellite System
  - NDE = NPOESS Data Exploitation
  - NPP = NPOESS Preparatory Project
  - OCO = Orbiting Carbon Observatory
  - STAR = office of SaTellite Applications and Research

Topics for Lectures

- Monday July 23, 2007
  - Introduction to AIRS & IASI and our plans to use *operational* sounders to retrieve atmospheric and surface products.
  - Introduction to Sounding Methodology
    - Cloud clearing
    - Statistical Regression Retrievals
- Tuesday July 24, 2007
  - Sidebar: Comparison of Dispersive and Interferometric Instruments
  - Introduction to Sounding Methodology (continued)
    - The forward model: Converting state vector to radiances.
    - The inverse problem: Converting radiances to a state vector.
- Wednesday July 25, 2007
  - Introduction to Sounding Methodology (continued)
    - Vertical Averaging Kernels & Error Covariance Matrices
  - Validation of Products
  - Atmospheric Carbon Retrievals

NASA Earth Observatories



NOAA/NESDIS 20 year Strategy Using Advanced Operational Sounders.

- Now: Develop and core & test trace gas algorithms using the Aqua (May 4, 2002) AIRS/AMSU/MODIS Instruments
  - Compare products to *in-situ* (*e.g.*, ESRL/GMD Aircraft, JAL, INTEX, etc.) to characterize error characteristics.
  - The A-train complement of instruments (*e.g.*, MODIS, AMSR, CALIPSO) can be used to study effects of clouds, surface emissivity, etc.
- 2007: Migrate the AIRS/AMSU/MODIS algorithm into operations with METOP (2006,2011,2016) IASI/AMSU/MHS/AVHRR. Study the impact on products due to differences between instruments, *e.g.*, effects of scene and clouds on IASI's ILS.
- 2009: Migrate the AIRS/IASI algorithm into operations for NPP (2009?) & NPOESS (2013?,2015?) CrIS/ATMS/VIIRS. These are NOAA Unique Products within the NOAA NDE program.

AIRS Was Launched on the EOS Aqua Platform May 4, 2002

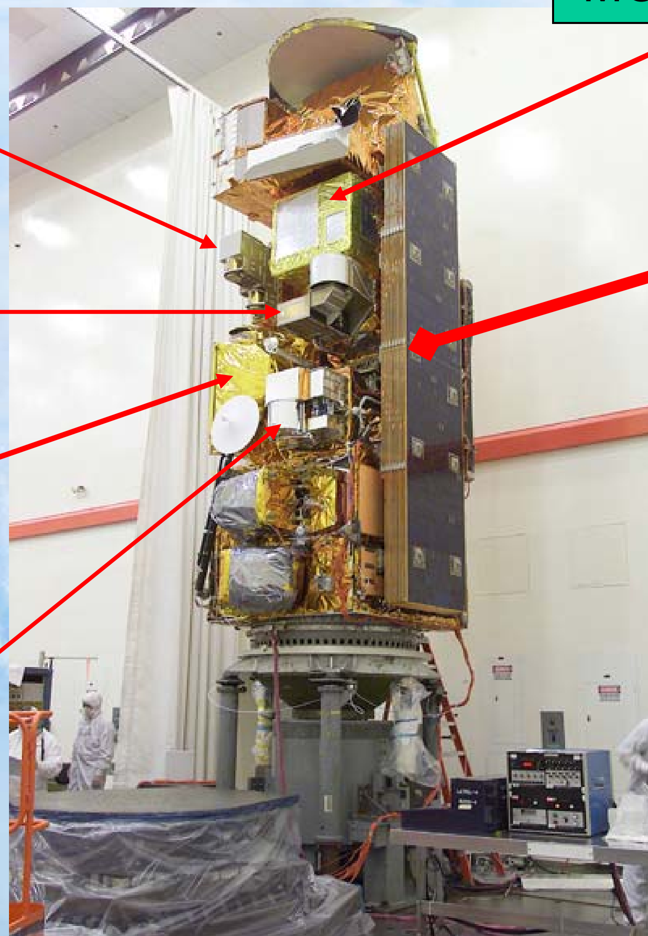
AMSU-A1(3-15

MODIS

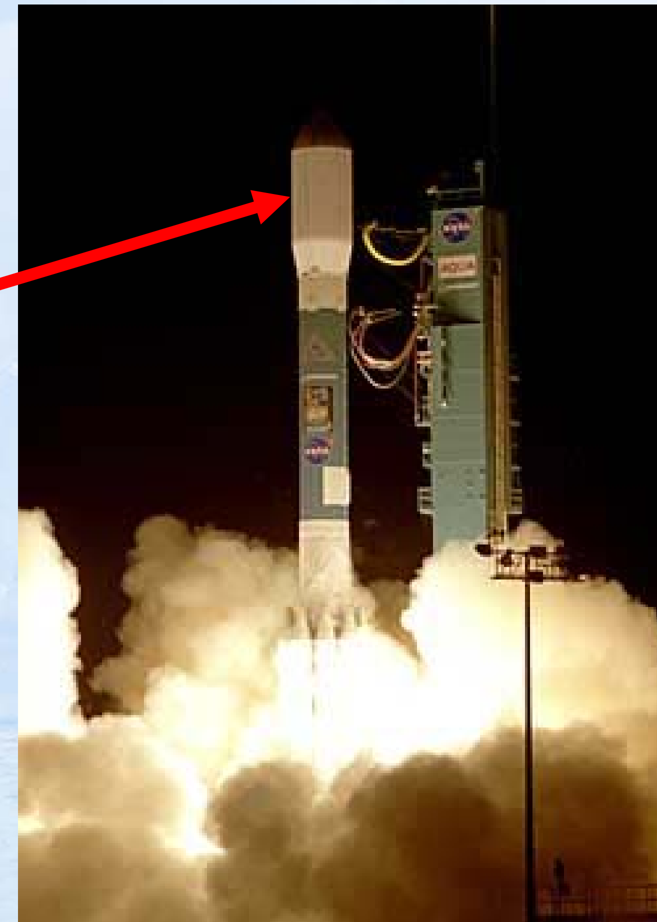
AMSU-A2(1-2)

