NOAA Infrared Sounder Workshop

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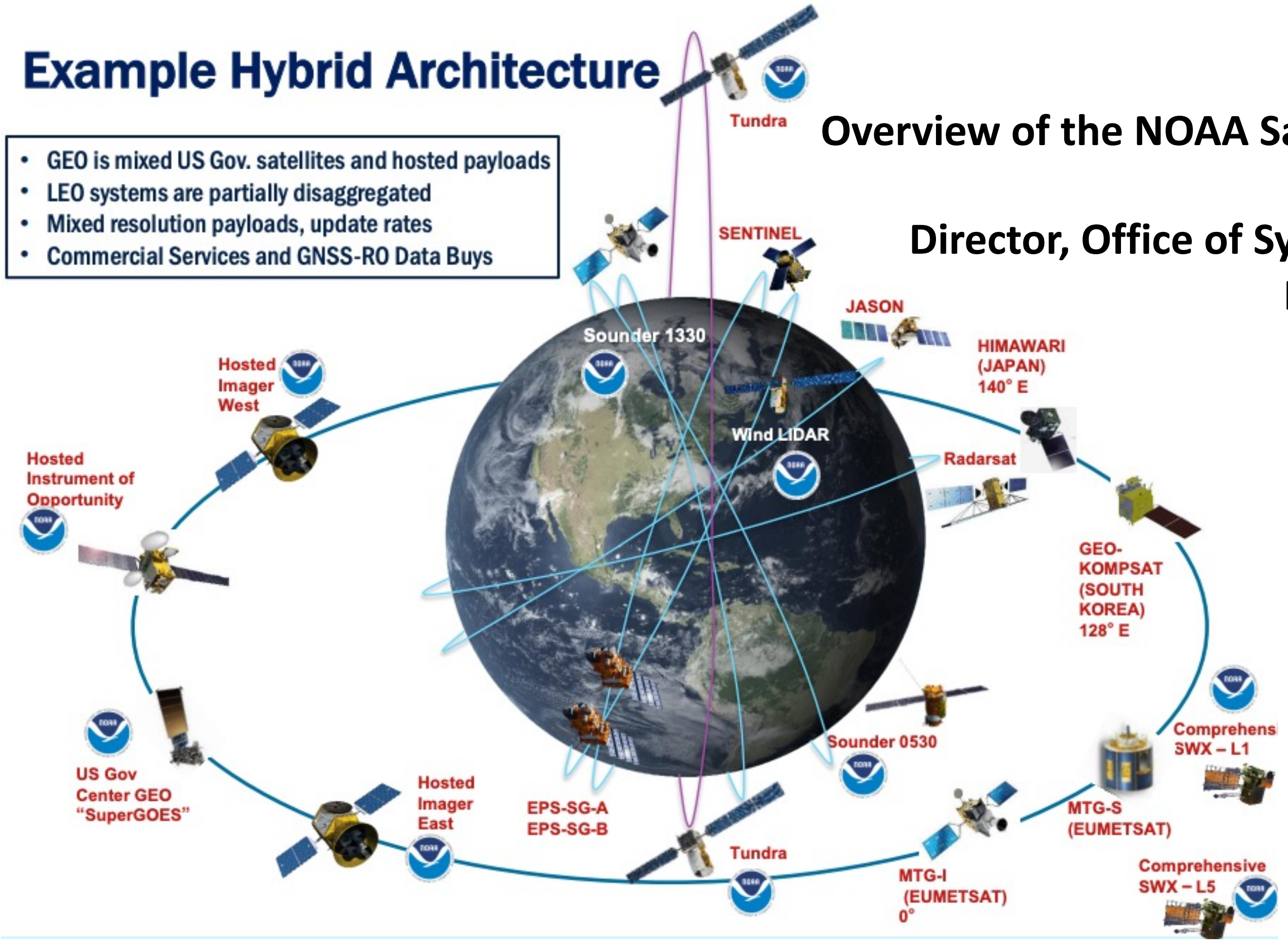
Space Science and Engineering Center (UW-Madison)



Overview of the NOAA Satellite Observing Systems Architecture (NSOSA)
Dr. Karen St. Germain
Director, Office of Systems Architecture and Advanced Planning
NSOSA Community Day

A Mix of GEO and LEO large & small satellites carrying a wide variety of passive visible, infrared, microwave, and active RADAR sensors to observe those surface and atmospheric parameters associated with weather, pollution, and climate

Low Earth Orbit (LEO) Infrared Sounding Activities at NOAA

Satya Kalluri, Ph.D., Program Scientist, LEP/JPSS Program

IR Instrument Properties Summary

Class	Possible Channels	NEDN/NEDT (T or q)	Resolution	T and q Precision	Spatial Resolution Single Cell
CrIS	SWIR, MWIR, LWIR (3.92 – 15.38 microns)		0.625 cm-1		14 km
IR-HIGH	SWIR, MWIR, LWIR (3.92 – 15.38 microns), possible hyperspectral	CrIS noise levels or better	CrIS or better	Similar or better than CrIS across all layers	10 km at nadir
IR-MID-SM	SW SmallSat: SWIR/ MWIR (3.7 – 8.6 microns)	CrIS NEDT x1.5	CrIS	Similar to CrIS across reduced layers (depends on band selection to be confirmed)	14 km at nadir
IR-MID-ML	LW SmallSat: MWIR/ LWIR (6.6-15.38 microns)	CrIS NEDT x1.5	CrIS	Similar to CrIS across reduced layers (depends on band selection to be confirmed)	14 km at nadir
IR-LOW	Single band – range specific to science need	CrIS NEDT x2.0	CrIS	Similar to CrIS across targeted layers	14 km at nadir

Overall guidance recommendations for classes of instruments, not to be construed as instrument designs

NOTES:

- BAA Studies showed resolution could be comparable or better than CrIS, although some configurations may have smaller swath and fly at lower altitude
- BAA Studies showed most efficient way to reduce cost is to remove wavebands/adjust detector size, impacting vertical coverage.

