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Lessons From Three Years Of Hyperspectral Data From the Atmospheric Infrared Sounder (AIRS) on EOS Aqua

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Introduction

- **The Atmospheric Infrared Sounder (AIRS) has been in routine operations for 3.5 years, longer than any previous hyperspectral infrared sounder**
- **The AIRS design emphasized**
  - ***Reliability (the spectrometer has no moving parts)***
  - ***Operational simplicity***
  - ***Radiometric accuracy***
  - ***Radiometric stability***
- **This paper uses comparisons of AIRS measured radiances with other sources to evaluate AIRS performance**
  - ***RTGSST (the NOAA real-time global sea surface temperature dataset)***
  - ***ECMWF***
- **These same techniques are applicable to future infrared hyperspectral infrared sounders**

Purpose

- Validate AIRS over its full spectral and dynamic range
  - *For trustworthy application of AIRS data to climate questions*
  - *Understand what to expect when using AIRS data in weather forecasting*
  - *Establish a system performance metric for the analysis of future hyperspectral sounders, such as IASI and CRIS*

Outline

- Describe methodology
- Describe AIRS data used
- Evaluate AIRS dynamic noise
- Evaluate AIRS radiometric accuracy and stability at 2616 cm^{-1} (the best window channel)
- Evaluate AIRS radiometric accuracy and stability at other frequencies
  - *Repeat 2616 analysis for other window channels*
  - *Use ECMWF to extend to all AIRS channels*
- Suggest metric for evaluation of future hyperspectral infrared sounders

Methodology

- **Define “obs” to be an observed AIRS quantity, either radiances or some other physical parameter derived from the radiances**
- **Define “calc” to be the same physical quantity observed or modeled by some external trusted source**
- **Examine the mean and standard deviation of (obs-calc)**
- **In this study we use two external sources for “calc”**
  - ***RTGSST from NOAA (sea surface temperatures measured by buoys and ships at sea)***
    - We restrict ourselves to measurements within 40° of the equator
  - ***Temperature/water vapor profiles from ECMWF (European Center for Medium range Weather Forecasting)***
- **These two sources were selected, after considerable experimentation, for their reliability and ease of use**
  - ***Each involves some minor difficulties to be discussed later***

AIRS Data Used

- **Only the simplest AIRS spectra are used**
  - ***Clear***
  - ***Night***
  - ***Over ocean***
- **Two subsets of the AIRS radiances are used**
  - ***AIRS Clear Dataset (ACDS), where "clear" means that the spectrum has survived a test for lack of clouds***
    - About 2% of the spectra are accepted and copied to the ACDS
    - The ACDS is roughly equally divided between nighttime and daytime
  - ***AIRS Calibration Dataset (ACalDS)—a subset of ACDS formed by extracting the 100 channels most important for calibration and restricting the data to nighttime only***
  - ***Both ACDS and ACalDS also save the 15 AMSU-A channels and the 4 AIRS Vis/NIR channels***

Cloud Filtering For the ACDS

- **The first test is for spatial homogeneity**
  - ***cx2616 = (max - min) of the radiance at the 2616 cm^{-1} window channel in a 3 x 3 group of AIRS footprints***
  - ***If cx2616 < 0.7 K, the center footprint passes the test (assumed possibly clear) and goes to the next test***
    - When the ACalDS is in use, the threshold is raised to 1.2K
- **The spatial test is followed by several spectral tests designed to eliminate low stratus.**
- **Data passing all these tests are put into the ACDS and ACalDS as described on a previous slide**
- **For special purposes, both the ACDS and ACalDS are sometimes filtered more heavily to further reduce any possible cloud contamination, at a cost of the yield of “clear” footprints**
- **There is of course no guarantee that any spectrum in either dataset is truly 100% clear**

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Evaluate AIRS Dynamic Noise

- **AIRS science software calculates the NE∆T for each channel for every six-minute data block (granule), based on looks at cold space and a hot on-board blackbody every scan line**
  - ***We consider this calculation to be a static measurement and refer to it as NE∆T_s (because it uses static targets)***
- **A more relevant measure would be NE∆T_d, a dynamic estimate of the noise made using actual scene data**
- **Such a dynamic estimate might be a little higher than NE∆T_s**
- **For AIRS we define NE∆T_d to be the mean of the absolute value of the differences between two adjacent clear ocean footprints**
- **For a well-designed sounder, NE∆T_d should equal NE∆T_s for channels meeting the following criteria:**
  - ***The channel is not at all sensitive to the surface, where land emissivity variations can appear to increase NE∆T_d***
  - ***The channel is not sensitive to water vapor, which often varies significantly over short distances***

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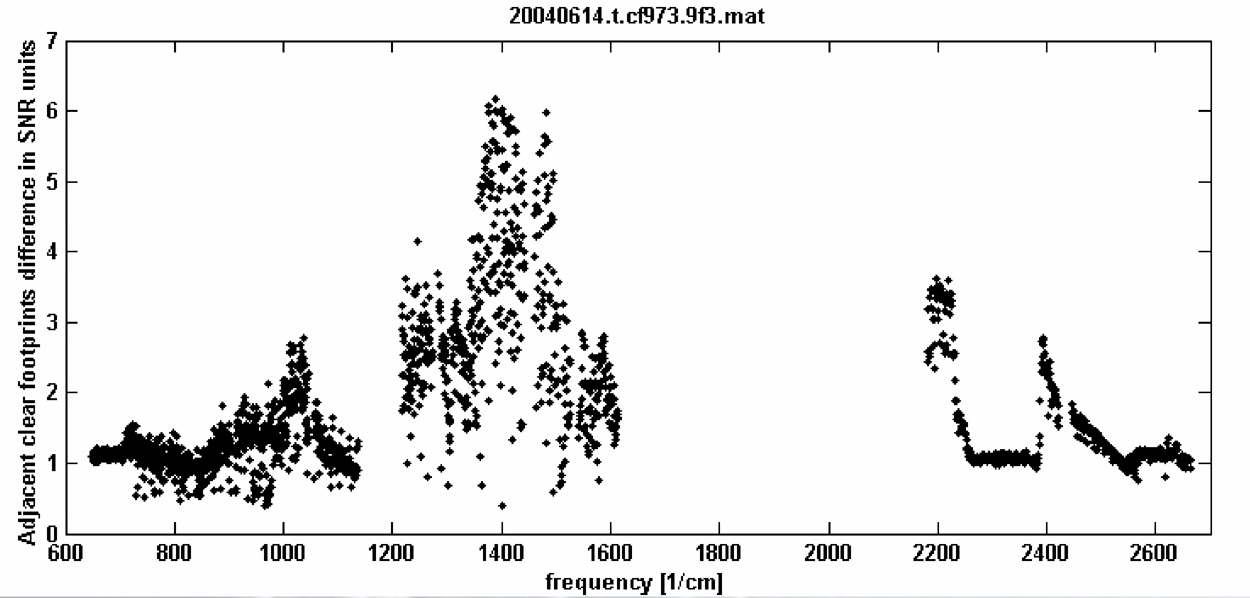
AIRS Ratio NEΔT_d/NEΔT_s