AIRS

HSB

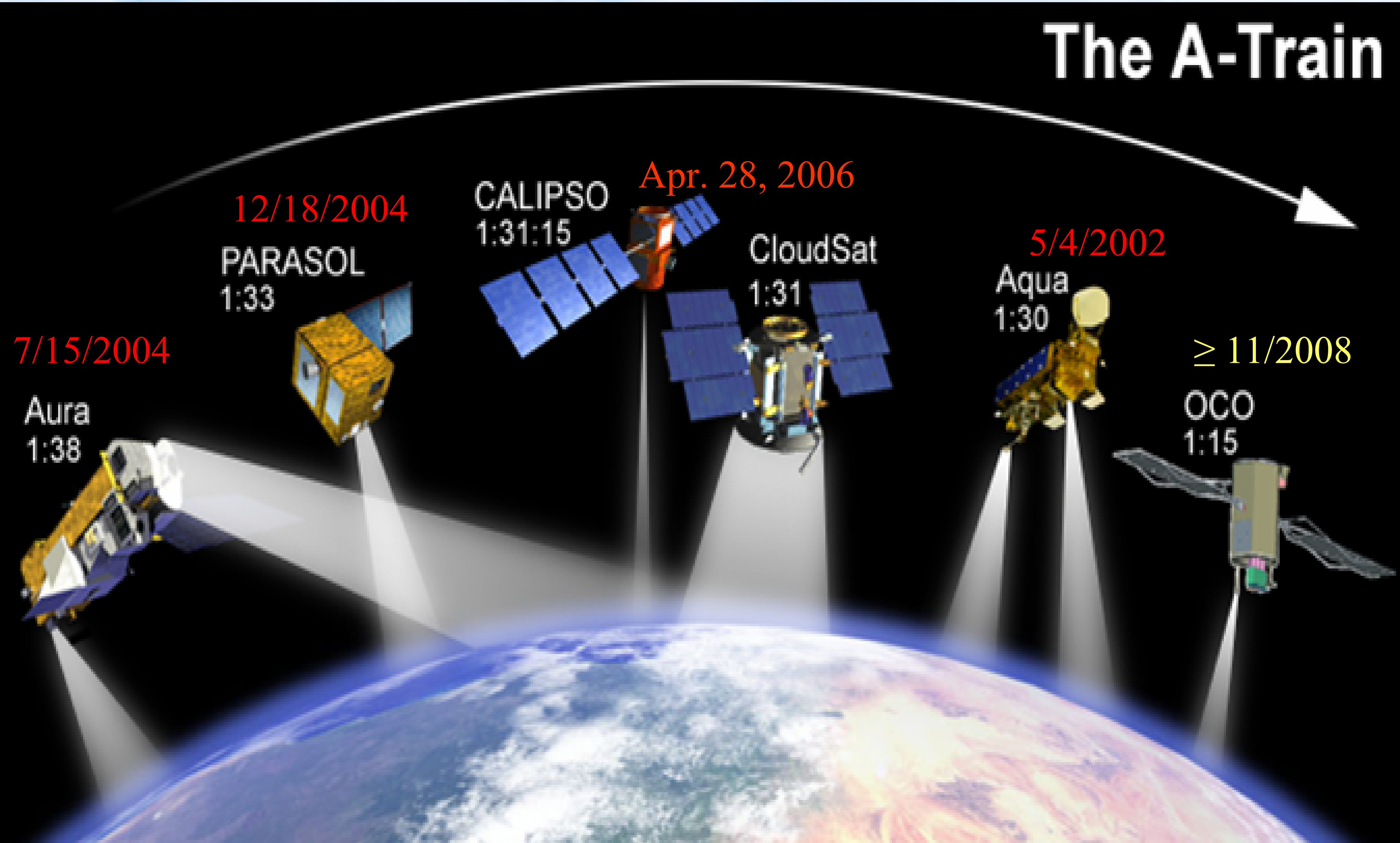


Aqua Acquires 325 Gb of data per day

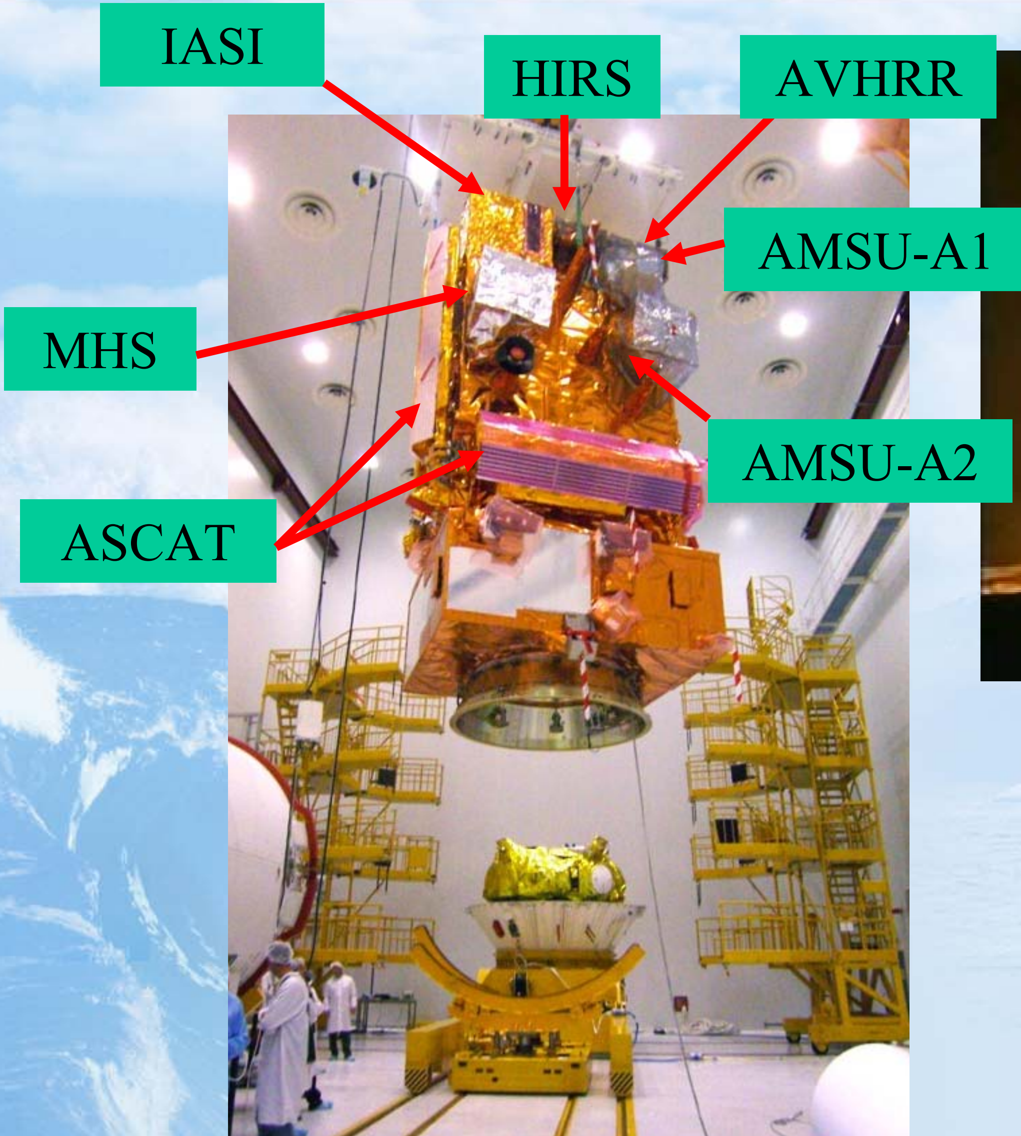


Delta II 7920

AIRS has a Unique Opportunity to Explore & Test New Algorithms for Future Operational Sounder Missions.



IASI was launched on the MetOp-A Satellite on Oct. 19, 2006

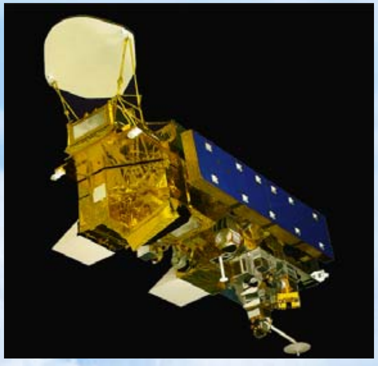


Soyuz 2/Fregat launcher,

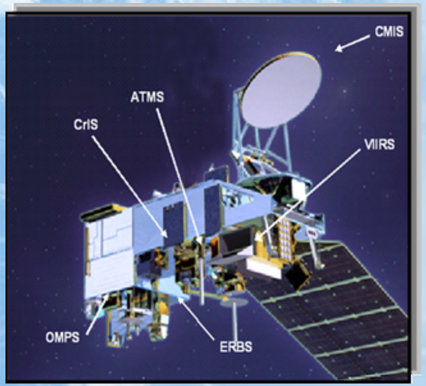
Baikonur, Kazakhstan

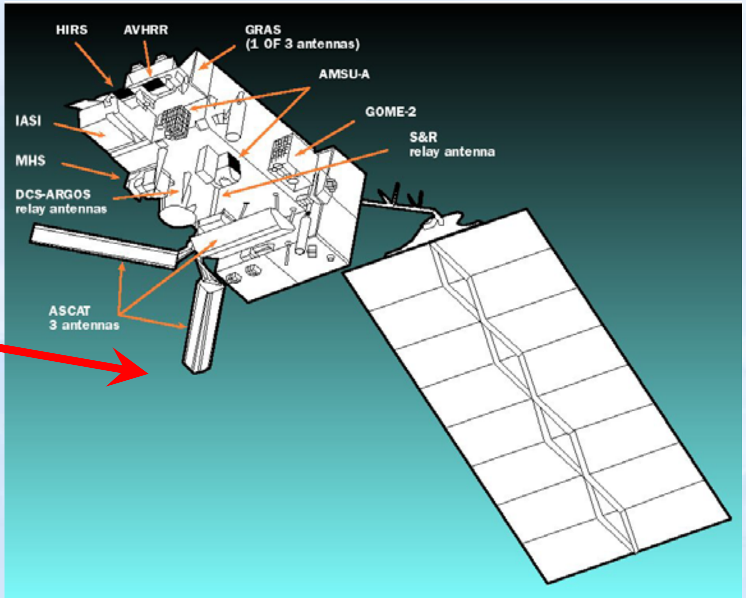
Initial Joint Polar System: An agreement between NOAA & EUMETSAT to exchange data and products.

NASA/Aqua
1:30 pm orbit (May 4, 2002)



NPP & NPOESS
1:30 pm orbit (2010)

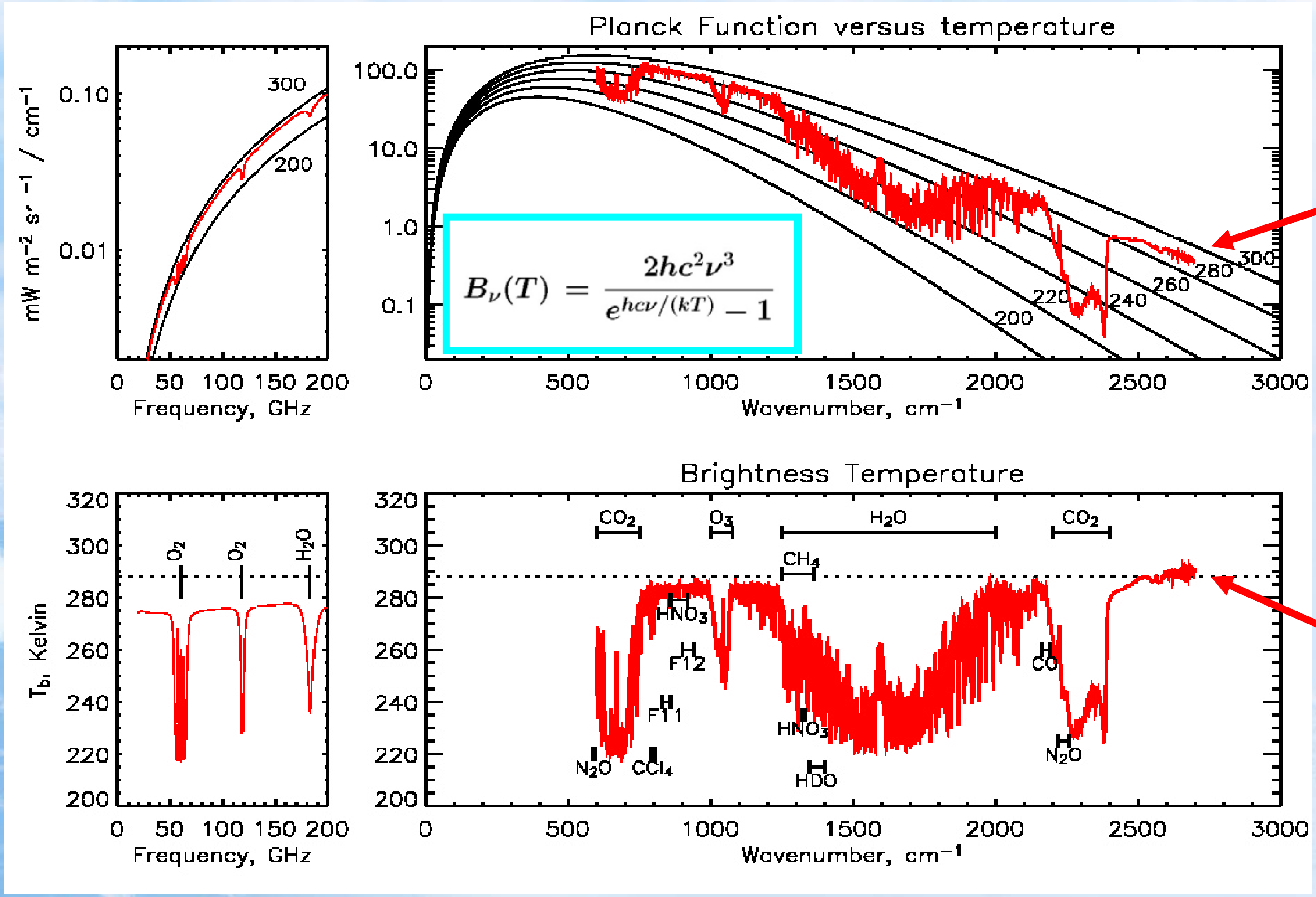




EUMETSAT/METOP-A
9:30 am orbit (Oct. 19, 2006)

Instruments measure radiance

(energy/time/area/steradian/frequency-interval)



This is what we measure and use the data.

This is how we usually show it.

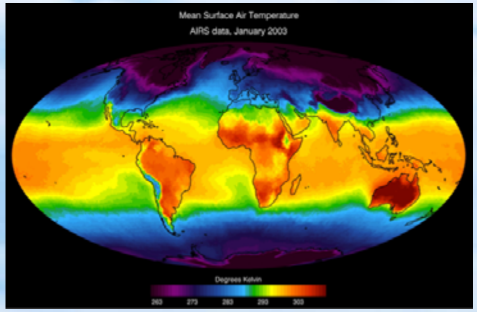
Convert to Brightness Temperature = Temperature that the Planck Function is equal to measured radiance at a given frequency.