CrIS Instrument Information Content/Degrees of Freedom

Nyquist-Shannon Sampling Theorem: *the resolution of features within a continuous time/frequency signal of finite bandwidth increases with the number of discrete measurements (e.g., a vertical profile feature sensed by a spectrum of radiances).*

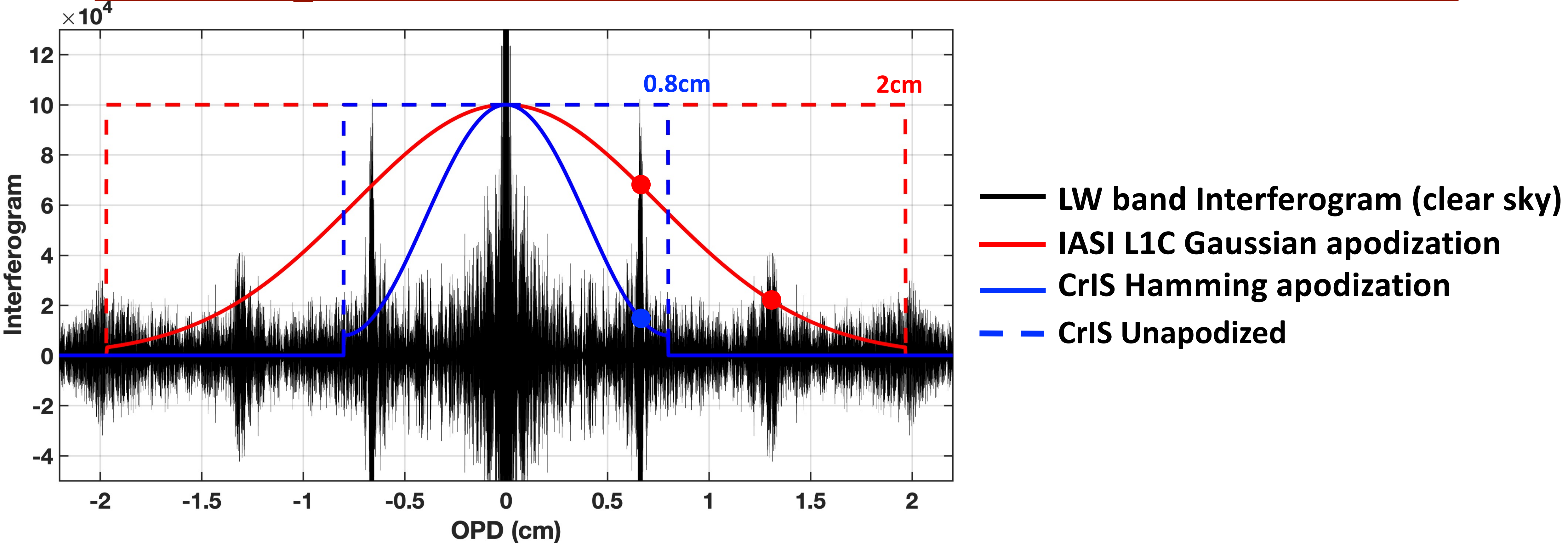
CrIS Bands	ALL	LW +MW	MW+SW	LW	MW	SW
Temperature Shannon IC	34.4	33.6	19.7	32.4	14.7	13.9
Humidity Shannon IC	32	32	29.6	14.5	29.1	4.2
Temperature DoF	10.1	9.8	6.3	9.6	4.1	5.5
Humidity DoF	6.5	6.4	5.5	2.8	5.2	1.3

LW and MW Bands Are Essential for Temperature and Moisture Sounding

* C. D. Rodgers CD, "Information content and optimization of high spectral resolution measurements," in *Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research II*, SPIE 2380, Hays PB, Wang J (eds), pp 136–147,1996.

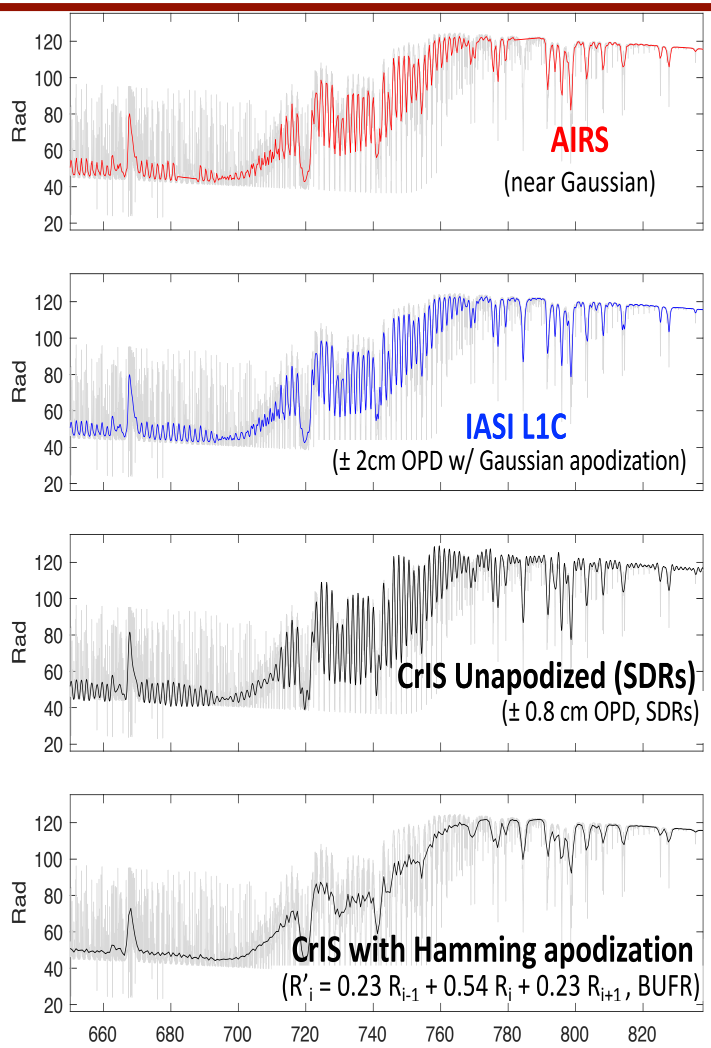
Parameters Used: spectral radiances at NOAA-20 CrIS noise level, 2K and 30% background RMSE, and profile error vertical correlation length = 3km