- AIRS channels meeting the criteria are in the range 650–800 cm^{-1}, 2250–2400 cm^{-1}, and 2500–2650 cm^{-1}
- The mean ratio for those 795 channels is 1.1 with standard deviation 0.1
- A few channels, mostly in the range 730–900 cm^{-1}, show ratios significantly less than 1—we believe the calibration software is overestimating NEΔT_s by 30% or more for those channels

Radiometric Accuracy And Stability At 2616 cm^{-1}

- **The radiometric system performance evaluation depends on a comparison between RTGSST and sst2616**
- **sst2616 is the sea surface temperature derived from the radiance of the most transparent AIRS channel, at 2616 cm^{-1}**
  - ***Derivation of sst2616 explicitly accounts for residual water vapor absorption using the difference between the 2616 channel and one at 2607.7 cm^{-1}***
  - ***Surface emissivity is also taken into account***
- **The next slide shows a 3-year sst2616 vs. rtgsst comparison**
  - ***Each point (one per day) is the mean of about 9200 match ups from night ocean clear footprints***
  - ***Exactly three years of data are shown (September 1, 2002 through August 31, 2005)***

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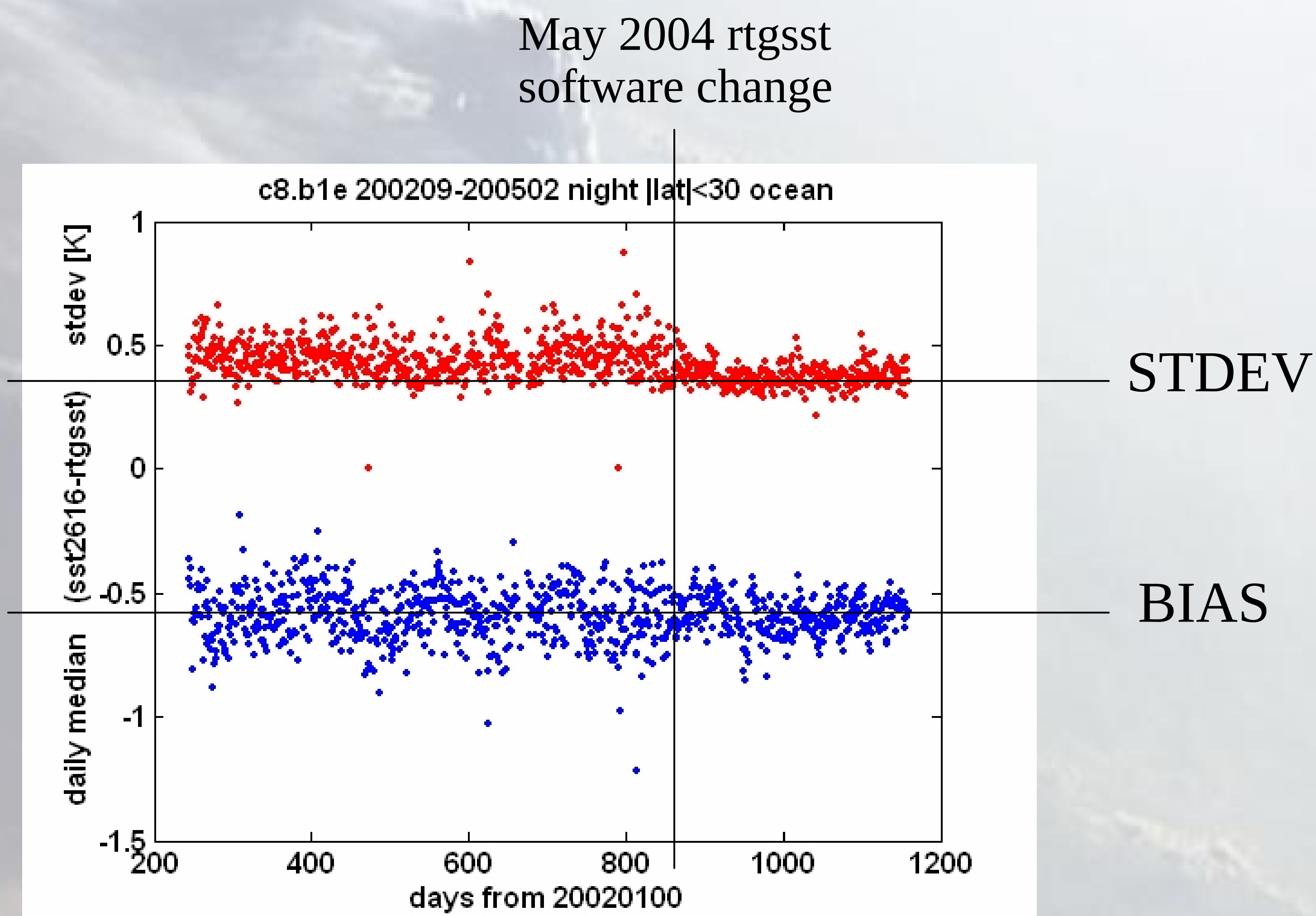
Three Years Of sst2616 vs. RTGSST



Notes On sst2616 vs. RTGSST

- **The mean difference, sst2616 - rtgsst, is -0.62K**
- **The standard deviation is 0.39K**
- **An rtgsst software upgrade took place in May 2004**
  - ***Slight shift in mean difference from -0.64K to -0.60K***
  - ***Noticeable decrease in standard deviation from 0.42K to 0.37K***
- **The trend in the bias of (sst2616-rtgsst) is -5 ±8 mK/year before the software change and -18 ±8 mK/year after the change**
- **The magnitude of the bias (about -0.6K) is discussed on the next slide**