Thermal Sounder "Core" Products (on 45 km footprint, unless indicated)

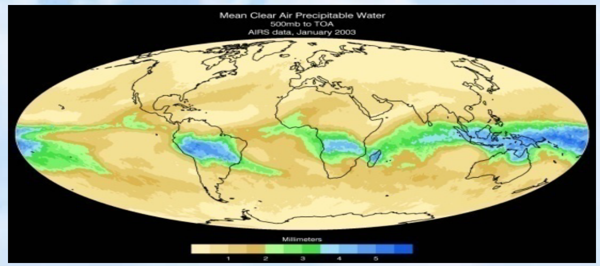
Radiance Products	*RMS Requirement*	*Current Estimate*
AIRS IR Radiance (13.5 km)	3%	< 0.2 %
AIRS VIS/NIR Radiance	20%	10-15%
AMSU Radiance	0.25-1.2 K	1-2 K
HSB Radiance (13.5 km)	1.0-1.2 K	(failed 2/2003)
Geophysical Products	***RMS Requirement***	***Current Estimate***
Cloud Cleared IR Radiances	1.0K	< 1 K
Sea Surface Temperature	0.5 K	0.8 K
Land Surface Temperature	1.0K	TBD
Temperature Profile	1K/1-km layer	1K/1-km
Moisture Profile	15%/2-km layer	15%/2-km
Total Precipitable Water	5%	5%
Fractional Cloud Cover (13.5 km)	5%	TBD
Cloud Top Pressures	0.5 km	TBD
Cloud Top Temperatures	1.0 K	TBD

AIRS Products

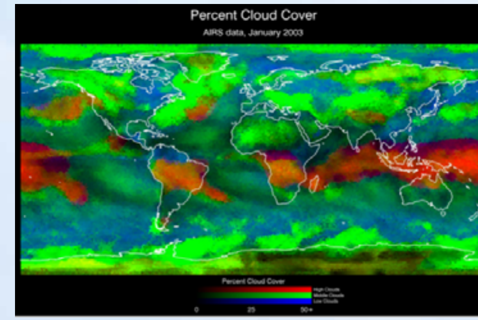
Temperature Profiles



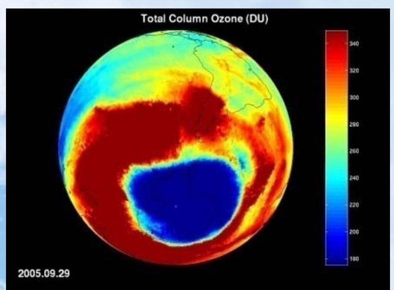
Water Vapor Profiles



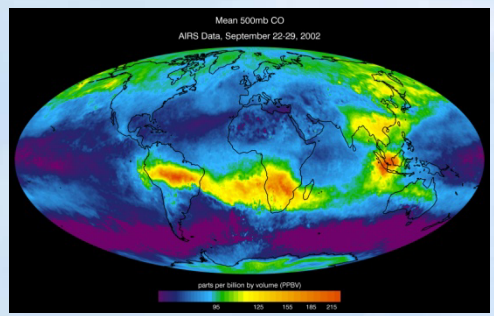
Clouds



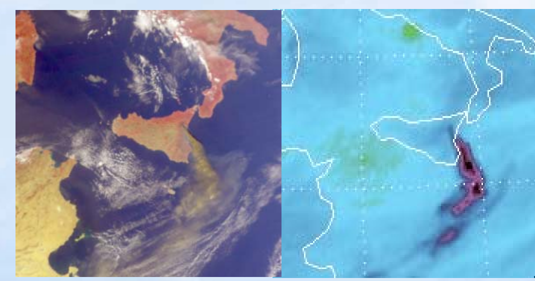
Ozone



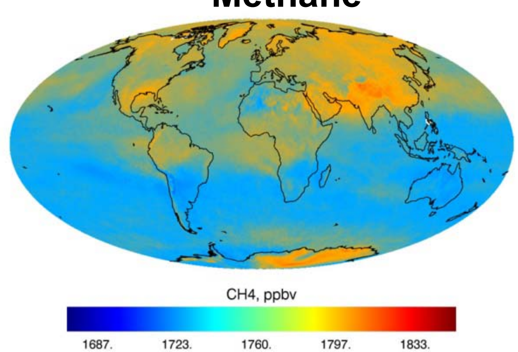
CO



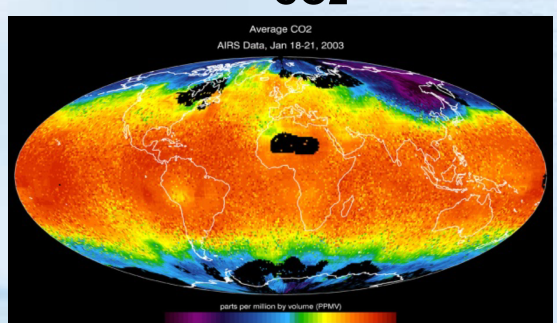
SO2



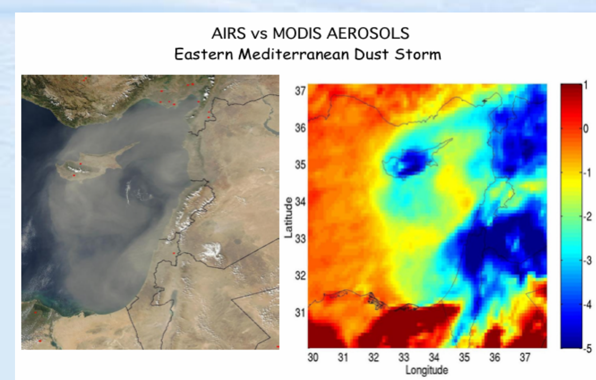
Methane



CO2



Dust

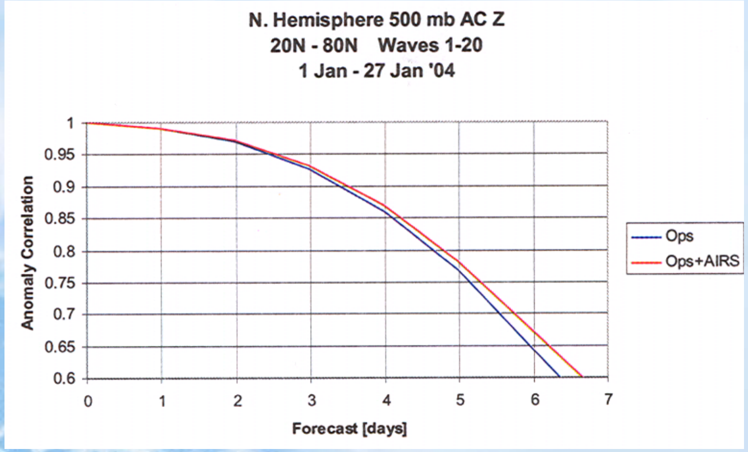


Radiances versus Products

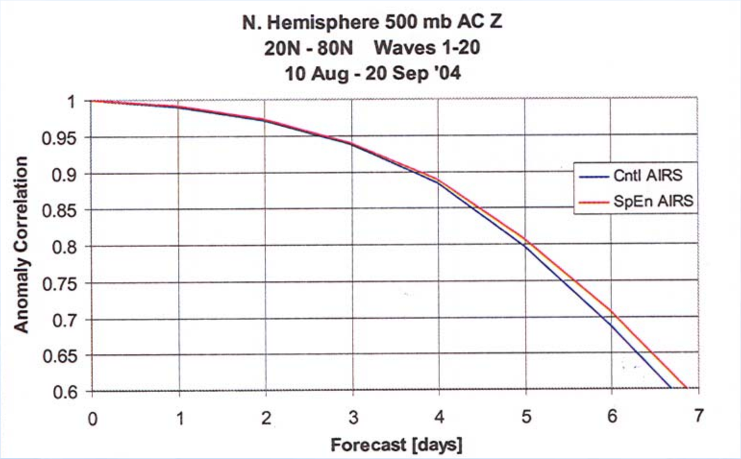
Radiance	Retrieval Products
Product volume is large: In practice, a spectral subset (10%), spatial subset (5%), and clear subset (5%) of the observations is made	Product volume is small: all instrument channels can be used to minimize all parameters (T,q,O_3,CO,CH_4,CO_2,clouds,etc.)
Instrument error covariance is usually assumed to be diagonal. For apodized interferometers (e.g. IASI) this is not accurate.	Product error covariance has vertical, spatial, and temporal off-diagonal terms.
Require very fast forward model, and derivative of forward model.	Most accurate forward model is used with a model of detailed instrument characteristics.
Small biases in T(p), q(p), O_3(p),due to model/satellite representation error, have large impact on derived products.	*A-priori* used in retrieval is different than assimilation model; however, vertical kernel information can be used to assimilate product.
Tendency to weight the instrument radiances lower (due to representation error) to stabilize the model. Need correlation lengths to stabilize model horizontally, vertically, and temporally.	Retrieval weights the radiances as high as possible, since determined state is on *instrument* sampling "grid."

AIRS Forecast Improvement

Improved Forecast Prediction
1 in 18 AIRS FOV's
(6 hours in 6 Days)
Northern Hemisphere
October 2004 *



Additional Improvement Using
All 18 AIRS FOV's
(11 hours total in 6 Days)
Northern Hemisphere
Preliminary

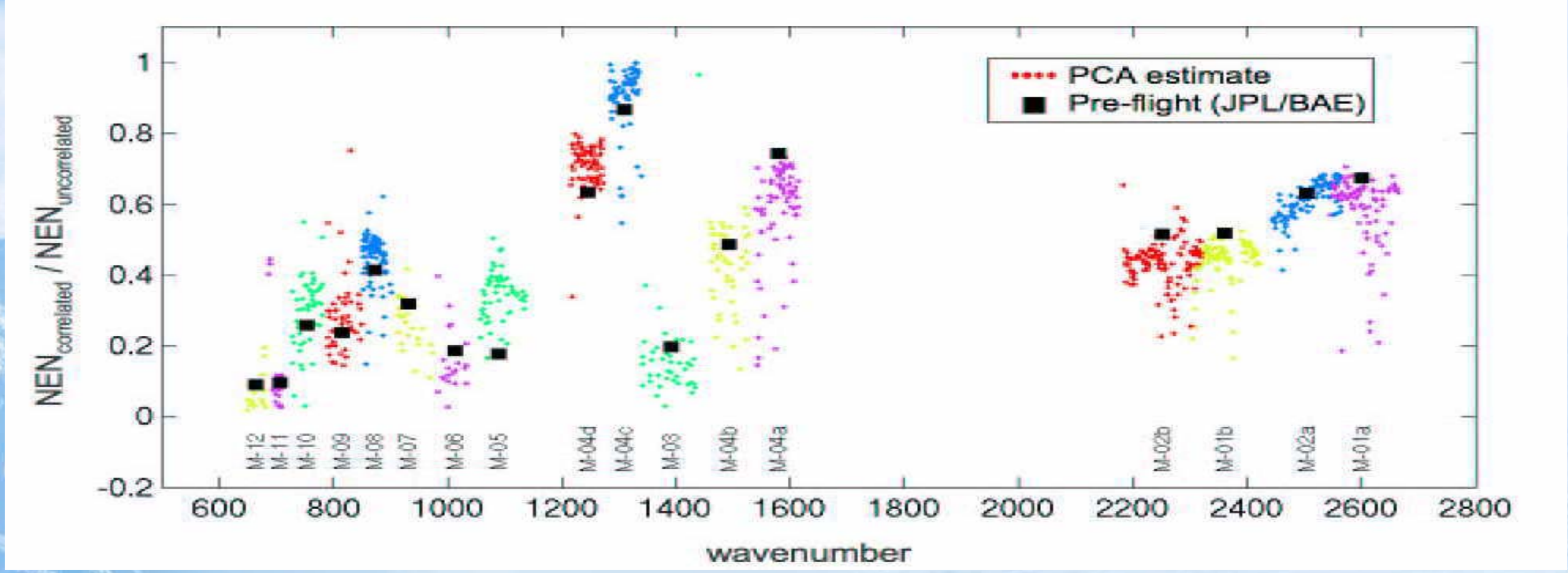


This AIRS instrument has provided a significant increase in forecast improvement in this time range compared to any other single instrument

J. LeMarshall, J. Jung, J. Derber, R. Treadon, S. Lord, M. Goldberg, W. Wolf, H. Liu, J. Joiner, J. Woollen, R. Todling, R. Gelaro "Impact of Atmospheric Infrared Sounder Observations on Weather Forecasts", EOS, Transactions, American Geophysical Union, Vol. 86 No. 11, March 15, 2005

Examples of off-diagonal elements in instrument coviance.