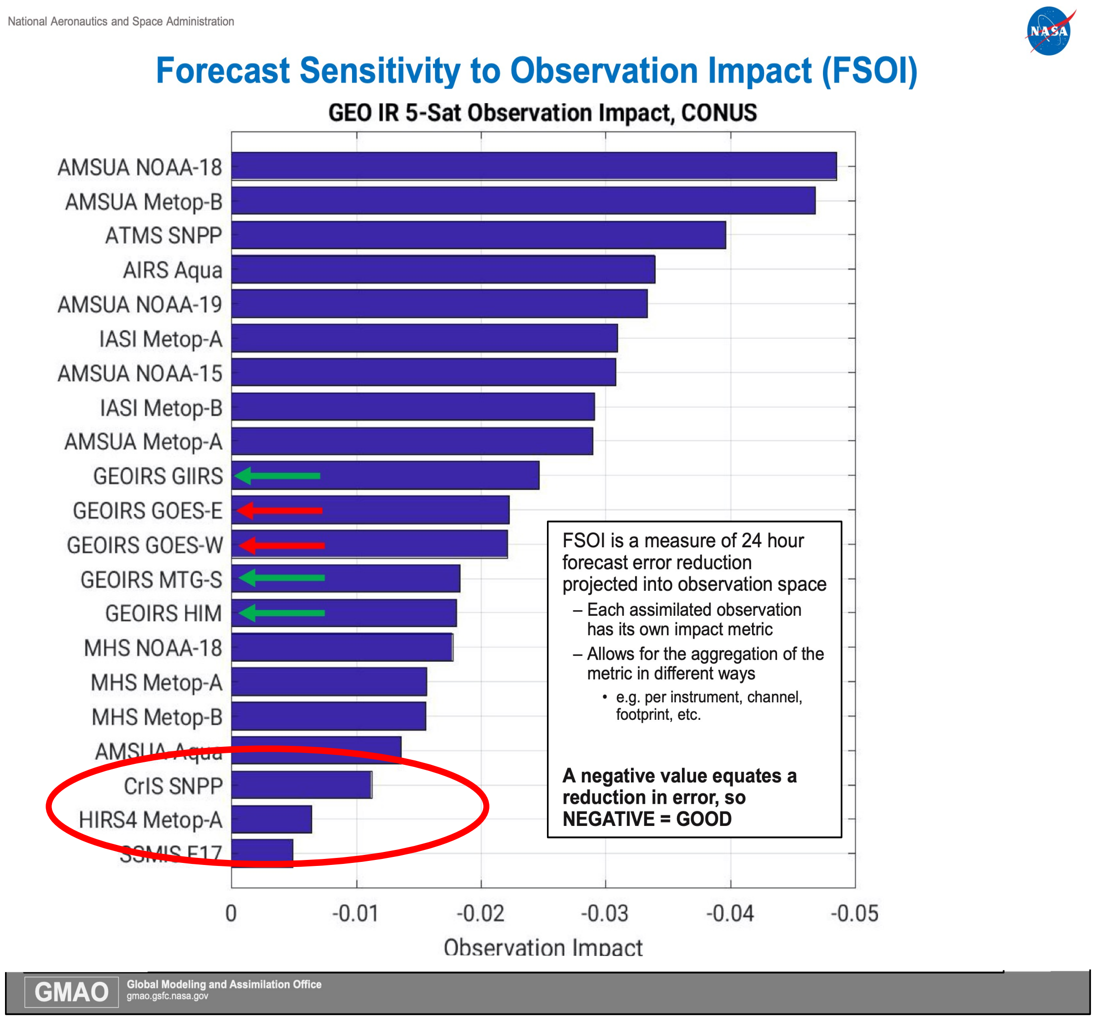
CrIS Spectral Resolution (Theoretical Basis)



- Resonances at 0.65 and 1.3 cm capture vertical sounding information from the 15μm CO_2 band
- IASI L1C Gaussian apodization retains 70% of the first resonance and 20% of the second resonance
- ➢ CrIS Hamming apodization retains only 10% of the first resonance
- ➢ Important to effectively remove the apodization, especially for CrIS
- Potential similar situation for MTG-IRS (maxOPD ~0.85 cm)