AIRS vs. RTGSST Cold Bias

- **There is a 600 mK cold bias, AIRS versus rtgsst, which has been explained to within 10±120 mK**
  - ***AIRS 2616 cm^{-1} measures skin temperature, whereas rtgsst measures a bulk temperature typical of a meter or two below the surface (-0.2K)***
  - ***The AIRS data used in this study are all nighttime, whereas rtgsst includes day and night (-0.2K)***
  - ***In spite of extensive filtering of data for this study, there is some unavoidable remaining cloud contamination***
    - Analysis of the cloud filter used, plus analysis of the co-located AIRS visible channels data, show that residual clouds account for an additional -0.24K bias
    - Details are in a forthcoming paper by Aumann et.al. in JGR May 2006

Radiometric Accuracy and Stability—Conclusions

- The standard deviation of 0.39K is a combination of
  - *Random error in sst2616*
  - *Residual cloud noise*
  - *Random error in rtgsst*
- Assuming pre-launch measurements of NEΔT_s of 0.08K for the two channels involved in sst2616, plus 0.24K estimated cloud noise, leaves 0.29K for the estimated random error of the rtgsst
- The quoted rms error for the rtgsst is 0.5K, but we believe that rtgsst values in clear areas are more accurate than the 0.5K quote (which is for all measurements) because of the inclusion of AVHRR data available in clear areas
- A safe estimate of the stability of the AIRS radiometric calibration is 16 mK/year, twice the standard deviation of the trend fits shown previously

Other Window Channels

- **The comparison to the RTGSST is limited to window channels**
- **For 2616 cm^{-1}, where the mean water absorption is 0.2 K, all but 10±120 mK of the observed 600 mK cold bias is explained and not calibration related**
- **We have done the calculation for 14 other window channels**
  - ***Basic result is the same***
  - ***More noise***
  - ***More unexplained offset***
  - ***The differences are due to the much larger (and more uncertain) water absorption in these channels***

Results For Other AIRS Channels

- **About 50% of the AIRS channels were analyzed in the AIRS Validation issue of JGR in November 2002**
  - ***Used one underflight of the University of Wisconsin's Scanning High-resolution Interferometer Sounder (SHIS)***
- **A different 50% were covered in another JGR validation issue in Von Walden's (obs-calc) analysis**
  - ***Data from December 2003 and January 2004***
  - ***Dome Concordia in Antarctica***
- **We use (obs-calc) to validate the full AIRS spectrum over a two year period**
  - ***In this case, "calc" is obtained using ECMWF***

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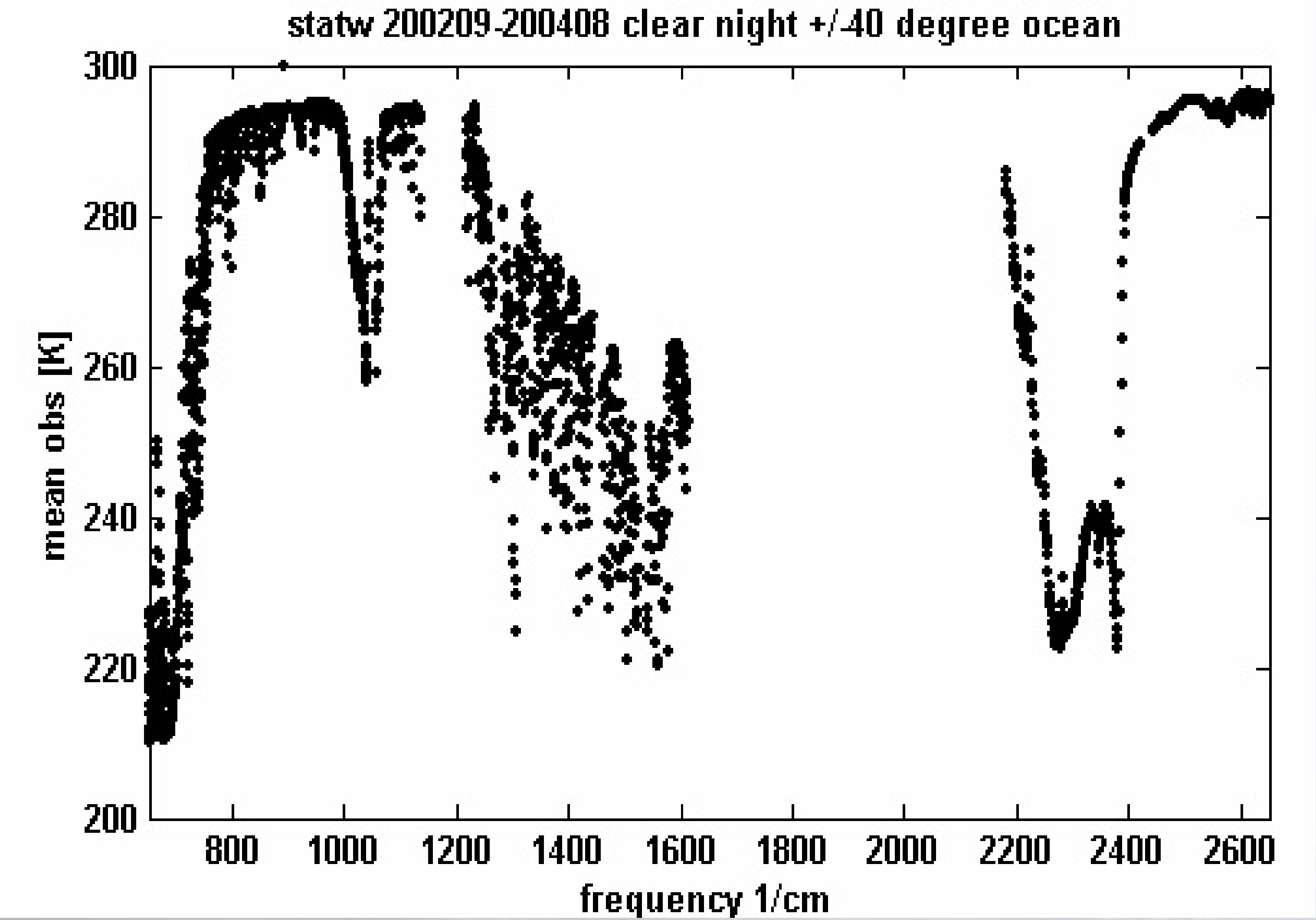
Two-year Mean AIRS Spectrum (Tropical Night Ocean)



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Two-year Mean Brightness Temperature Analysis