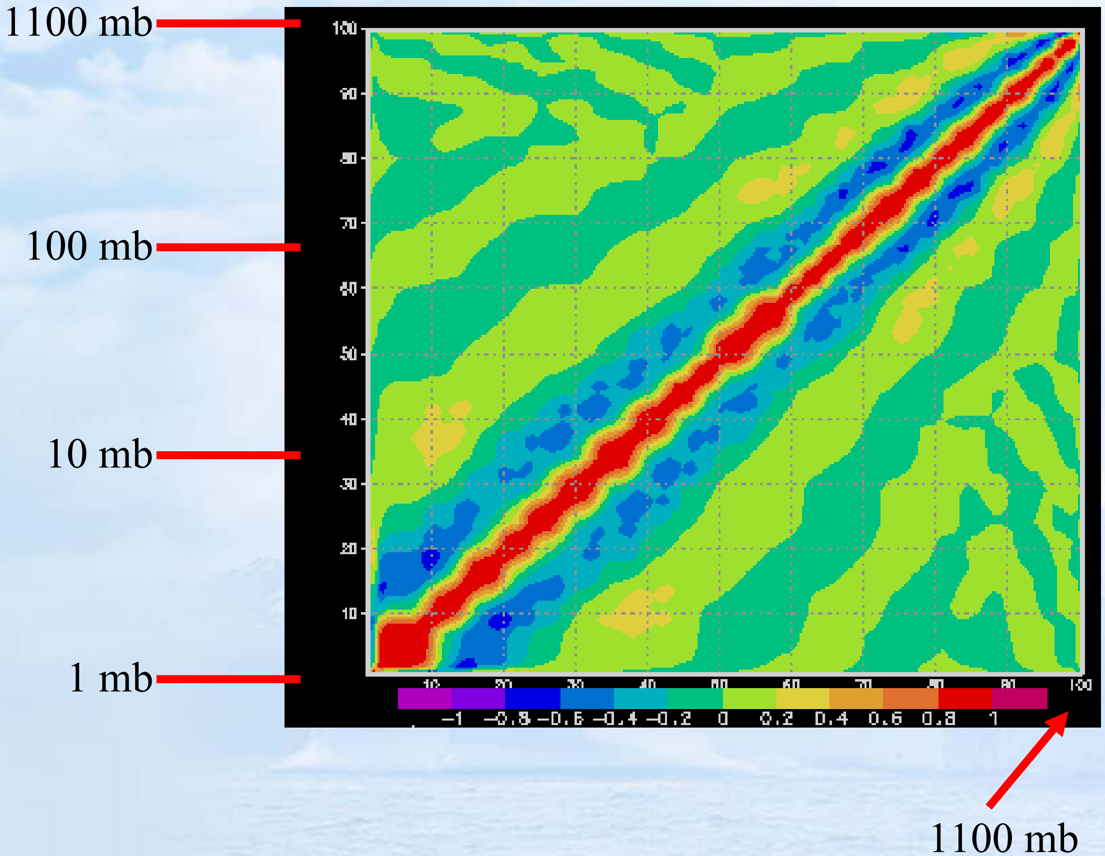
- In any instrument there are optical, electrical, and processing components that can correlate signals.
- In interferometers, for example, processing includes as step called apodization to make the instrument spectral characteristics localized (necessary for efficient radiance computations). But, apodization causes a local spectral correlation (a channel is 62% correlated with neighbor (±1 channel), 13% correlated with ±2 channels, 1% correlated with ±3 channels, etc.)
- In dispersive instruments each detector array has spectral correlation due to a common electronics system. For example, in AIRS the spectral correlation is a function of the array module:



Therefore, the best use of satellite radiances requires ability to characterize ever detail of the instrument and processing.

Example of Temperature Retrieval Error Covariance

- An example of temperature retrieval correlation (minimum variance method) for the AIRS instrument
- Top of atmosphere radiances are used to invert the radiative transfer equation for T(p).
- This results in a correlation that is a vertical oscillatory function.



Therefore, the use of retrieval products requires knowledge of retrieval "averaging kernels" and errors estimates.

AIRS Science Team: Algorithm Components

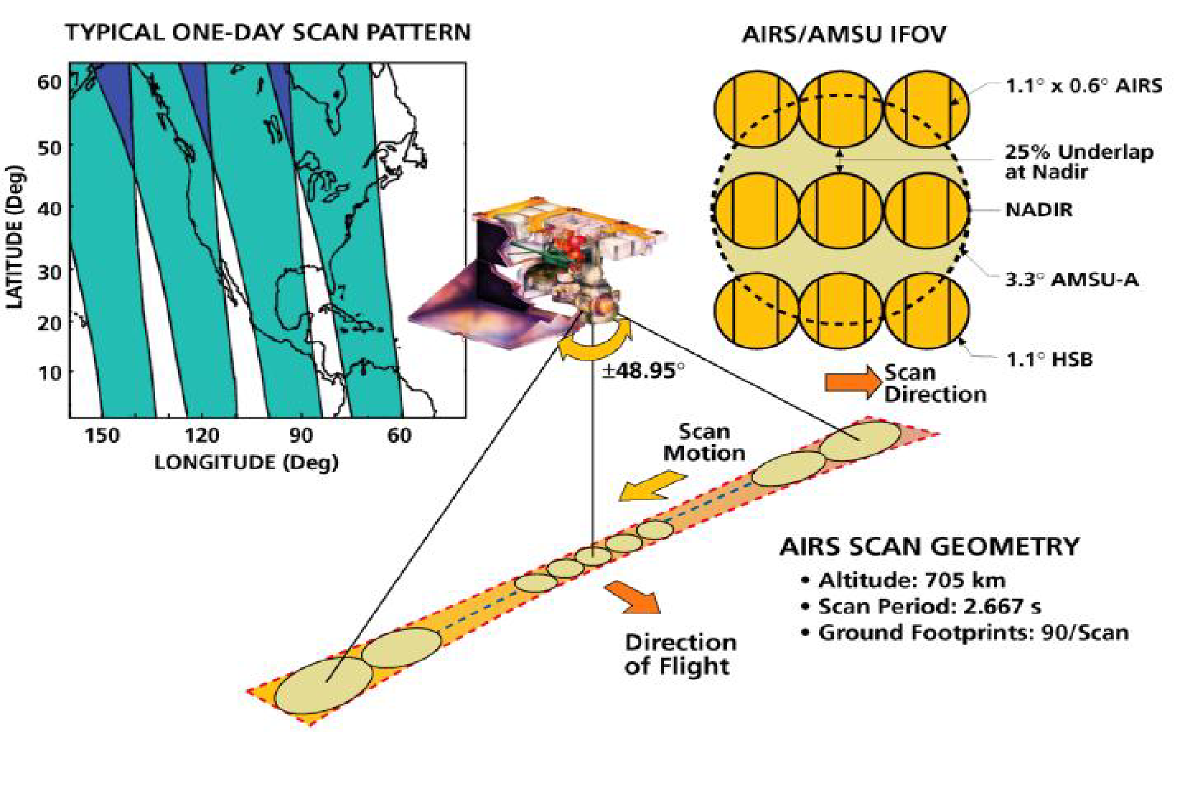
- Phil Rosenkranz (MIT)
  - Microwave (MW) radiative transfer algorithm
  - Optimal estimation algorithm for T(p), q(p), LIQ(p), MW emissivity(f), Skin Temperature
- Larrabee Strow (UMBC)
  - Infrared (IR) radiative transfer algorithm
- Larry McMillin (NOAA)
  - Local Angle Correction (LAC) algorithm
- Mitch Goldberg (NOAA)
  - Eigenvector regression operator for T(p), q(p), O3(p), IR emissivity(υ), and Skin Temperature
- Joel Susskind (GSFC) & Chris Barnet
  - Cloud Clearing Algorithm
  - Physical retrieval using SVD for T(p), q(p), O_3(p), Ts, ε_{IR}, CTP, Cloud Fraction
- Chris Barnet (NOAA)
  - Physical Retrieval (currently using SVD) for CO(p), CH4(p), CO2(p), HNO3(p), N2O(p), SO2

Constraints and Assumptions for the AIRS Science Team Algorithm

- One Granule of AIRS data (6 minutes or 1350 "golf-balls") must be able to processed, end-to-end, using $\leq$ 10 CPU's (originally 10 SGI 250 MHz CPU's). That is, one retrieval every 0.266 seconds.
- Only static data files can be used
  - One exception: model surface pressure.
  - Cannot use output from model or other instrument data.
  - Maximize information coming from AIRS radiances.
- Cloud clearing will be used to "correct" for cloud contamination in the radiances.
  - Amplification of Noise, A, is a function of scene $0.33 \leq A < \approx 5$
  - Spectral Correlation of Noise is a function of scene
- IR retrievals must be available for all Earth conditions within the assumptions/limitations of cloud clearing.
- Temperature retrievals: 1 K/1-km was the single "success criteria" for the NASA AIRS mission.

Sounding Strategy in Cloudy Scenes: Co-located Thermal & Microwave (& Imager)

- Sounding is performed on 50 km a field of regard (FOR).
- FOR is currently defined by the size of the microwave sounder footprint.
- IASI/AMSU has 4 IR FOV's per FOR
- AIRS/AMSU & CrIS/ATMS have 9 IR FOV's per FOR.
- ATMS is spatially over-sampled can emulate an AMSU FOV.



AIRS, IASI, and CrIS all acquire 324,000 FOR's per day

Spatial variability in scenes is used to correct radiance for clouds.

- Assumptions, $R_j = (1-\alpha_j)R_{clr} + \alpha_j R_{cld}$
  - Only variability in AIRS pixels is cloud amount, α_j
    - Reject scenes with excessive surface & moisture variability (in the infrared).
  - Within FOR (9 AIRS scenes) there is variability of cloud amount
    - Reject scenes with uniform cloud amount
- We use the microwave radiances and 9 sets of cloudy infrared radiances to determine a set of 4 parameters and quality indicators to derive 1 set of cloud cleared infrared radiances.
- Roughly 70% of any given day satisfies these assumptions.

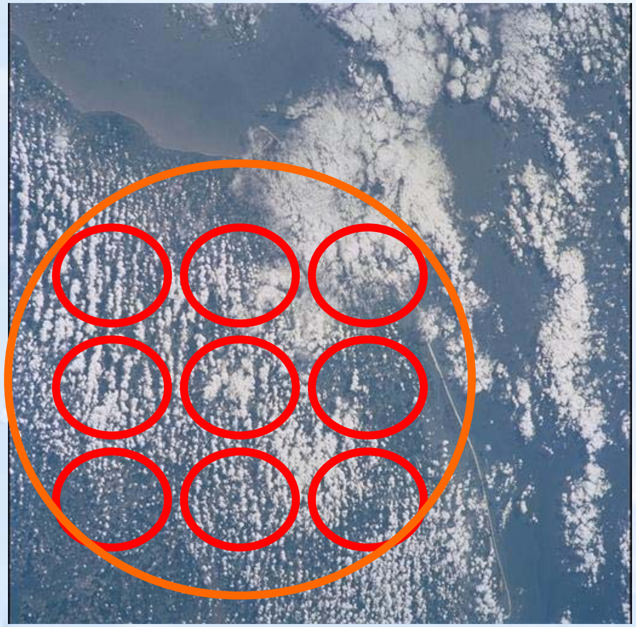


Image Courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center (http://eol.jsc.nasa.gov). STS104-724-50 on right (July 20, 2001). Delaware bay is at top and Ocean City is right-center part of the images.

Spatial variability in scenes is used to correct radiance for clouds.