Dependence on Forecast Influence on Spectral Resolution

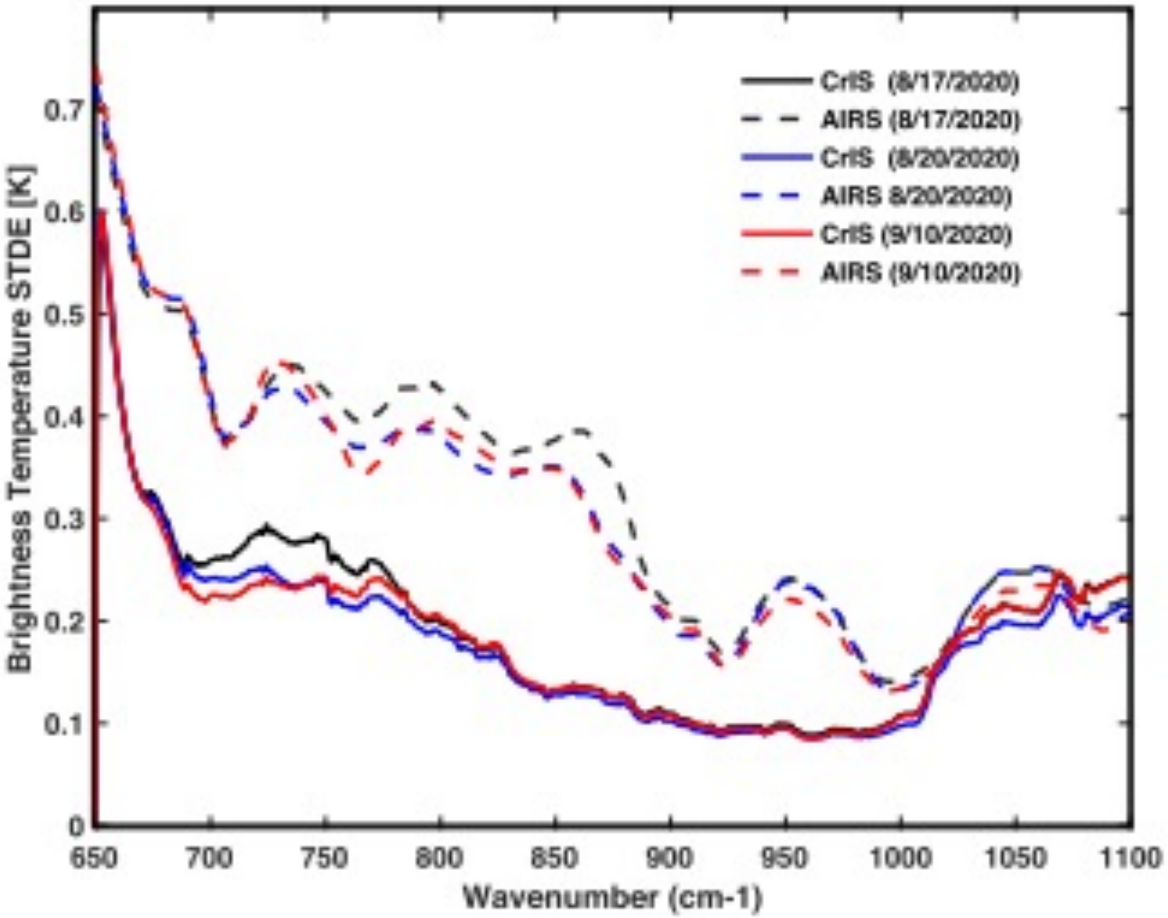




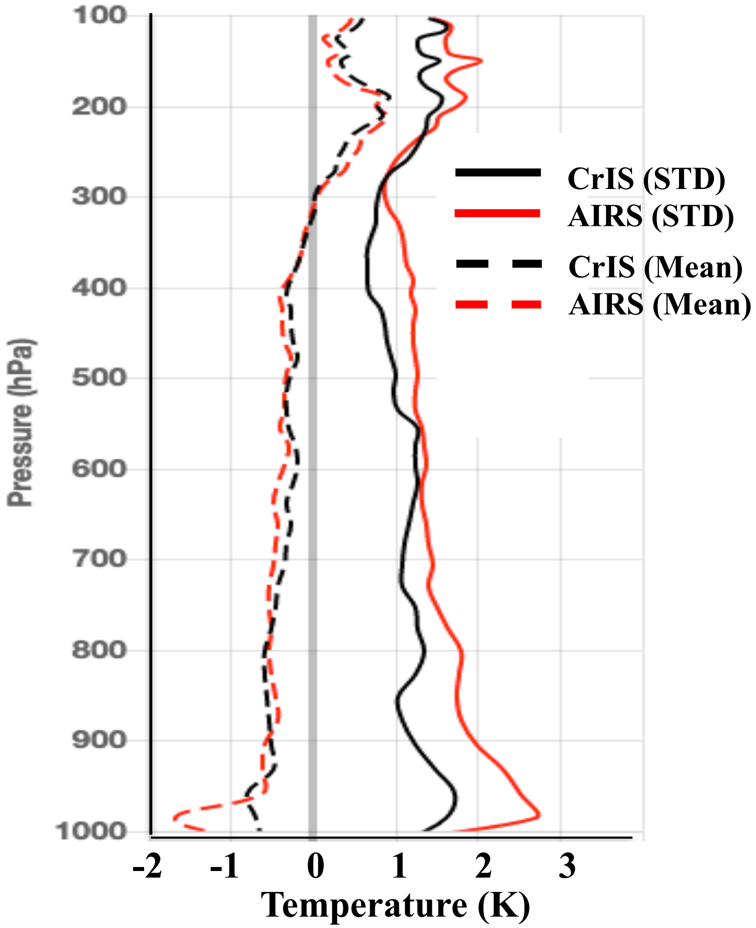
The NWP use of CrIS data shown here was limited to 70 apodized LW CrIS channels, which made the CrIS impact equivalent to HIRS4. This result clearly shows the importance of using all the CrIS unapodized spectral channels to gain the full information content of the satellite measurements.

Detector Co-Registration Impacts Spectral Fidelity & Profile Accuracy

Standard Deviation of 'Observed' minus 'Calculated' Brightness Temperature Differences Showing the Spectrally Random Component of the Radiance Measurement Error (i.e., spectral fidelity of the radiance measurements)



Standard Deviation and Mean Difference Between Clear-sky 'Radiance Retrieved' Temperature and 'Radiosonde Observed' Temperature for 59 Profile Comparisons on 8/17 and 9/11, 2020.



