Hyperspectral Radiance Sounding Information Content

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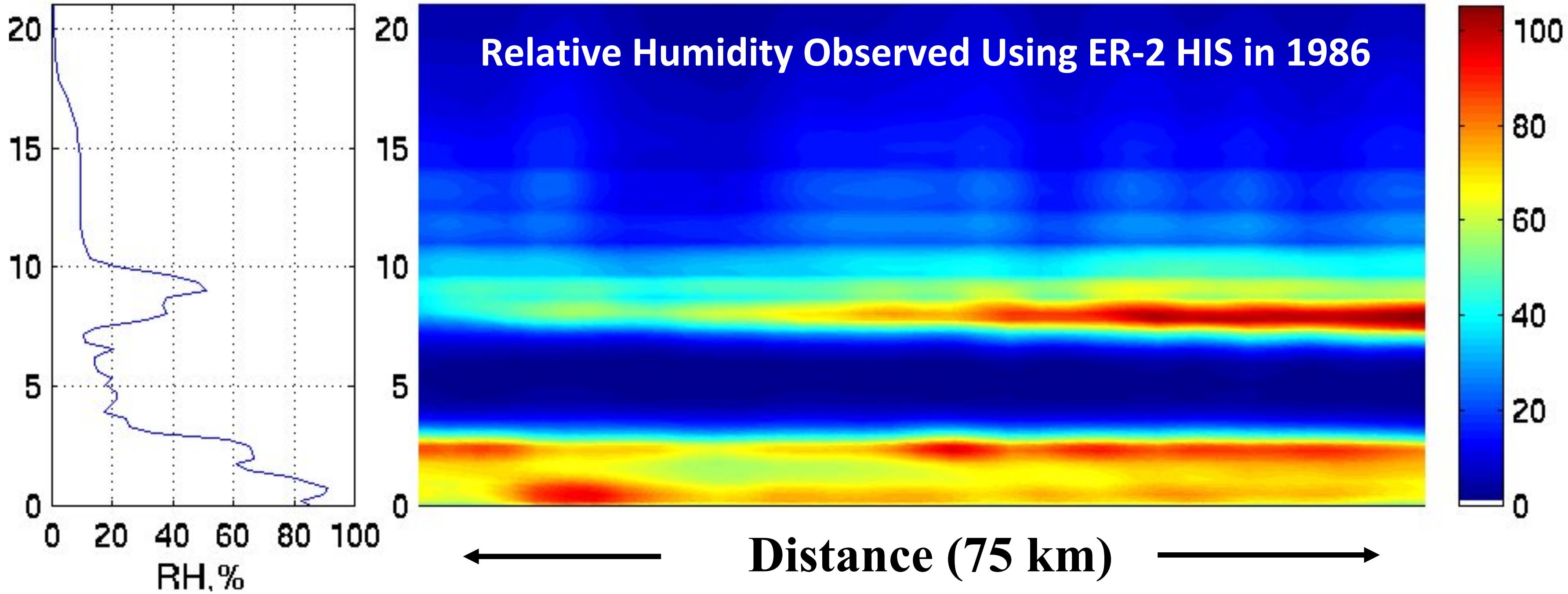
Historical Background

Interferometer Hyperspectral Infrared Sounding Concept Origin:

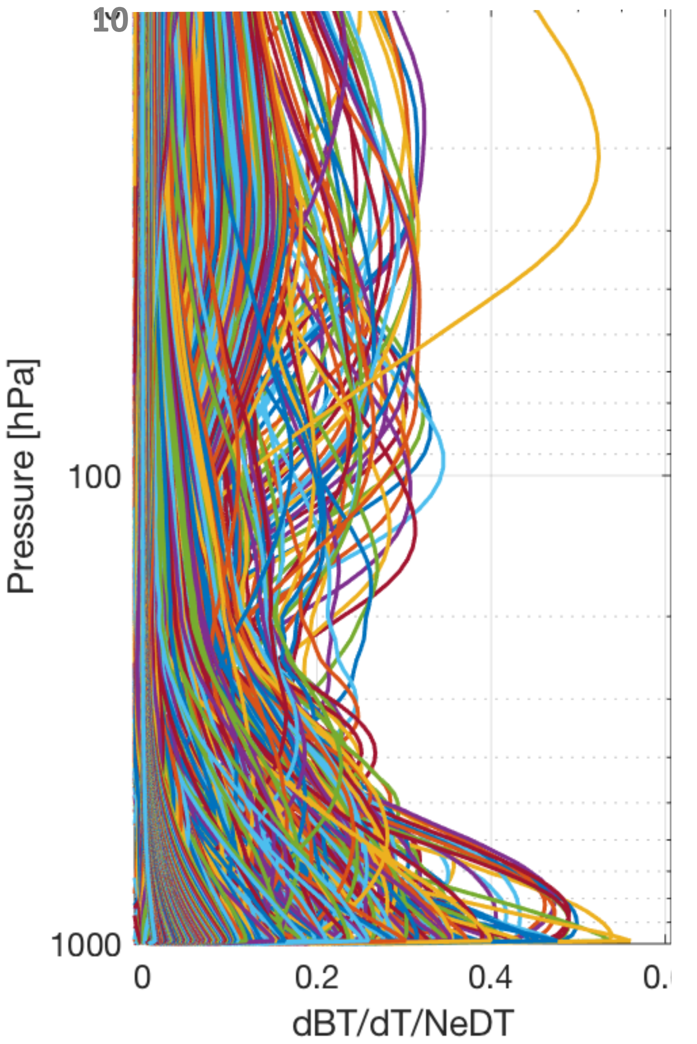
- Kyle, 1977 (Temperature Sounding with a Partially Scanned Interferogram, Applied Optics 326-333)
- Smith, Howell, and Woolf, 1979 (The Use of Interferometric Radiance Measurements for Sounding the Atmosphere, Journal of the Atmospheric Sciences, Vol. 36, No. 4 April 1979)
- Revercomb, 1980: NASA and NOAA funded the UW-SSEC to build a High-resolution Interferometer Sounder (HIS) to experimentally demonstrate the concept using the NASA ER-2 Aircraft



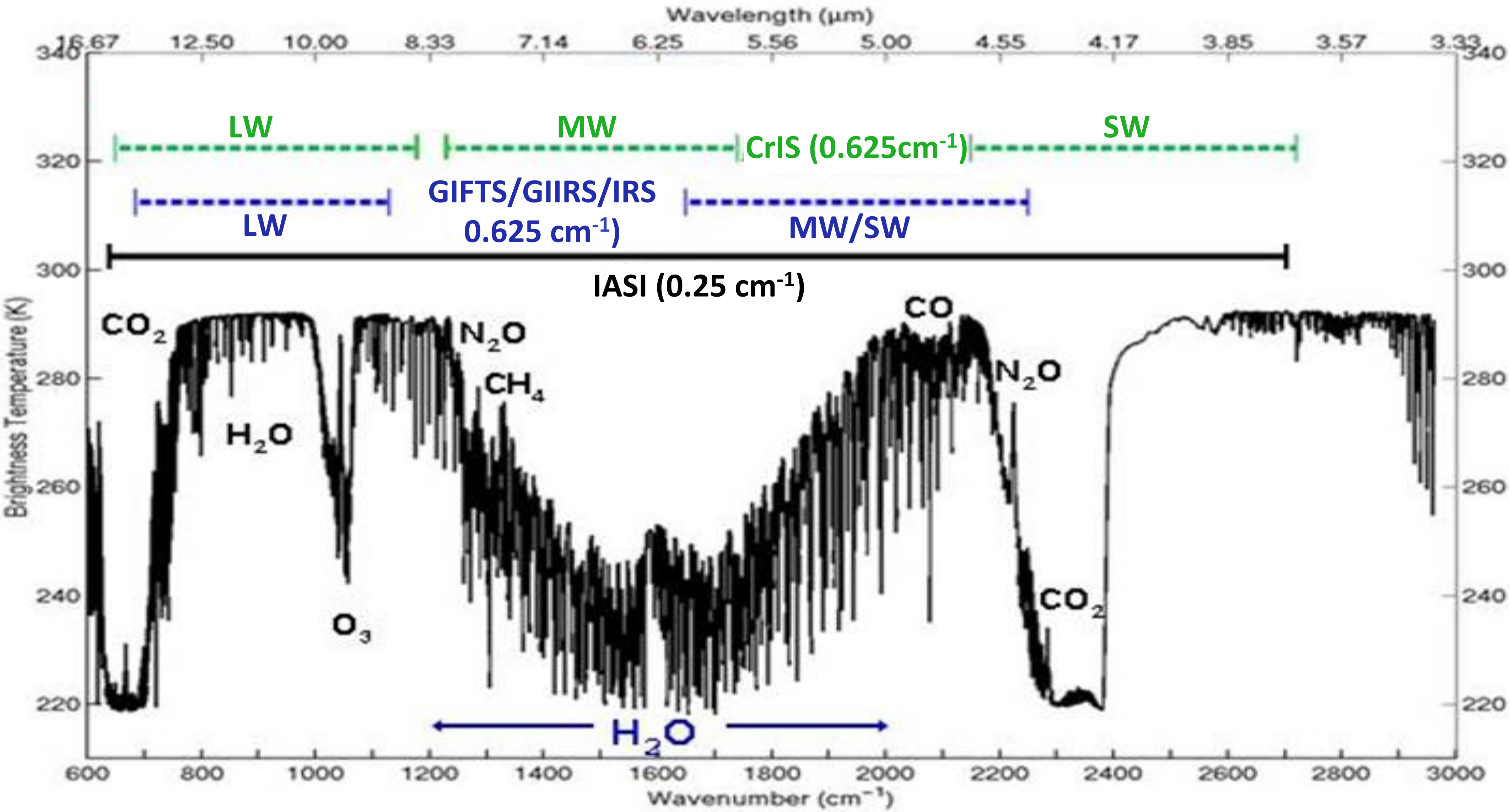
Shannon Sampling Enables High Vertical Resolution to Be Realized With Hyperspectral Measurements