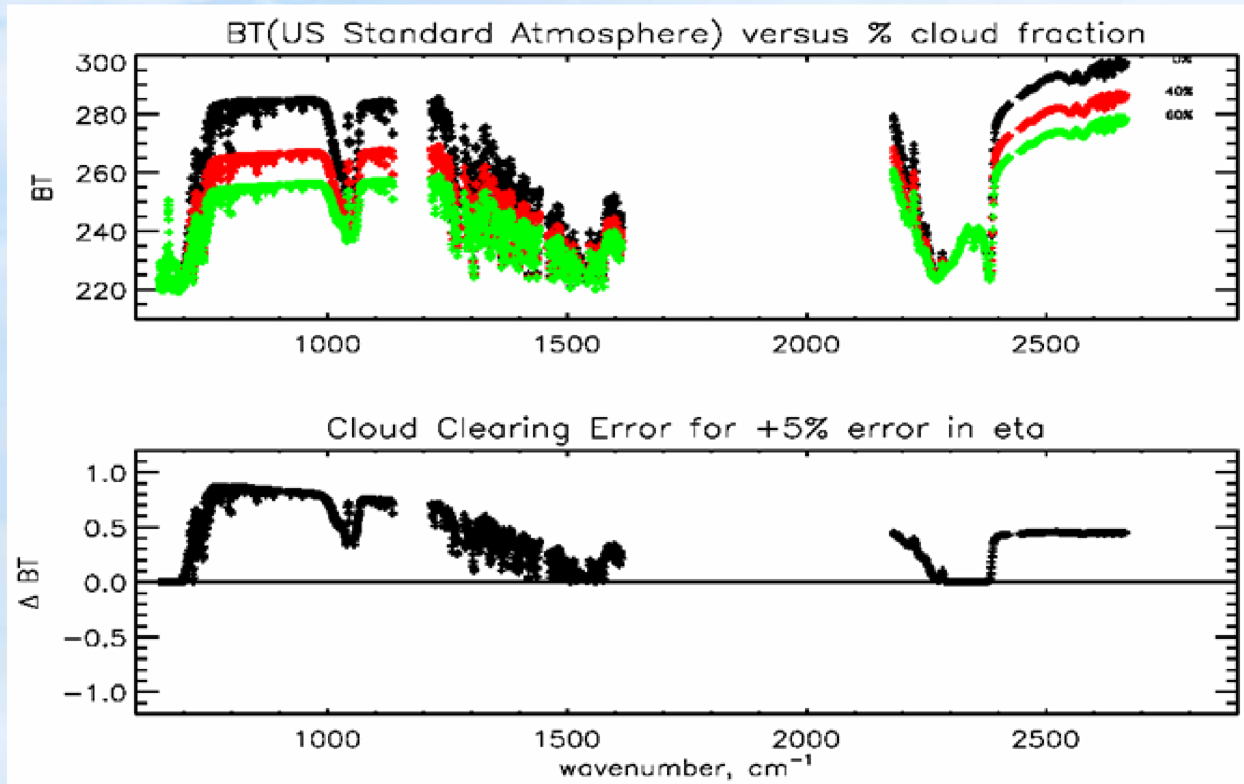
- We use a sub-set (≈ 50 chl's) of computed radiances from the microwave state as a clear estimate, $R_n = R_n(X)$ and 9 sets of cloudy infrared radiances, $R_{n,j}$ to determine a set of 4 parameters, η_j.

$$\hat{R}_n = < R_{n,j} >_j + (< R_{n,j} >_j - R_{n,j}) \cdot \eta_j$$

- Solve this equation with a constraint that $\eta_j \leq 4$ degrees of freedom (cloud types) per FOR
- A small number of parameters, η_j, can remove cloud contamination from thousands of channels.
  - Does not require a model of clouds and is not sensitive to cloud spectral structure (this is contained in radiances, $R_{n,j}$)
  - Complex cloud systems (multiple level of different cloud types).

Example of AIRS Cloudy Spectra

Example AIRS spectra at right for a scene with α=0% clouds (black), α=40% clouds (red) and α=60% clouds (green).

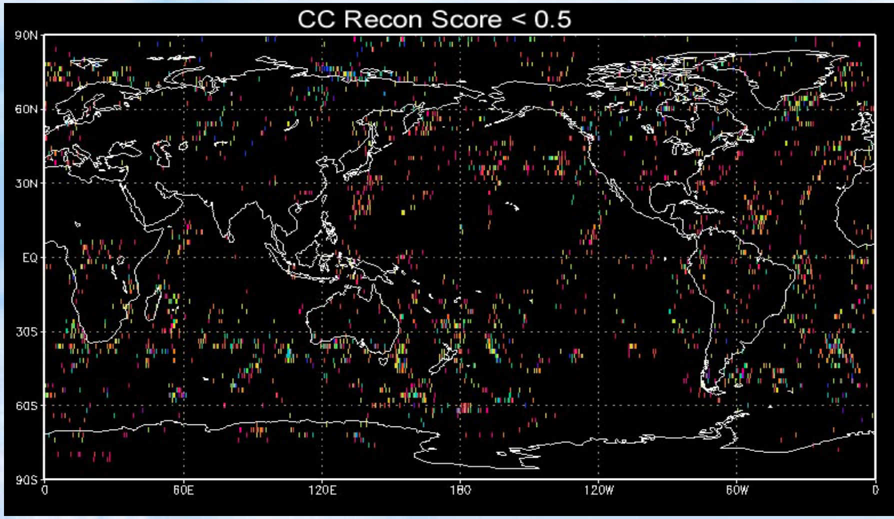


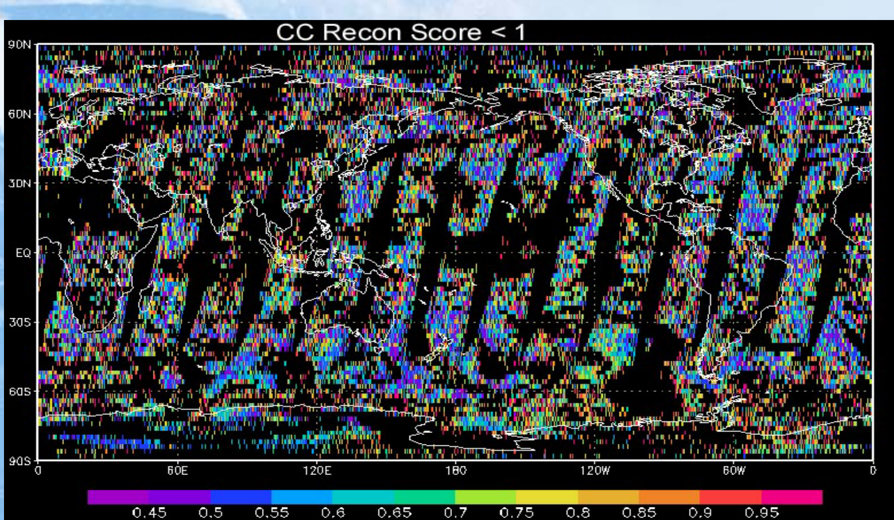
Can use any channels (*i.e.*, avoid window regions, water regions) to determine extrapolation parameters, η_j

Note that cloud clearing produces a spectrally correlated error

In this 2 FOV example, the cloud clearing parameters, η_j, is equal to $\frac{1}{2}\langle\alpha\rangle/(\alpha_j-\langle\alpha\rangle)$

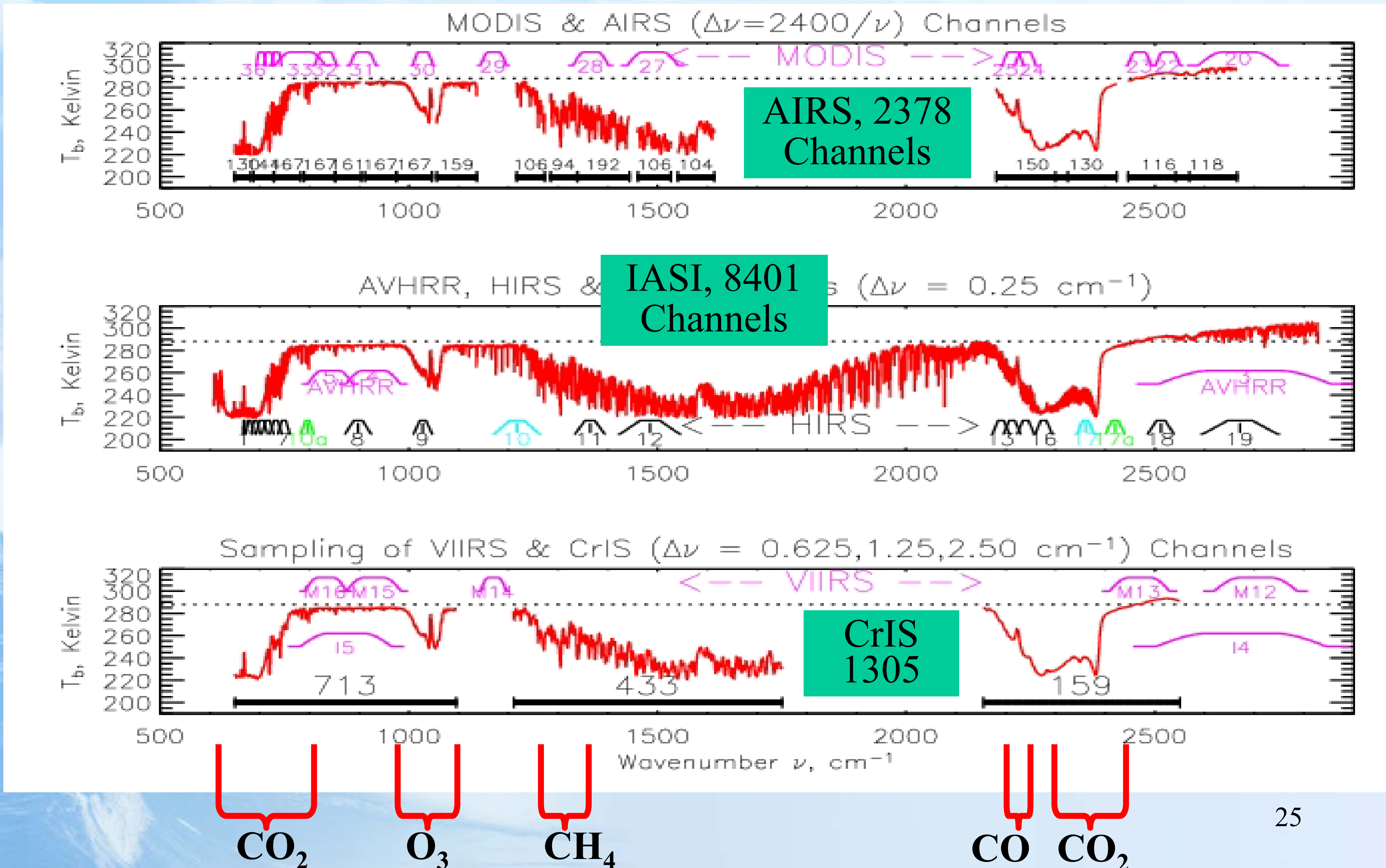
Cloud Clearing Dramatically Increases the Yield of Products