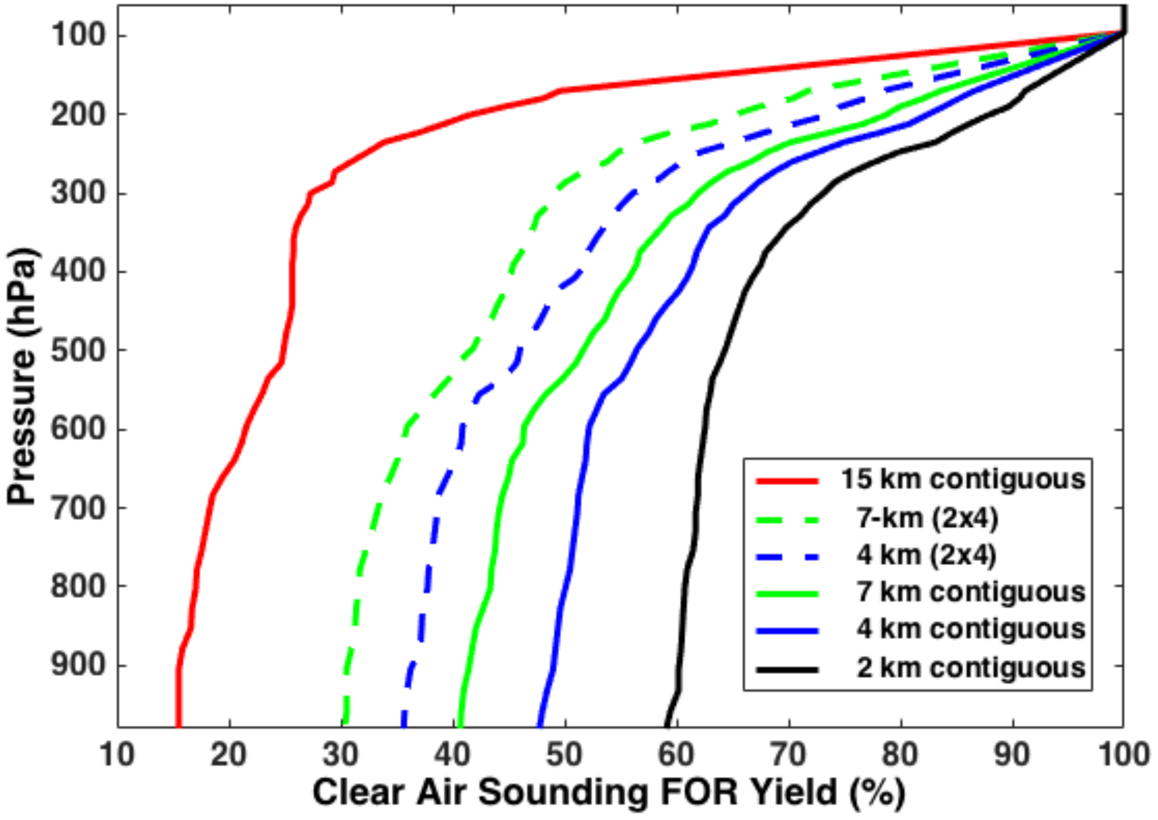
Single Detector per Band (CrIS) Vs Multiple Detectors per Band (AIRS) FOV Co-registration Impacts Spectral Fidelity

Detector Spatial Resolution (Cloud Impacts)

Real data shows impact of FOV/GSD on temperature and humidity profile retrieval accuracy

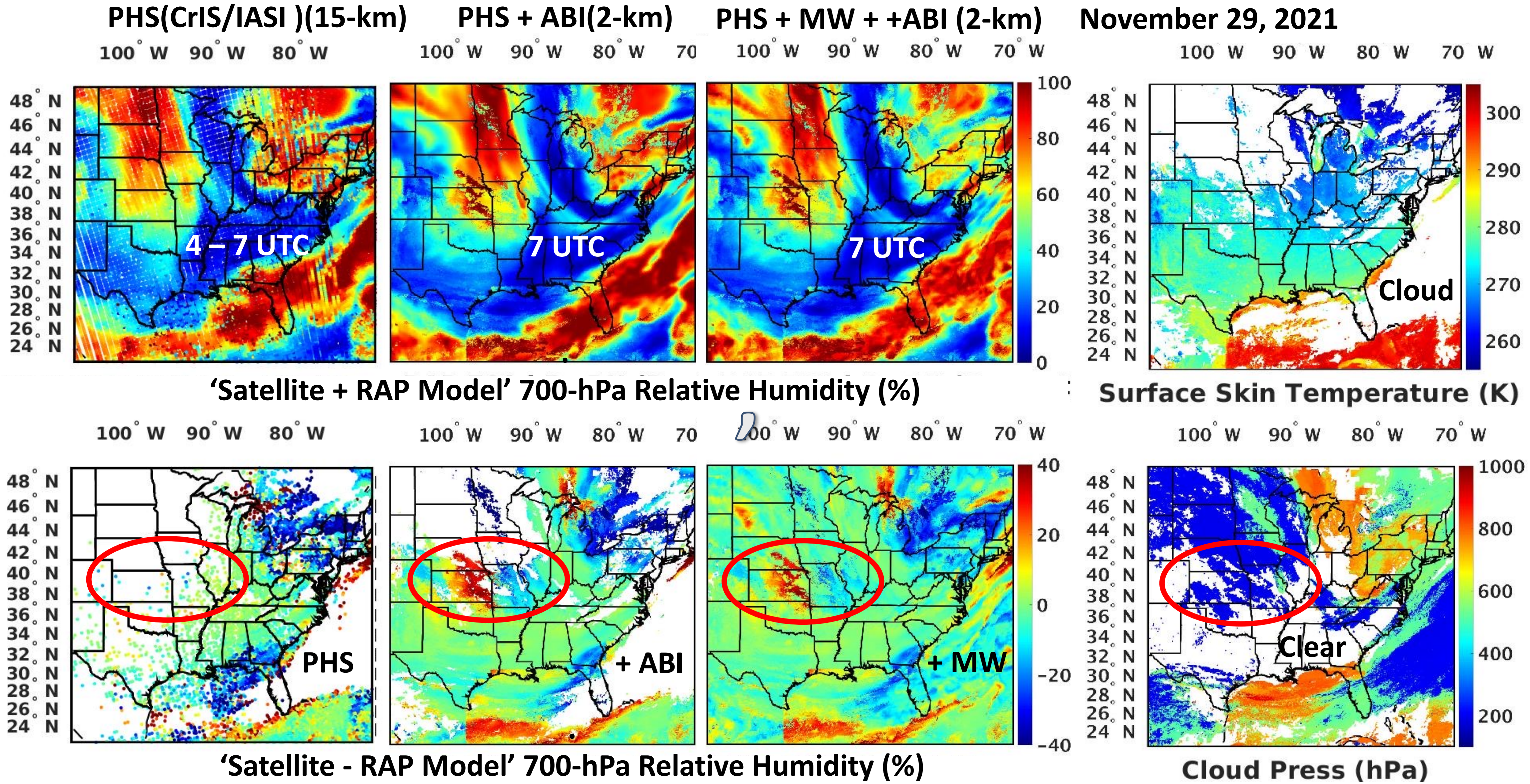
- Aircraft IR hyperspectral soundings (Scanning HIS) and dropsonde measurements compared for partly cloudy conditions
- Improved spatial resolution increases tropospheric sounding yield (15% to 60%)
- FOR sounding accuracy improves with higher spatial resolution due to decreased cloud contamination
- Sounding accuracy is much more dependent on cloud contamination than it is on detector noise
- Smaller FOV/GSD greatly increases FOR yield with relatively small impact on profile accuracy.