The hyperspectral resolution sounding concept is based on Shannon Information Theory, which explains how a small signal, buried in random noise, can be amplified by accumulating repetitive samples.

- *The signal level is amplified at a much faster rate (i.e., SQRT of the sample number) than is the noise*
- *A single measurement cannot "see" fine-scale vertical structure features because a radiance signal arises from a very large depth of the atmosphere (large weighting function width).*
- *However, as one uses more spectral noise independent radiance measurements in the profile retrieval, small-scale vertical features begin to be resolved.*
- *This is why hyperspectral sounding instruments have been designed to observe the radiance in thousands of spectral channels.*



Atmospheric Sounding Spectral Bands



LW Band Information Importance

The LWIR observations are critical for the following reasons:

- **Provides the highest vertical resolution temperature sounding**
- **Radiances not contaminated by cloud and surface reflected sunlight,**
- **Radiance measurements across the 9 to 12 micron "window" region**
  - **Surface skin temperature**
  - **Cloud top ice/water phase (aircraft icing)**
  - **Planetary Boundary Layer (PBL) profile measurements**
  - **Detection of dust aerosol concentration and layer top altitude**
- **Atmospheric ozone (9.6µm O_3 band radiance spectrum)**

Optimal Estimation (OE) Theory Retrieval and Information Content Definitions

Rodgers, C.D., Inverse methods for atmospheric sounding: Theory and Practice, World scientific, 2000