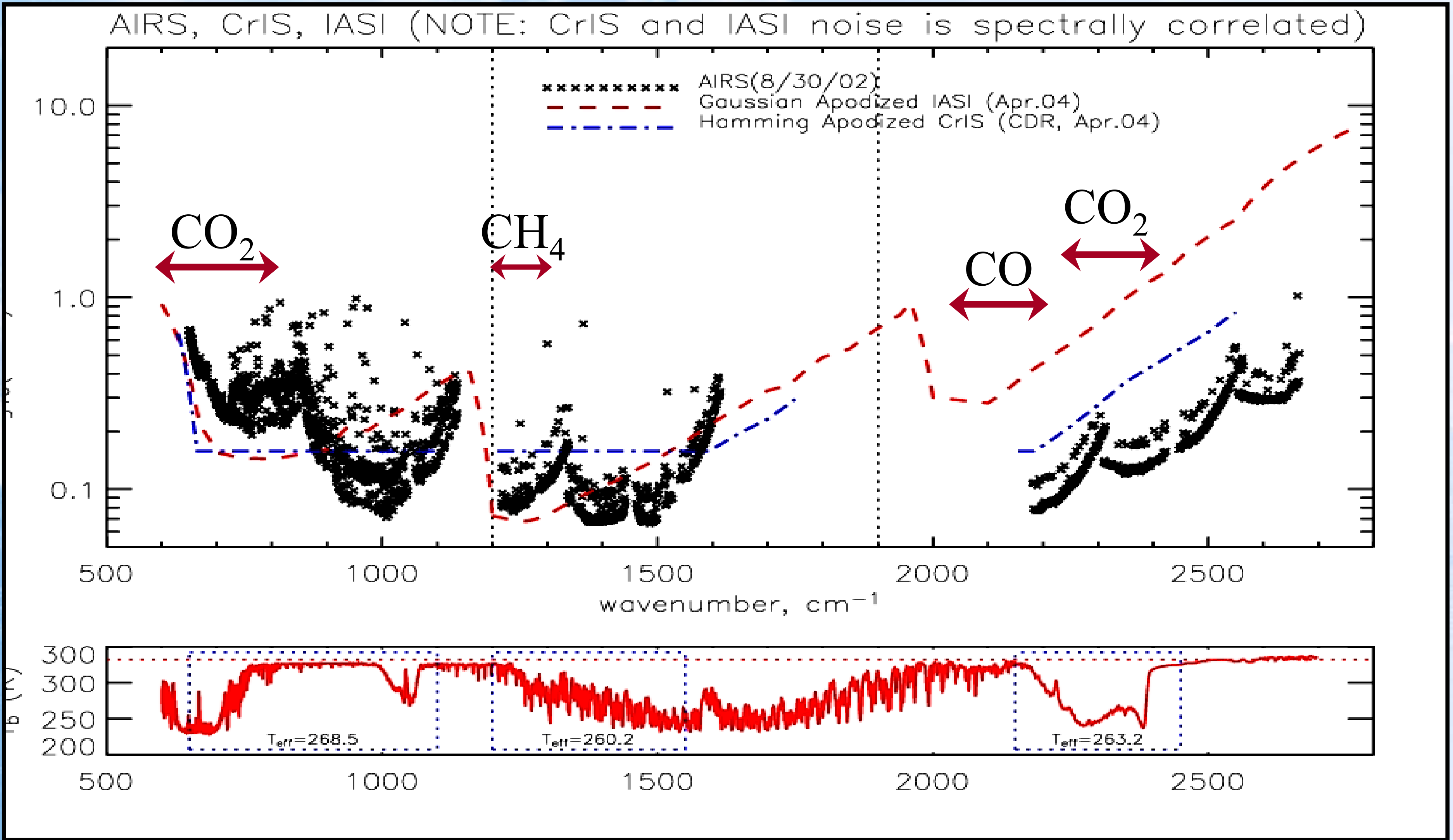


- ***AIRS experience:***
  - **Typically, less than 5% of AIRS FOV's (13.5 km) are clear.**
  - **Typically, less than 2% of AIRS retrieval field of regard's (50 km) are clear.**
- **Cloud Clearing can increase yield to 50-80%.**
- **Cloud Clearing reduces radiance product size by 1:9 for AIRS and 1:4 for IASI.**

Spectral Coverage of Thermal Sounders (Example BT's for AIRS, IASI, & CrIS)

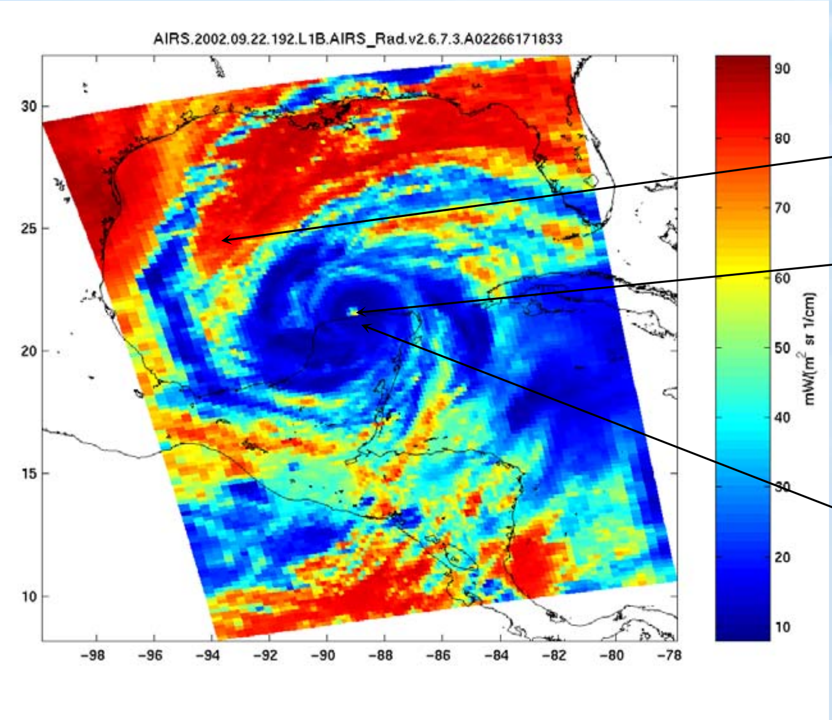


Instrument Noise, NEΔT at 250 K (Interferometers Noise Is Apodized)

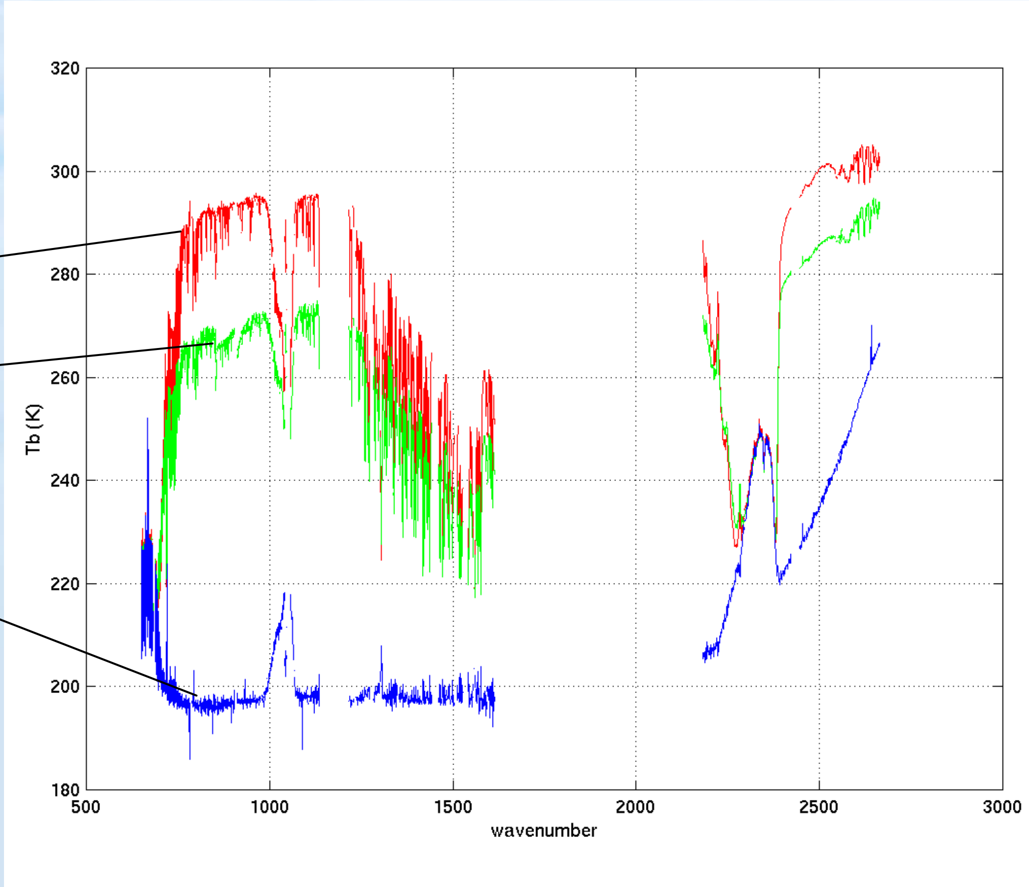


Brightness Temperature Spectra reveal changes in atmosphere from eye to boundary of Tropical Cyclone