30 km x 50 km Field of Regard



Detector Field-of-View Size & Density Impacts the Ability to Sound the Troposphere

Spatial Resolution Requirements (Polar/Geo Sat Data Fusion)

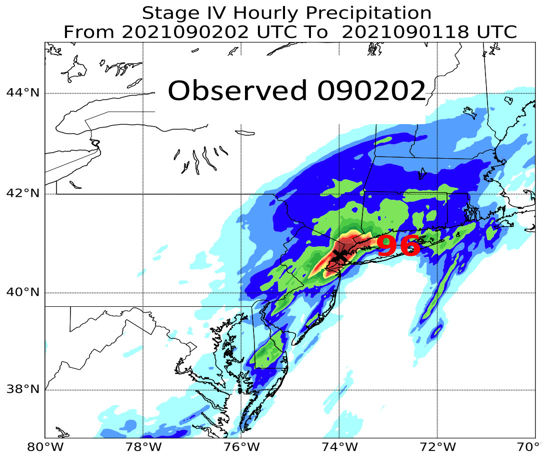


Important Spatial Water Vapor Features Are Resolved With High Horizontal Resolution (2-km) Radiance Data

Spatial Resolution (Resolving Convection Processes)

3-Km and 8-Km High-resolution Satellite Data Assimilated 8-hour Forecasts Vs. Operational HRRR (3-Km) and RAP (13-Km) 8-hour Precipitation Forecasts