Radiative transfer equation	$\mathbf{y} = \mathbf{K}\mathbf{x} + \varepsilon$	**y**=radiance vector (mx1), K= weighting function matrix (mxn), x=atmospheric state vector (1xn), ε=measurement error vector (mx1)
Optimal estimation solution	$\hat{\mathbf{x}} = \mathbf{x}_{ap} + \hat{\mathbf{S}}\mathbf{K}^T\mathbf{S}_\varepsilon^{-1}(\mathbf{y} - \mathbf{K}\mathbf{x}_{ap})$	**x**=retrieved state estimate, $\mathbf{x}_{ap}$=a priori vector, $\hat{\mathbf{S}}$= retrieval error covariance matrix, $\mathbf{S}_\varepsilon$= measurement error covariance matrix,
Retrieval error covariance matrix	$\hat{\mathbf{S}} = (\mathbf{K}^T\mathbf{S}_\varepsilon^{-1}\mathbf{K} + \mathbf{S}_{ap}^{-1})^{-1}$	Retrieval error covariance matrix is an nxn matrix in which the square root of the diagonal is the standard deviation of the error
Gain (contribution) function matrix	$\mathbf{G} = \hat{\mathbf{S}}\mathbf{K}^T\mathbf{S}_\varepsilon^{-1} = \frac{\partial\hat{\mathbf{x}}}{\partial\mathbf{y}}$	Columns of **G** reflect how each measurement contributes to the retrieval
Averaging kernel matrix	$\mathbf{A} = \mathbf{G}\mathbf{K} = \frac{\partial\hat{\mathbf{x}}}{\partial\mathbf{x}}$	Rows of **A** are the retrieval vertical resolution functions which reflect how the true state is vertically resolved by the retrieved state
Degrees of freedom for signal	$d_s = tr(\mathbf{A})$	How many independent pieces of information can be measured
Signal-to-noise matrix	$\tilde{\mathbf{K}} = \mathbf{S}_\varepsilon^{-\frac{1}{2}}\mathbf{K}\mathbf{S}_{ap}^{\frac{1}{2}}$	Describes the relative influence of the uncertainties to the retrieval
Shannon information content	$H = \frac{1}{2}\log_2\left\|\tilde{\mathbf{K}}\tilde{\mathbf{K}}^T + \mathbf{I}\right\|$	Describes the information gained by making a measurement

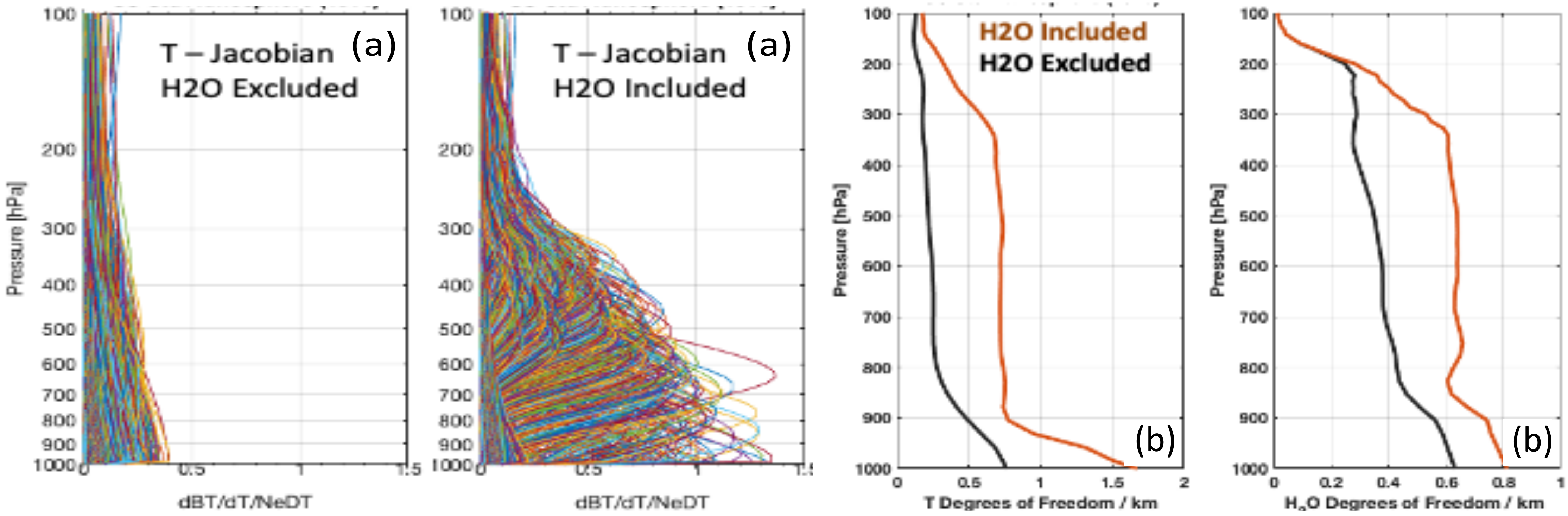
Implementation of OE Theory for Instrument Spectral Specifications