~999 cm^{-1} radiances

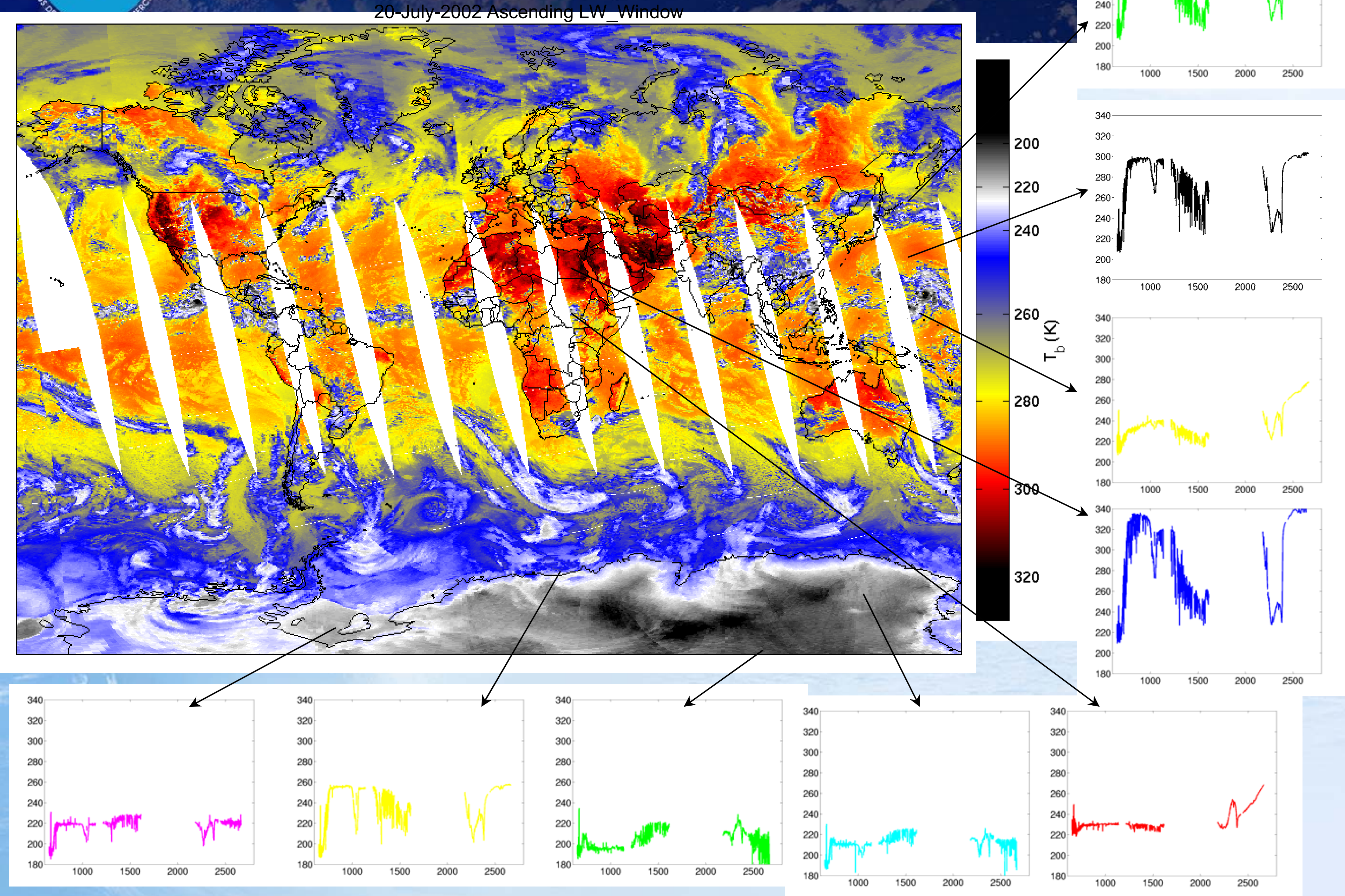


Brightness temperature spectra

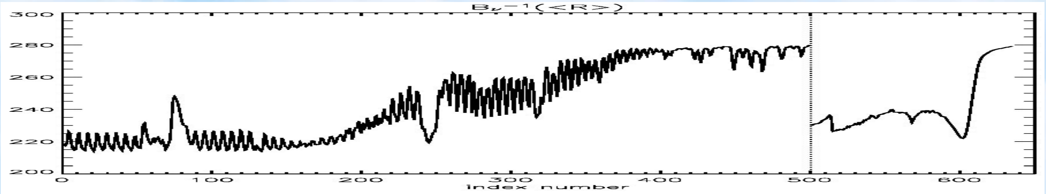


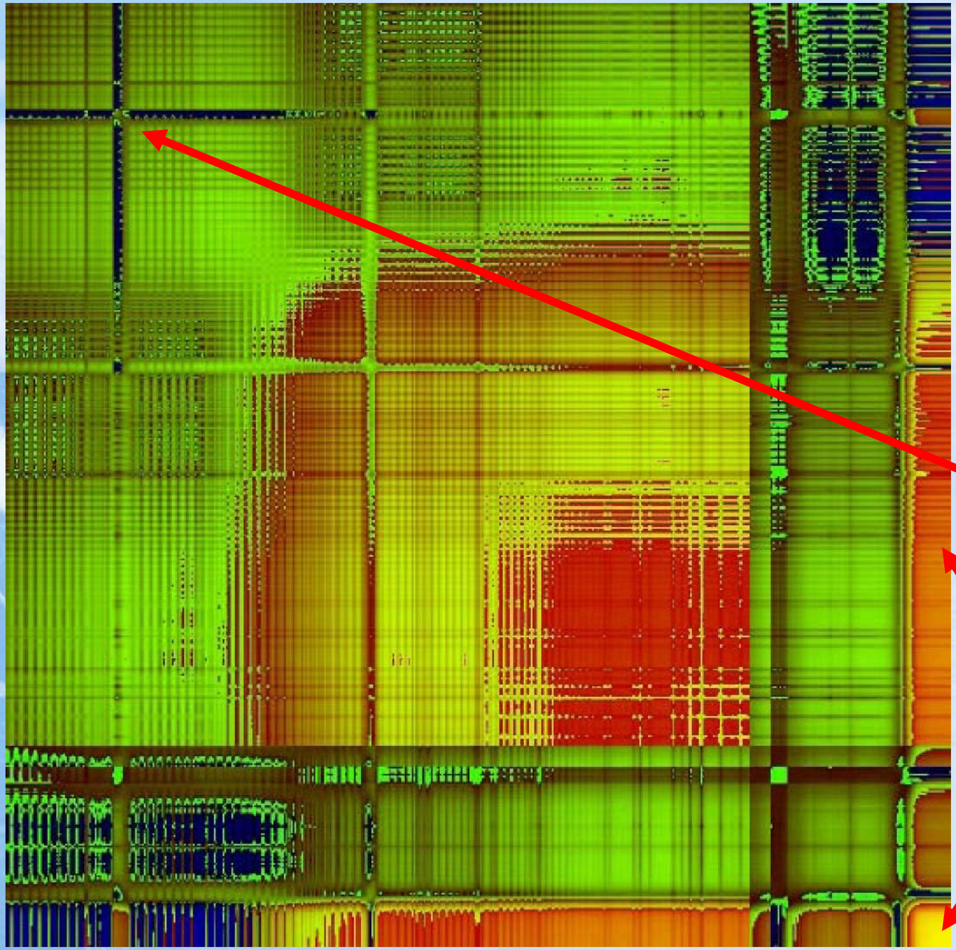
AIRS observations of tropical storm Isadore
on 22 Sept 2002 @ ~19:12-19:18 UTC

AIRS Spectra from around the Globe



For a large <u>global</u> ensemble we can compute <R> and RR^T





Anticorrelated: BLUE

Positive: Correlation: Green → Yellow → Red

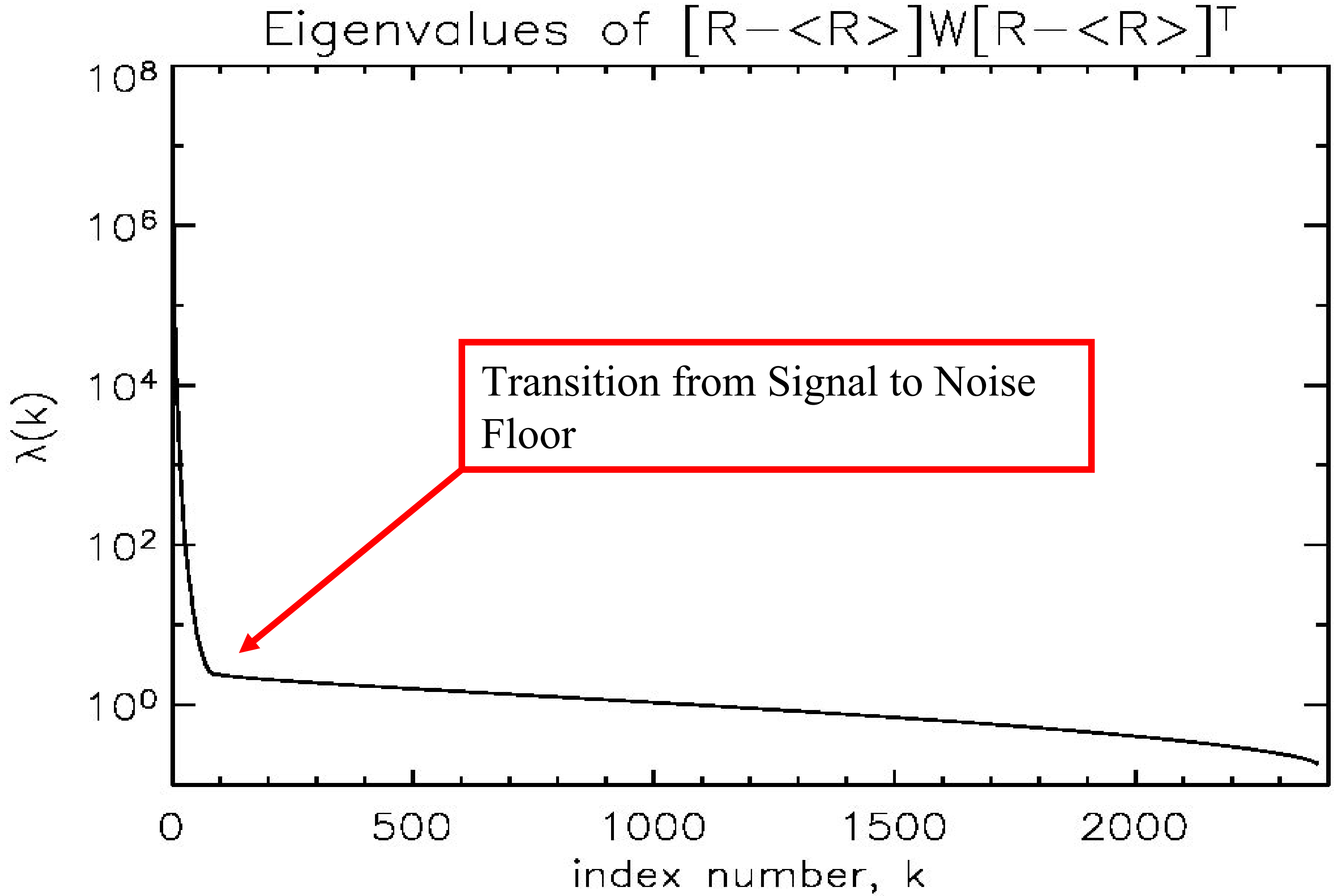
Diagonal is from upper left to lower right in this figure

"Checkerboard" pattern results from wings of lines begin correlated with near neighbor cores of lines.

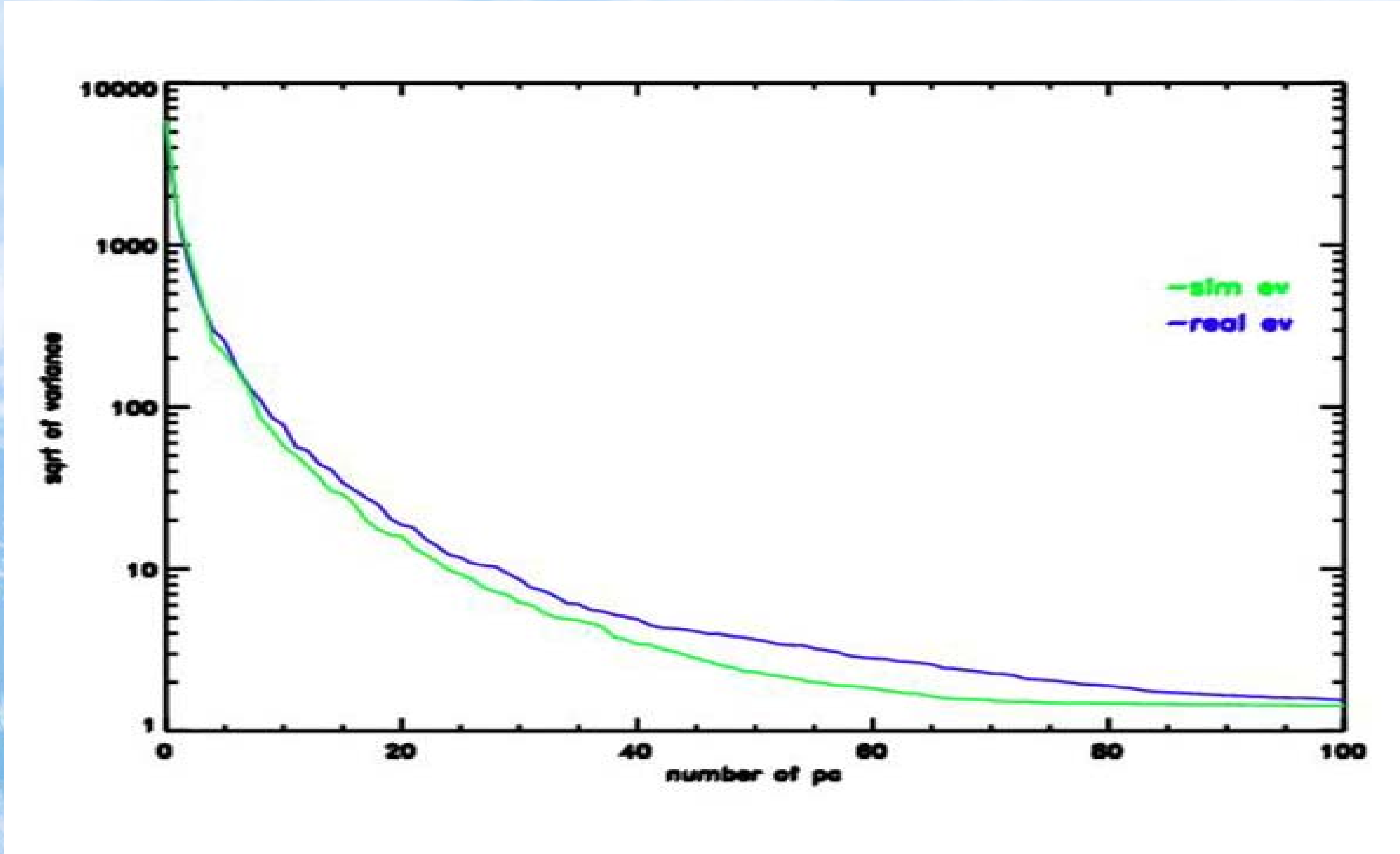
667 cm^{-1} (stratospheric) is anticorrelated with tropospheric channels.