- For "calc" we use
  - *ECMWF T(p) and q(p)*
  - *T_{surf} from AIRS observed sea surface temperature from 12 window channels*
  - *Total water is normalized using bt2616 - bt2607*
  - *The first post-launch version (2003) of the AIRS rapid transmission algorithm was then used to calculate radiances*
  - *Only clear night ocean cases within ±40° of the equator*
- The instrument must be stable globally on this time scale for this to work
- For 2253 of the 2378 channels (excluding all channels with NEΔT > 1 K)
  - *(obs-calc) = 0.06±0.28 K*
  - *Min = -1.3 K*
  - *Max = +1.5 K*

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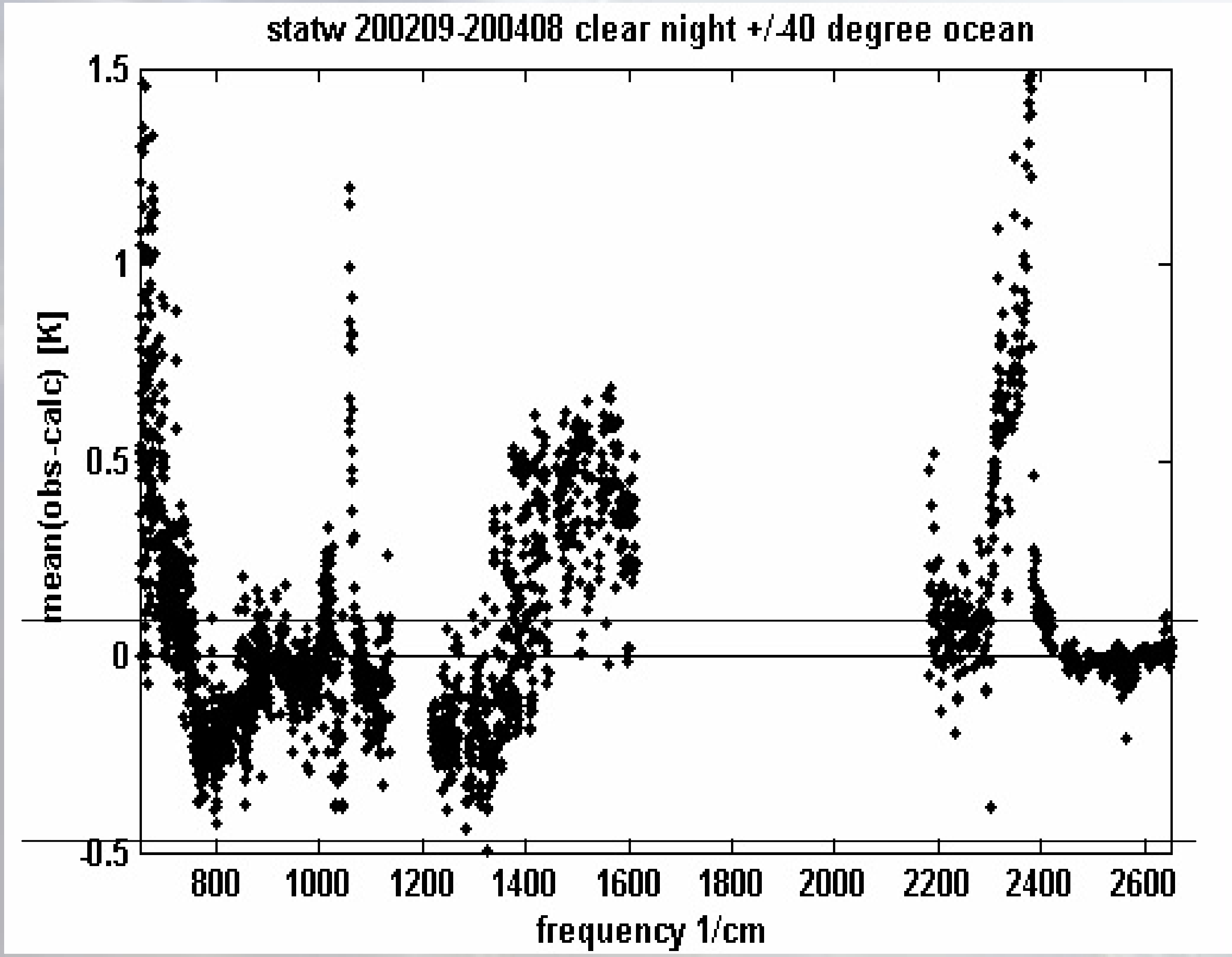
Two-year Mean Brightness Temperature (obs-calc)



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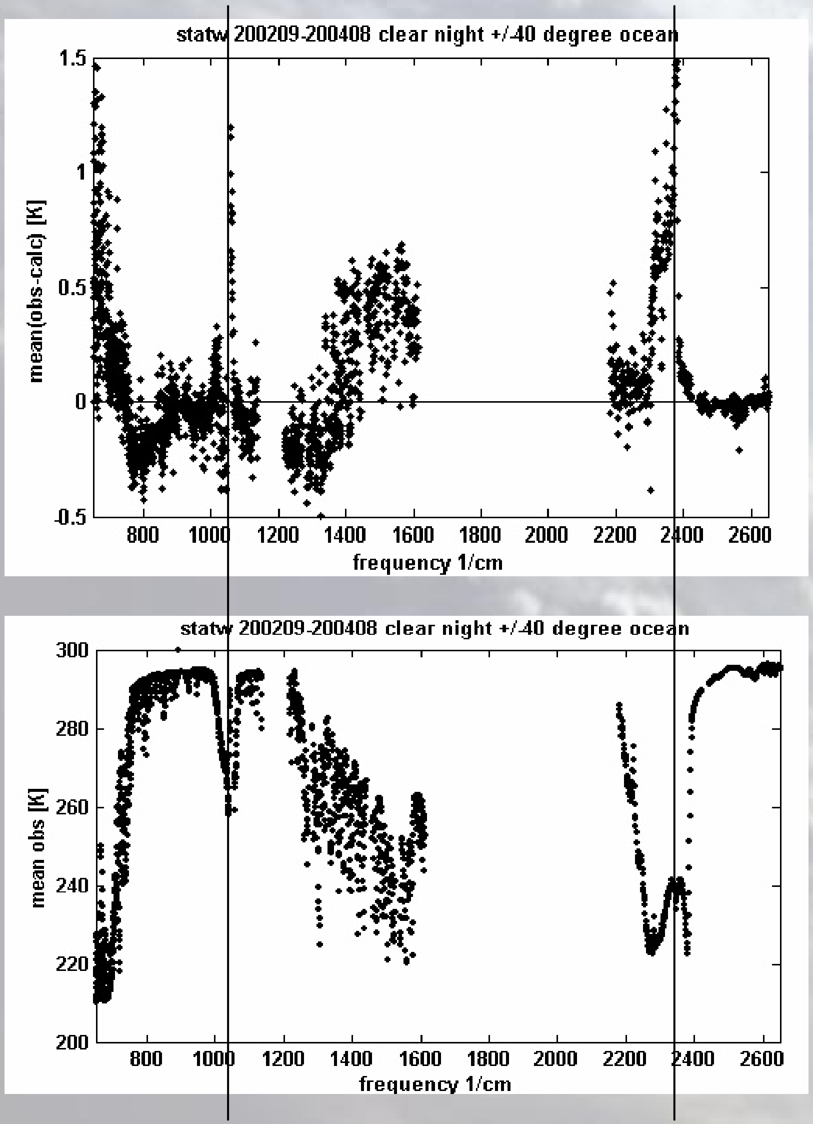
(obs-calc) Discussion