Sept. 1, 2021
Deadly New York
Flash Flood
10 to 11 PM EDT



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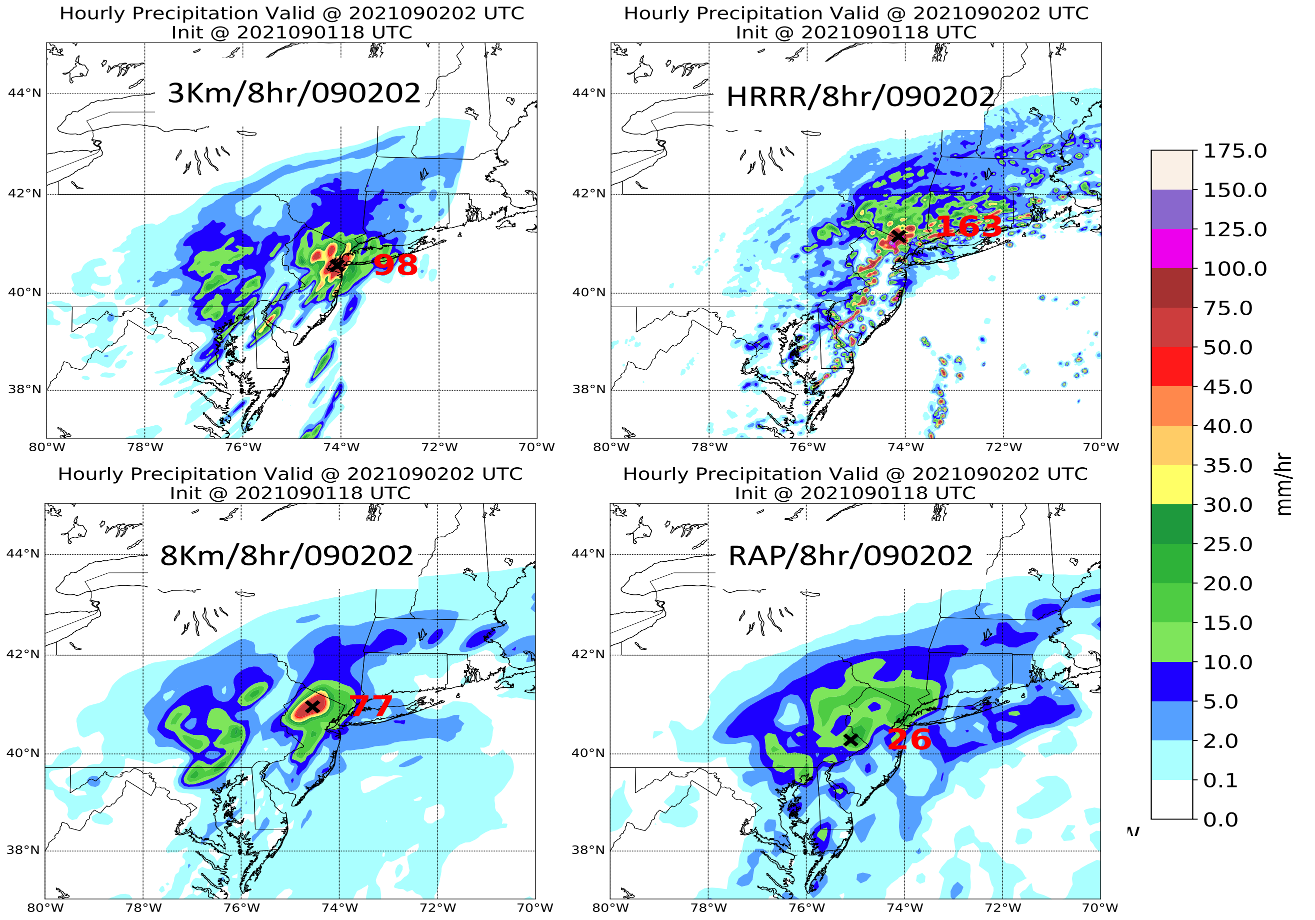
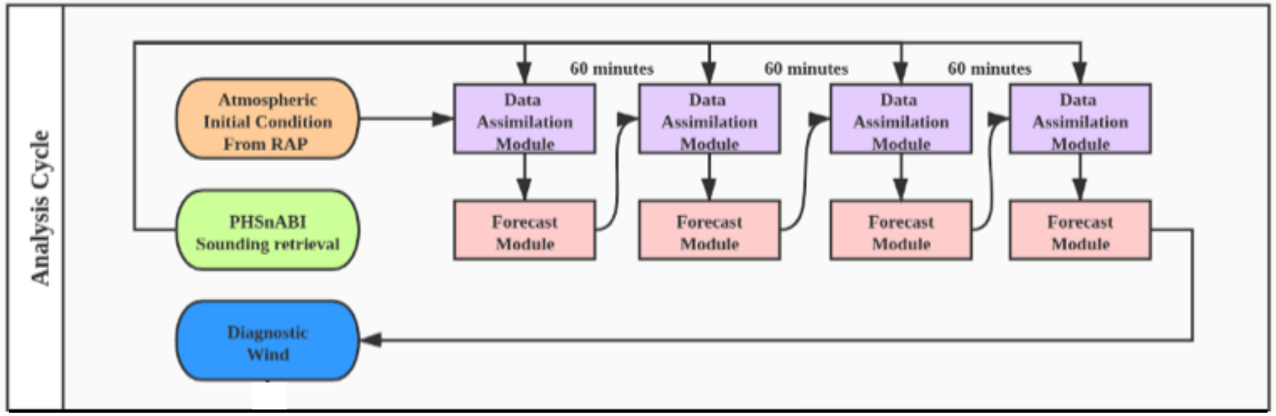
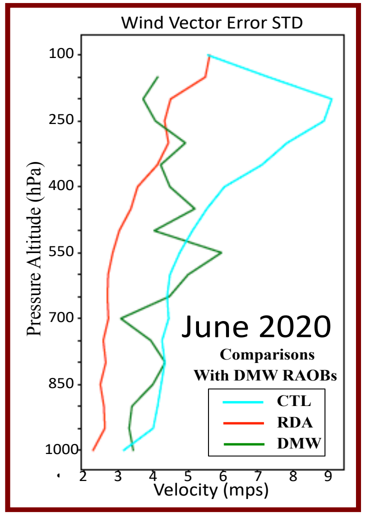


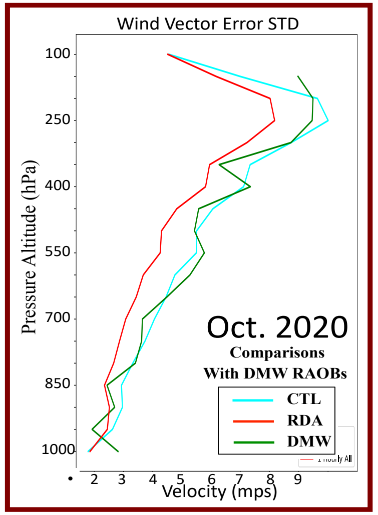
Higher Horizontal Resolution Satellite Data and Forecast Models Provide More Accurate Convective Weather Precipitation Forecasts

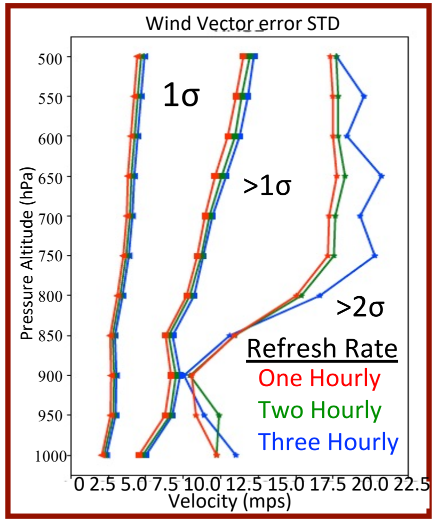
Temporal Resolution (Resolving 3-D Winds) Through Continuous Assimilation of Temperature & Humidity Profiles

- Winds Are Diagnosed by the Continuous (e.g., hourly) Assimilation of High-Resolution Satellite Thermodynamic Profiles
- Forecast Model Primitive Equations of Motion Force the Model's Dynamical Processes (i.e., 3-D Winds) to Conform to the Spatial and Temporal Changes in the Thermodynamic Observations Being Assimilated.
- Radiosonde Wind Comparisons Show Satellite Retrieval Data Assimilated (RDA) Errors Are Less Than Control (CTL) & Derived Motion Wind (DMW) Errors









Combined High-resolution (2-km) Sounding Data Assimilation Shows That a Two-Hourly Interval Thermodynamic Sounding Refresh Rate Minimizes Large (>2σ) Model Diagnosed Wind Errors