15 µm band (600-700 cm^{-1}) and 4.3 µm band (2390 cm^{-1}) are correlated (measure same thing)

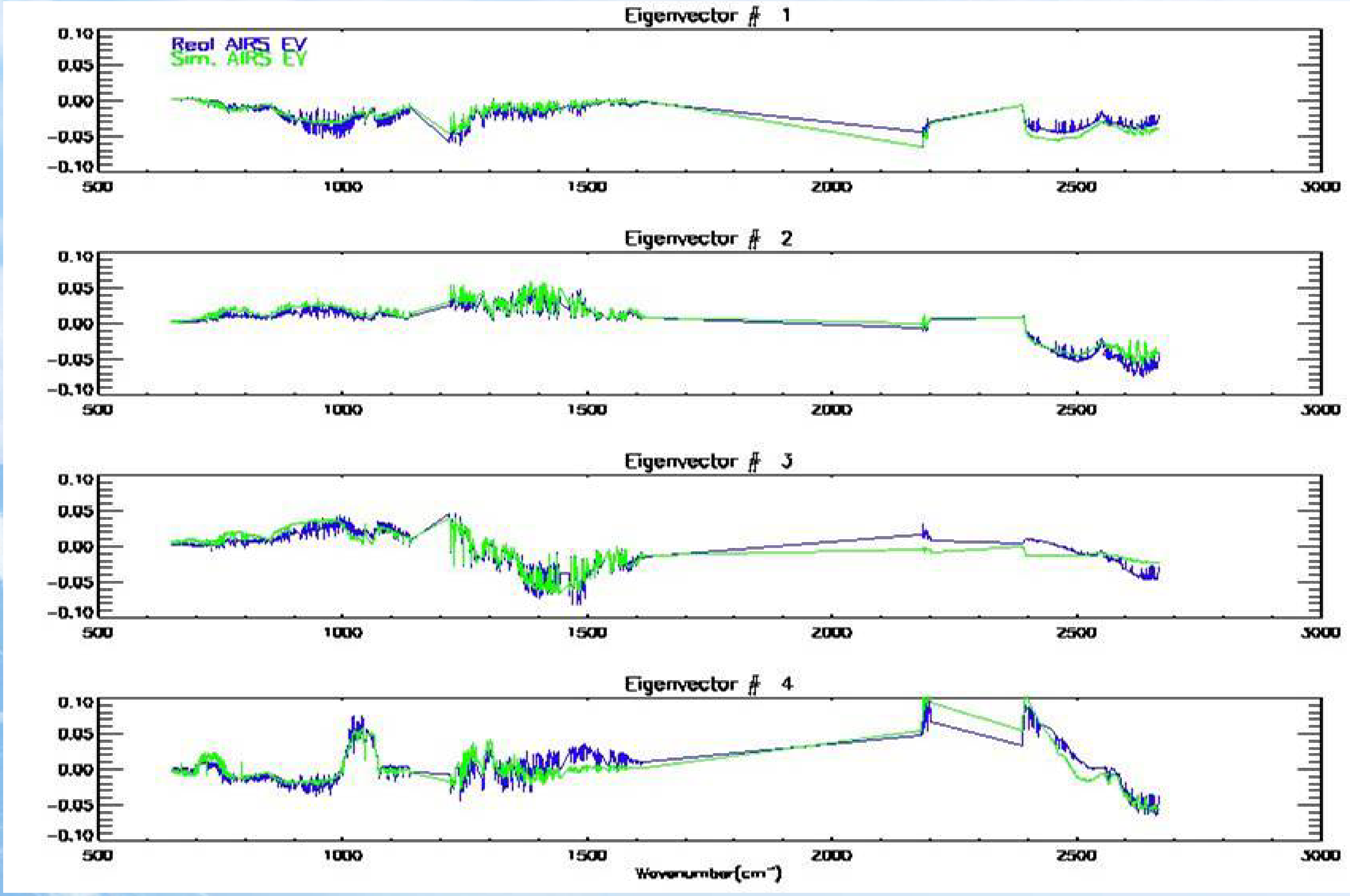
Information Content of AIRS: Eigenvalues of RR^T



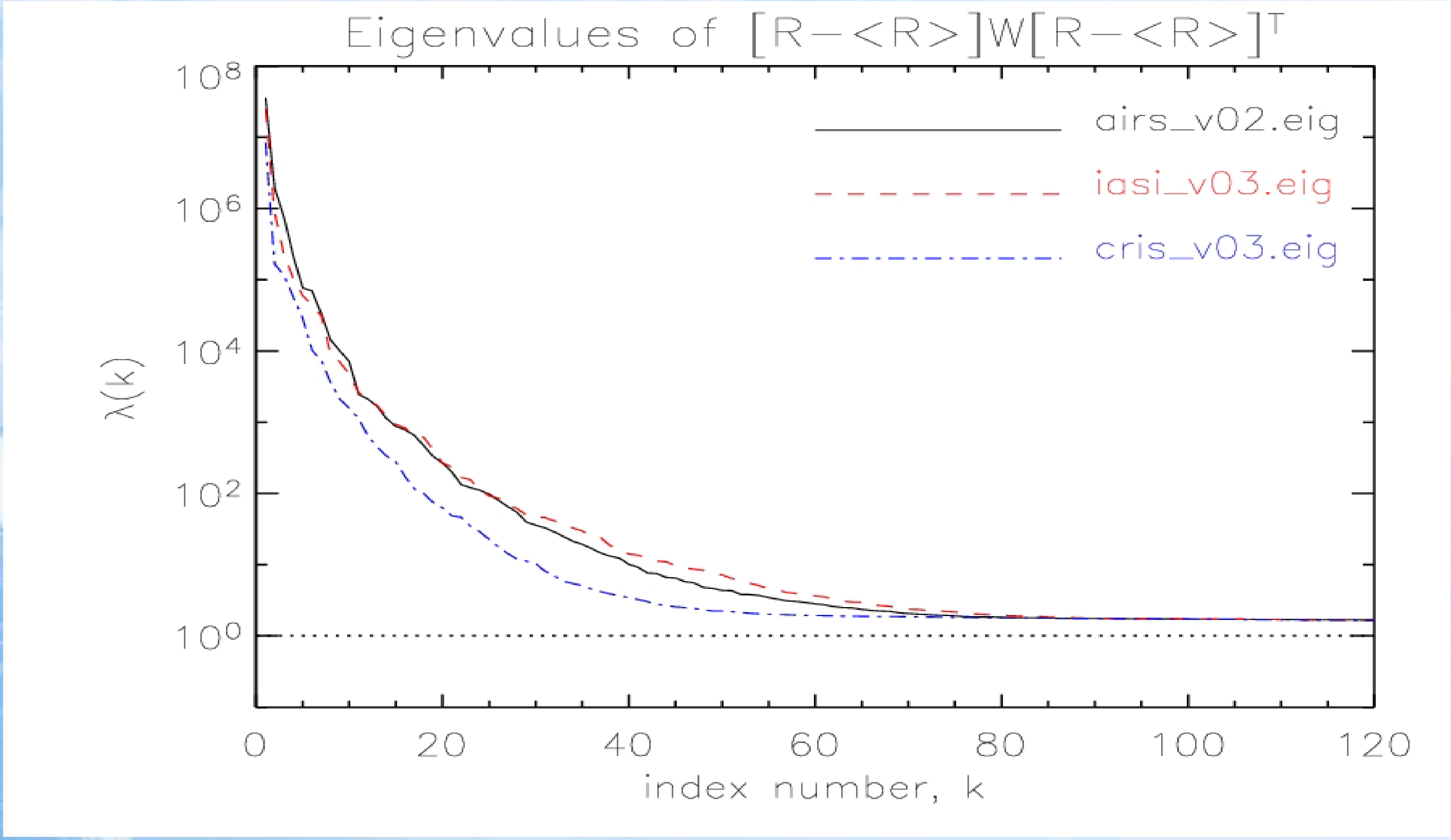
AIRS has roughly 90 pieces of information in 2378 chl's



First 4 Eigenvectors of AIRS Radiances: Real & Simulated



Information content of the AIRS, IASI, and CrIS Radiances is the same.



Statistical Regression Retrievals (see Goldberg et al. 2003)

- Statistical eigenvector regression uses J_e observed spectra (on a subset of M "good" channels) to compute eigenvectors. Spectral radiance for scene j, $R_{n(m),j}$, can then be represented as principal components, $P_{k,j}$

$$\Delta\tilde{\Theta}_{m,j} \equiv \frac{R_{n(m),j}}{\mathrm{NE\Delta N}_{n(m)}} - < \tilde{\Theta}_{m,j} >_{J_e}$$

$$P_{k,j} = \frac{1}{\sqrt{\lambda_k}} \cdot E_{k,m} \cdot \Delta\tilde{\Theta}_{m,j}$$

- A regression, $A_{i,k}$, between a "truth" state parameter i, $X_{i,j}$, and principal components can be computed.

$$X_{i,j} =< X_{i,j} >_{J_r(v,L)} + A^v_{i,k} \cdot \Delta P_{k,j}$$

Pro's and Con's Of Statistical Regression Retrievals

Pro's	Con's
Does not require a radiative transfer model for training or application.	Training requires a large number of co-located "truth" scenes.
Application of eigenvector & regression coefficients is VERY fast and for hyper-spectral instruments it is very accurate.	The regression operator does not provide any diagnostics or physical interpretation of the answer it provides.
Since real radiances are used the regression implicitly handles all systematic instrument calibration issues. This is a huge advantage early in a mission.	The regression answer builds in correlations between geophysical parameters. For example, retrieved O_3 in biomass regions might really be a *measurement* of CO with a statistical correlation between CO and O_3.
Since clouds are identified as unique eigenvectors, a properly trained regression tends to "see through" clouds.	Very difficult to assess errors in a regression retrieval without the use of a physical interpretation.