- The patterns in the bias suggest the larger values are due to calc, not obs
- The ECMWF temperature, ozone, and water are suspect above 200 mbar
- The less water sensitivity the lower the bias in windows
- AIRS has more water vapor in the lower troposphere and in the upper troposphere than ECMWF (due to AMSU-A assimilation?)
- The stratosphere is 1.5 K warmer than ECMWF at 4 microns and at 15 microns

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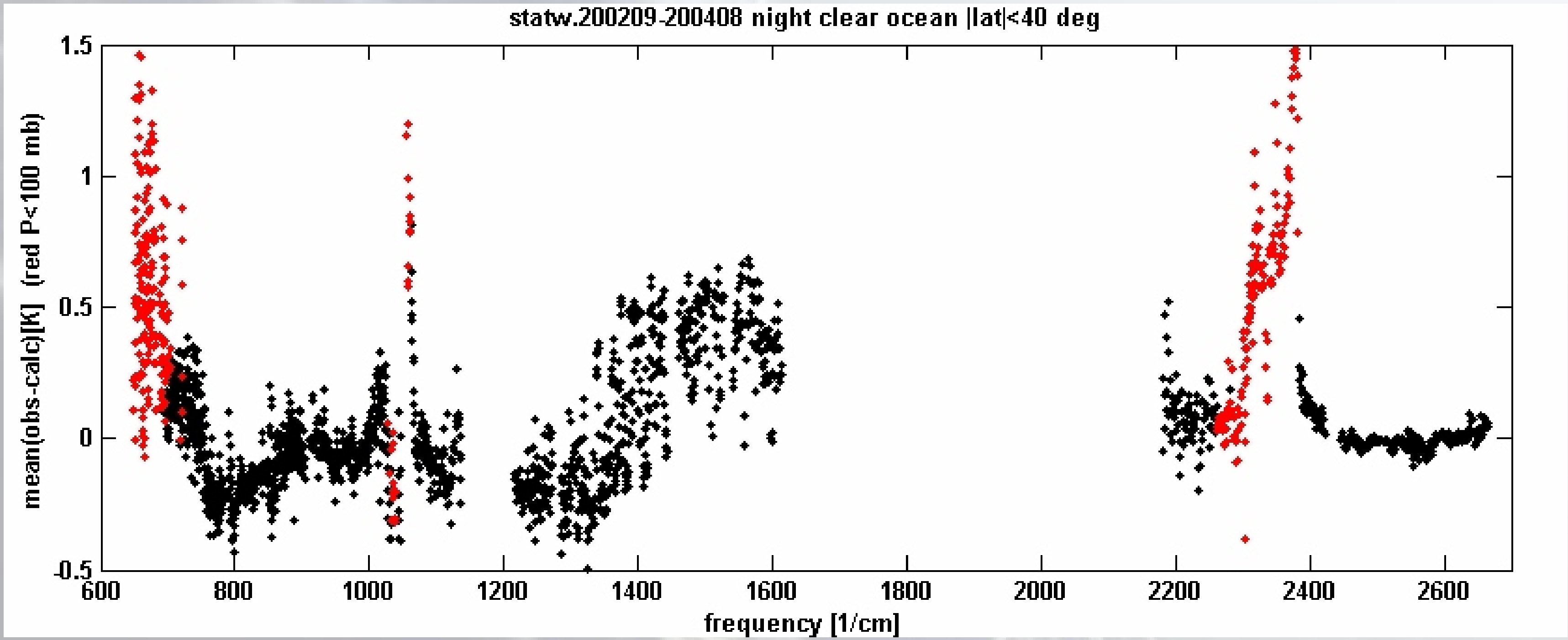
(obs-calc) Without Channels Above 100mb



- (obs-calc) = -0.0188 K for 1903 channels
- Standard deviation is 0.2028 K
- AIRS calibration is good to 200 mK for channels between the surface and 100 mbar
- Consistent with SHIS November 2002 result from 70 mbar altitude

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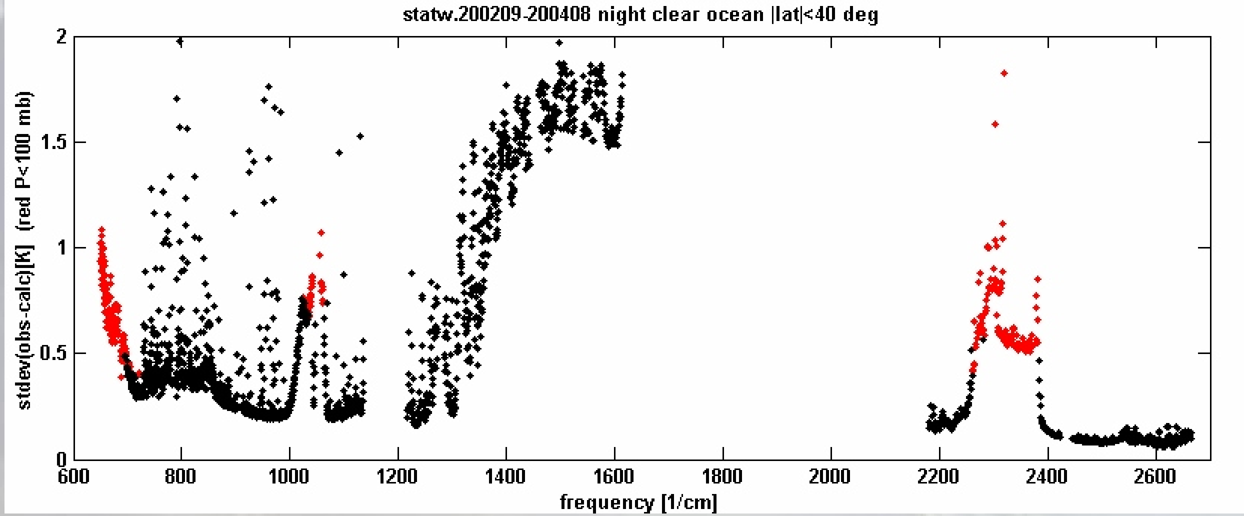
Standard Deviation Trends Similar To Mean