Summary IR Sounding Measurement Recommendations

- *All future hyperspectral sounders should include longwave and midwave spectral measurement bands (The ideal system maintains all three bands).*
- *Measurement spectral resolution should be equal to or better than 0.625 cm^{-1}.*
- *Data should be provided at its unapodized spectral resolution.*
- *Within band spectral detector Field-Of-View (FOV) co-registration errors should not cause radiance errors to exceed the detector spectrally random noise level*
- *Within Field-of- Regard (FOR) spectral detector FOV size should be minimized, and spatial density should be maximized, to optimize clear sky data and provide the ability to detect small-scale storm processes*
- *For resolving 3-D winds and forecasting extreme dynamical weather processes, a temporal resolution/sounding refresh rate should be equal to or less than 2-hours.*
- *Day/night visible wavelength imagery measurements (spatial resolution < 0.5-km) are recommended for detecting, and accounting for cloud and aerosol contributions, which can contaminate the temperature and water vapor sounding radiance observations*

Questions to the Community

Questions to the Community Answers (Highlights in Red)

- **What is the Ideal IR Backbone System?**
  - For NWP, the backbone measurements should have quasi-continuous spectral coverage from 4 to 15 microns with a spectral resolution no poorer than 0.625 cm^{-1}, unapodized.
  - Instrument FOV size should approach 2-km in order to optimize clear air sampling and resolve dynamical moisture processes as required to predict severe weather. PCA's can also be used to reduce radiance data volume and transmission data rate.
  - Spatial resolution should approach a spatial resolution of 1-to 4-km. (Future global forecast models is expected to have grid point spacing of 1 to 2-km in the 2030 to 2050-time frame. Twice model resolution Nyquist sampling is desired.)
  - Measurement noise should be as small as practically possible but not be limited by the instrument's spatial resolution since the impacts of single sample noise can be minimized by intelligent spatial averaging and optimal spectral convolution (e.g., use of Principal Component Analysis).
  - Consist of no less than 6 polar satellites in complimentary orbits providing a global 2-hr refresh rate.
  - Include a suite of sensors in the 1330 orbit which has the calibration accuracy , stability, traceability, swath width, and data quality is as good as the current CrIS. Ideally all supplemental orbit sensors should have these characteristics as well.
  - Consist of 5 Geostationary satellites equally spaced around the equator to provide a global refresh rate of 1-hour and regional refresh rates as small as 15-minutes.
- **What additional IR measurements would be ideal to augment the backbone?**
  - Additional polar satellite to reduce global refresh rate to one-hour
  - Additional geo-satellites to enable stereo measurements to enhance the atmospheric sounding vertical resolution beyond the spectral monochromatic limit.
  - Higher spatial and temporal resolution increases the ability to predict smaller scale weather systems with extended lead-times (e.g., longer severe weather warning times).
  - Additional Measurement to augment the backbone could be at higher noise level of measurement assuming that fixed instrument performance parameters (i.e., FOV size, Spectral Coverage, and Spectral Resolution, that cannot be enhanced during ground data processing), meet the back-bone requirements.

Questions to the Community Answers Continued

- **Wavelength Selection?**
  - Improving the vertical and temporal resolution of lower tropospheric /Planetary Boundary Layer (PBL) measurements would be most impactful for increasing severe convective storm warning time.
  - Because PBL moisture information is contained in the spectral window region of the LW-band and the LW-band low level temperature profile information is needed to account for surface and cloud reflected short-wave radiation, contaminating the most sensitive shortwave PBL temperature profile measurement, all three spectral bands (LW, MW, and SW) are needed to optimize lower tropospheric temperature and moisture observations. However, the acceptable noise level for the LW band could be increased significantly above that required for the back-bone system. It is also feasible to decrease the spectral coverage of the LW, MW, and SW bands to exclude observations dominated by contributions from above the lower troposphere.
  - In general, since the vertical resolution of the low-level spectral band instruments depends on resolving the entire vertical column radiance contributions, measurements from the backbone system would need to be fused with the lower tropospheric measurements in order to account for radiance contributions above the lower troposphere.

Other Applications?
  - **Atmospheric Composition:** the measurement of IR radiance contributions from water vapor, clouds, and greenhouse and pollutant gases need to be made over the entire spectral range and with the spectral resolution of the backbone measurement system. However, the spectral, spatial, and temporal resolution may be quite different than that required for weather forecasting. Shortwave reflectance measurements would help PBL sounding.
  - **Radiation Budget:** Can be defined from the combination of Backbone measurements and radiative transfer calculations from atmospheric profile measurements. Climate applications would greatly benefit from a single on-orbit CLARREO type sensor to provide SI traceability of the operational satellite measurements.
  - **3-D Winds:** Specified through continuous assimilation of thermodynamic profile measurements.

Questions to the Community Answers Continued

- **Impact in regional and global models?**
  - Greatest impacts have been shown by NWP centers that use the greatest amount of spectral and spatial information of the data. Users need to utilize all the spectral and spatial information to maximize improvements of NWP.
- **Optimum Latency?**
  - Global model latency can be as much as a few hours. Regional model latency should be no greater than one-hour.
- **Do IR & MW sounders need to be co-located on the same platform or can they be on free-flying spacecraft?**
  - Temporal and spatial measurement co-location is highly desirable but not necessary for atmospheric sounding forecast applications. Fusion techniques can be used to co-locate the observations with sufficient accuracy needed to utilize the information provided by Infrared and Microwave systems operated from different platforms if they have a similar spatial coverage and frequency of observation.
- **Impact of re-analysis for climate studies?**
  - Impact will be significant once all the data at full spectral and spatial resolution are used for NWP and re-analysis. Climate applications would greatly benefit from SI traceability of the operational satellite measurements provided by a single on-orbit CLARREO type sensor.
- **Do you use IR soundings for both retrievals as well as direct assimilation? How are retrievals used?**
  - I use vertically model background de-aliased retrievals, which are equivalent to 'all-radiance' data assimilation.
- **Are IR soundings used at the Field of Regard resolution or at the Field of View resolution?**
  - Field of View Resolution (i.e., single footprints for all-sky conditions)
- **Are there other factors that we should consider?**
  - Yes, future model resolution and enabling use of data over land and for all-sky cloud conditions.

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