- Standard deviation of (obs-calc) is used in data assimilation as an empirical component in the noise covariance matrix
- We have seen from mean(obs-calc) that the ECMWF background field is questionable at P < 100 mb and in the water profile
- This plot of standard deviation supports the idea that (obs-calc) differences above 100 mb and in channels affected by water are primarily due to problems in the ECMWF

Standard Deviation (obs-calc)



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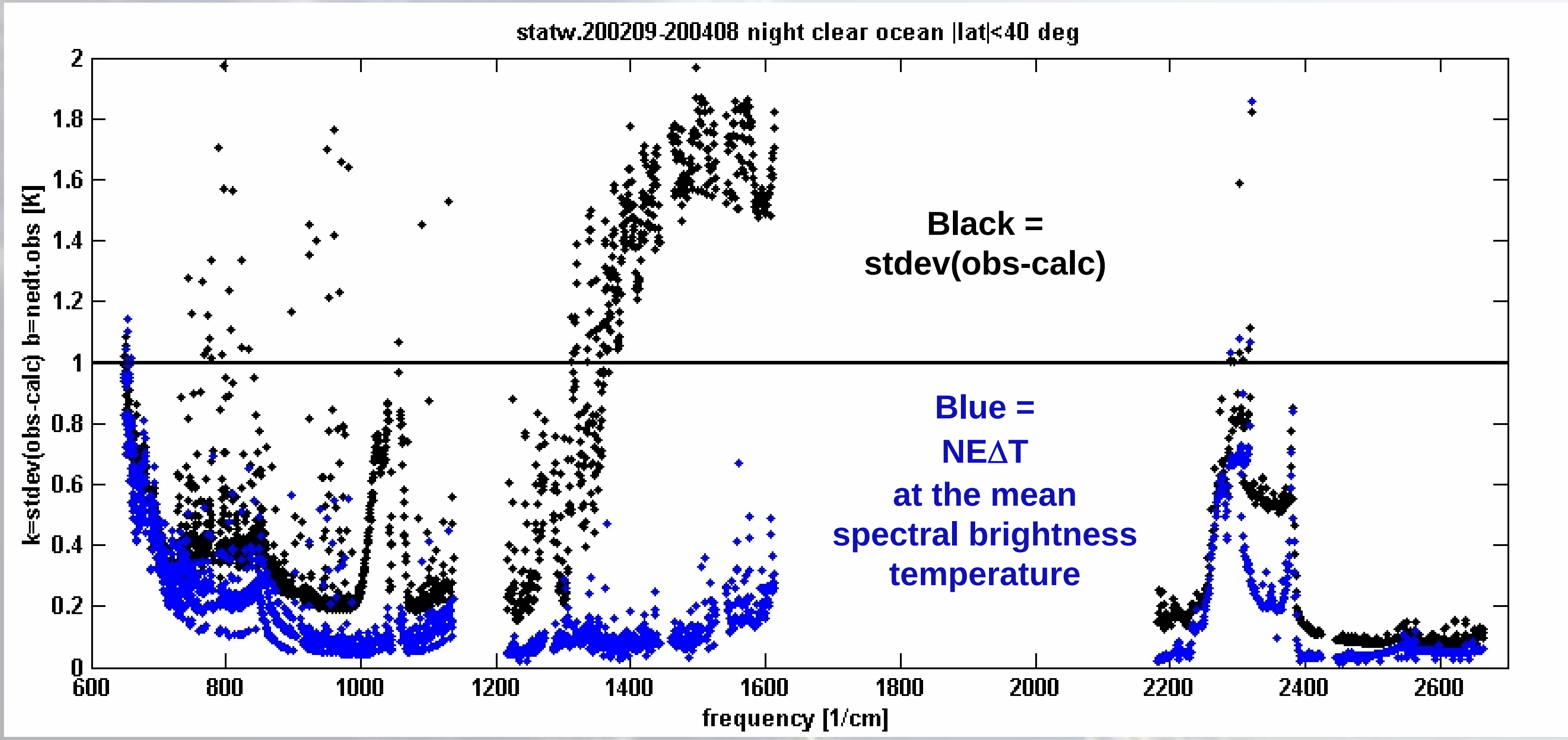
Adjusted NEΔT Compared To stdev(obs-calc)



- Where ECMWF is reliable, the two plots agree well
- Where ECMWF is not reliable, (obs-calc) is high, weakening the potential weight of AIRS data in the assimilation process

AIRS Stability Comparing To ECMWF

- **We evaluate the stability of AIRS using the difference between the mean of one year versus the mean of another year**
- **The direct difference of year1 - year2 simply shows interannual differences**
  - ***We have to use double differences***
  - ***Stdev(obs-calc) for year1 - year2***
  - ***Bias(obs-calc) for year1 - year2***
  - ***Ensure that the same RTA and channel frequency table are used in the processing of both years***
- **If a change is noticed, we have to analyze whether the difference is primarily due to AIRS or ECMWF**

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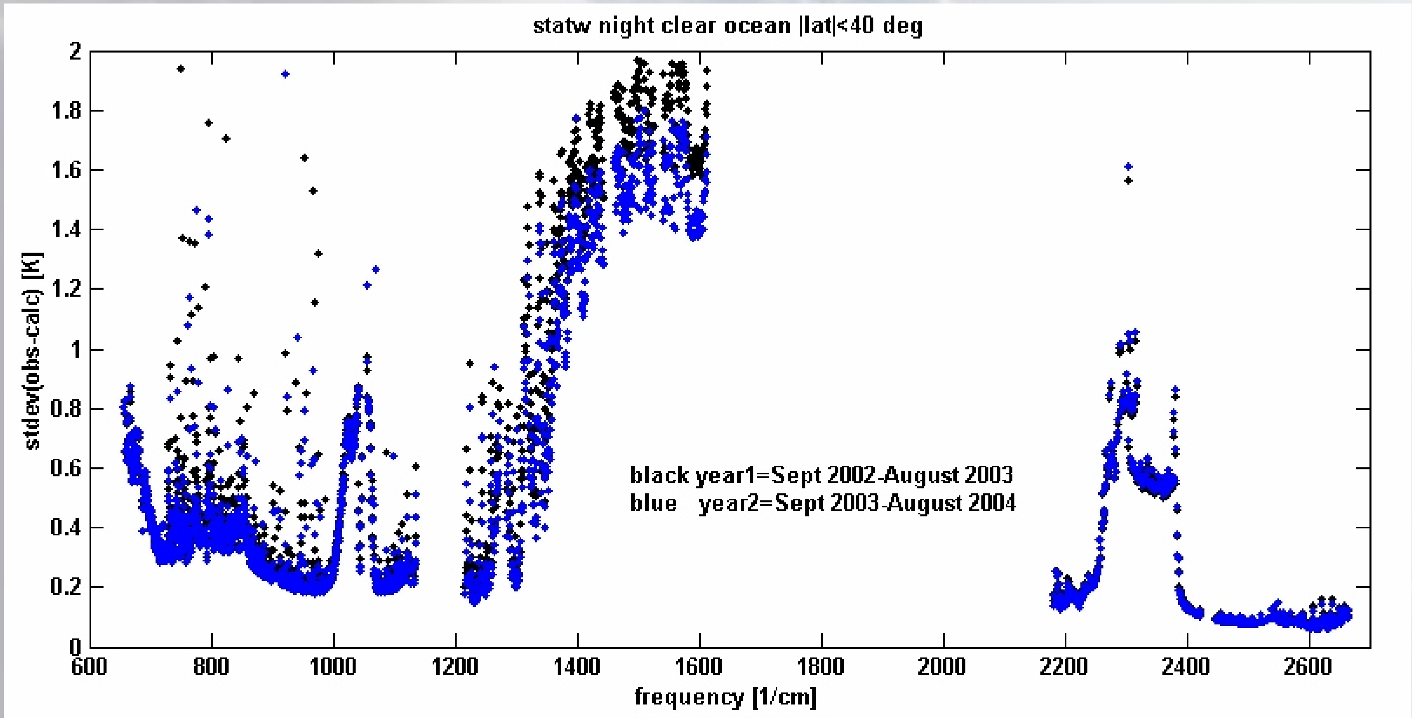
Stdev(obs-calc) Difference

- **Stdev(obs-calc) decreases in the second year for channels sensitive to water**
- **Is this due to the fact that ECMWF began assimilating AIRS data in the second year?**



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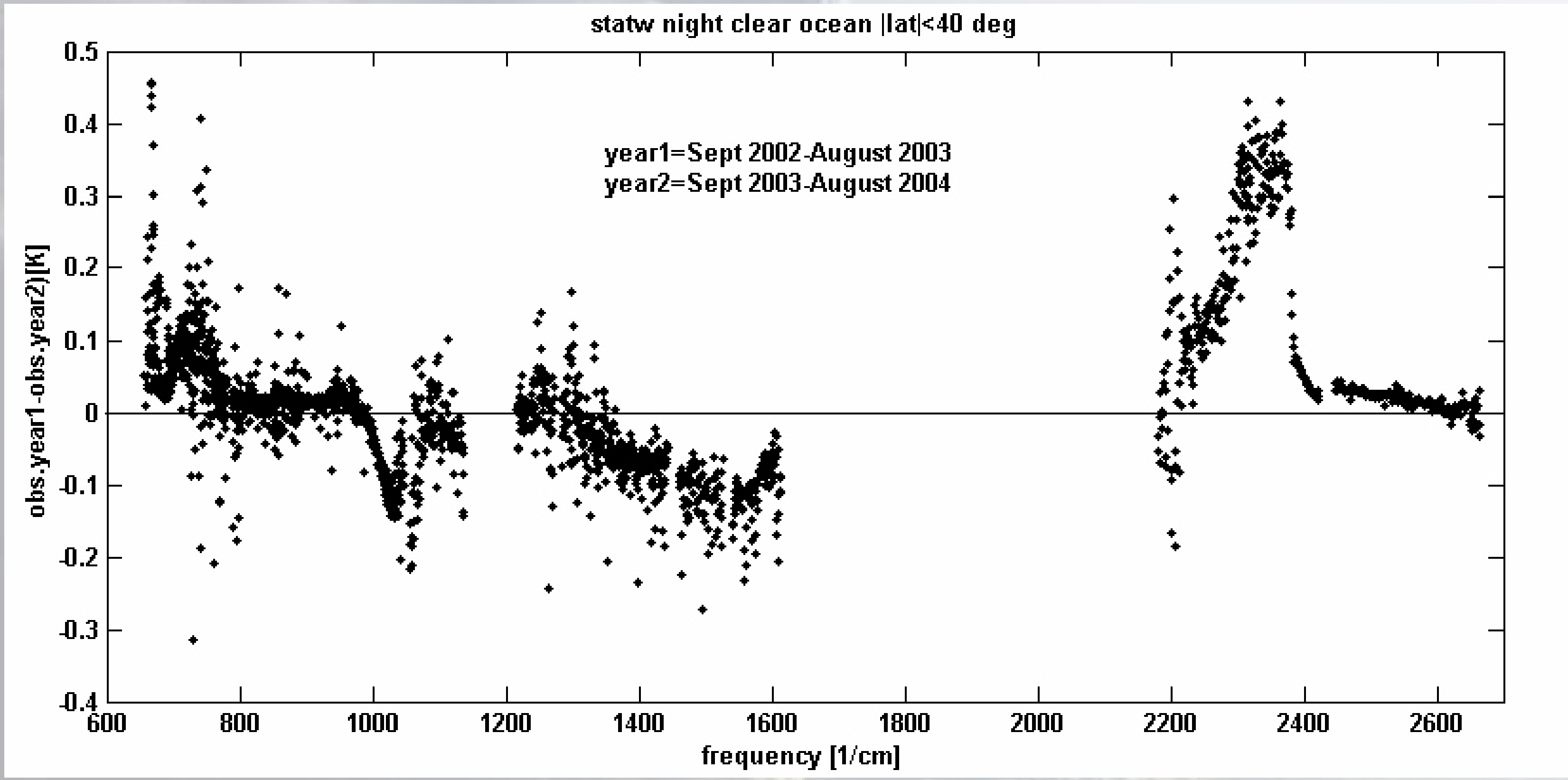
Differences Related To Changes At ECMWF



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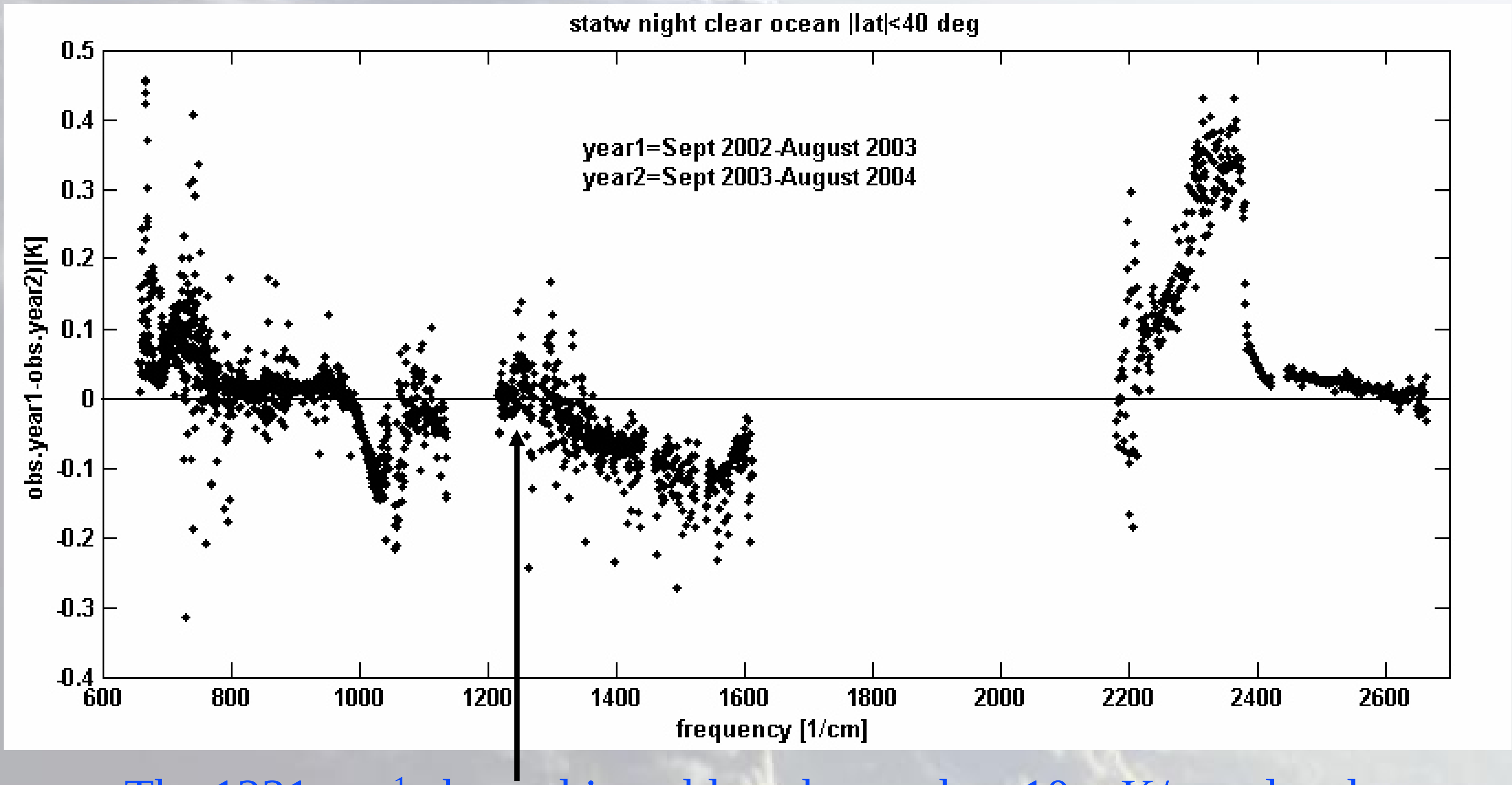
Bias Shift Less Than 20 mK In Uncontested Spectral Areas



The 1231 cm^{-1} channel is stable at better than 10 mK/year level

Summary and Conclusions

- We analyzed (obs-calc) [sst2616-rtgsst] for three years of night clear ocean data within ±40° of the equator
  - *AIRS is stable compared to rtgsst to about 16 mK/year*
  - *The differences for window channels between AIRS and rtgsst appear to be very small (≈ 10 mK) but with an uncertainty of 120 mK*
- We analyzed (obs-calc) [AIRS-ECMWF] for two years of night clear ocean data within ±40° of the equator
  - *The differences with ECMWF for two consecutive years for channels not sensitive to ECMWF changes are typically less than 20 mK*
  - *The standard deviation of (obs-calc) for channels where the ECMWF is reliable agrees well with the dynamic NEΔT reported by the AIRS radiometric calibration software*
- The AIRS (obs-calc) analysis establishes an accuracy and stability benchmark for IASI and CRIS

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Suggested Metric—stdev(obs-calc) = Dynamic NEΔT

- A two-year analysis of bias [mean(obs-calc)] can be generated for any instrument
  - *If properly tuned, the bias can be made arbitrarily small*
- If:
  - *the instrument is radiometrically and spectrally stable regionally and globally on a two year time scale*
  - *The atmosphere is accurately known*
- Then:
  - *Standard deviation of (obs-calc) should equal dynamic NEΔT*

- # Backup Slides

Background

- Previously, we have used clear night ocean data to validate the absolute accuracy and stability of the AIRS radiance in the 2616 cm^{-1} window channel
- The accuracy of AIRS at 2616 cm^{-1} in the 290–305 K range is 10±120 mK with stability better than 16 mK/year for all data from September 2002 through August 2005
- We want to know how good the calibration is for the other 2377 AIRS channels

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Results For AIRS Channel At 1231 cm^{-1}

- **Mean water absorption is 2.5 K**
- **800 mK cold bias**
  - ***-170 ± 160 mK explained***
  - ***May 2004 shift in RTGSST processing algorithm is less obvious because of increased noise***