- The Rodger's information analysis tool in its linear form applies to radiance information content of atmospheric profiles if they are known 'a priori', rather than to be measured.
- Two important implementation procedures are necessary for using the linear form of OE theory for instrument specifications since the atmospheric profiles cannot be assumed to be known prior to their measurement.
  - A dry atmospheric condition must be assumed to exclude erroneous water vapor radiance contributions to the Temperature profile Jacobians.
  - The water vapor density error dependence on temperature retrieval error must be included for calculating water vapor profile accuracy and information content. This is accomplished by first computing the OE estimates of radiance related temperature and water vapor profile error covariances and then adding the water vapor density error covariance matrix determined from temperature profile error covariance using the ideal gas law for moist air.

MW+SW Temperature Jacobians Assuming H_2O is Known Vs. H_2O Unknown

(a) Atmospheric temperature profile weighting functions

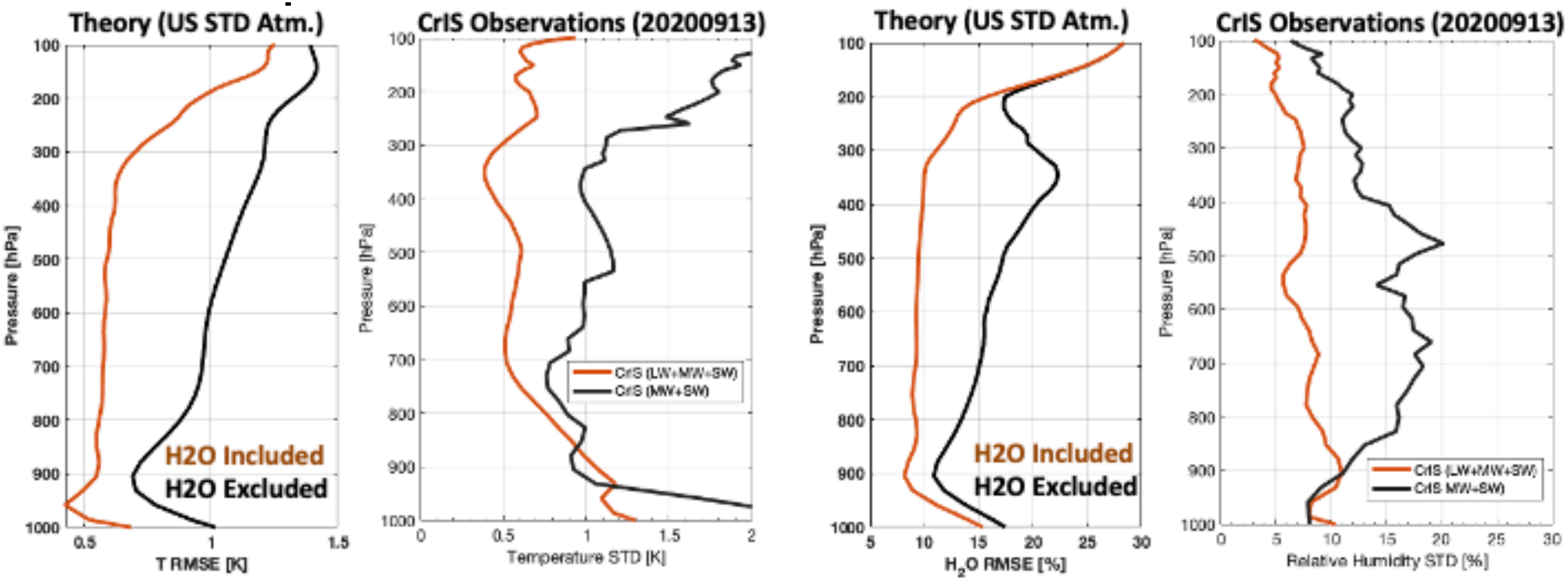
(b) T & H_2O Degrees of Freedom (/km) for mid-wave plus short-wave spectrometer estimated by “including” and “excluding” H_2O Temperature Jacobians in OE estimation.



Including H_2O Channel T- Profile Jacobians Greatly Overestimates the T & H_2O Number of Degrees of Freedom per Km (i.e., Inverse Vertical Resolution) of Profile Retrieval

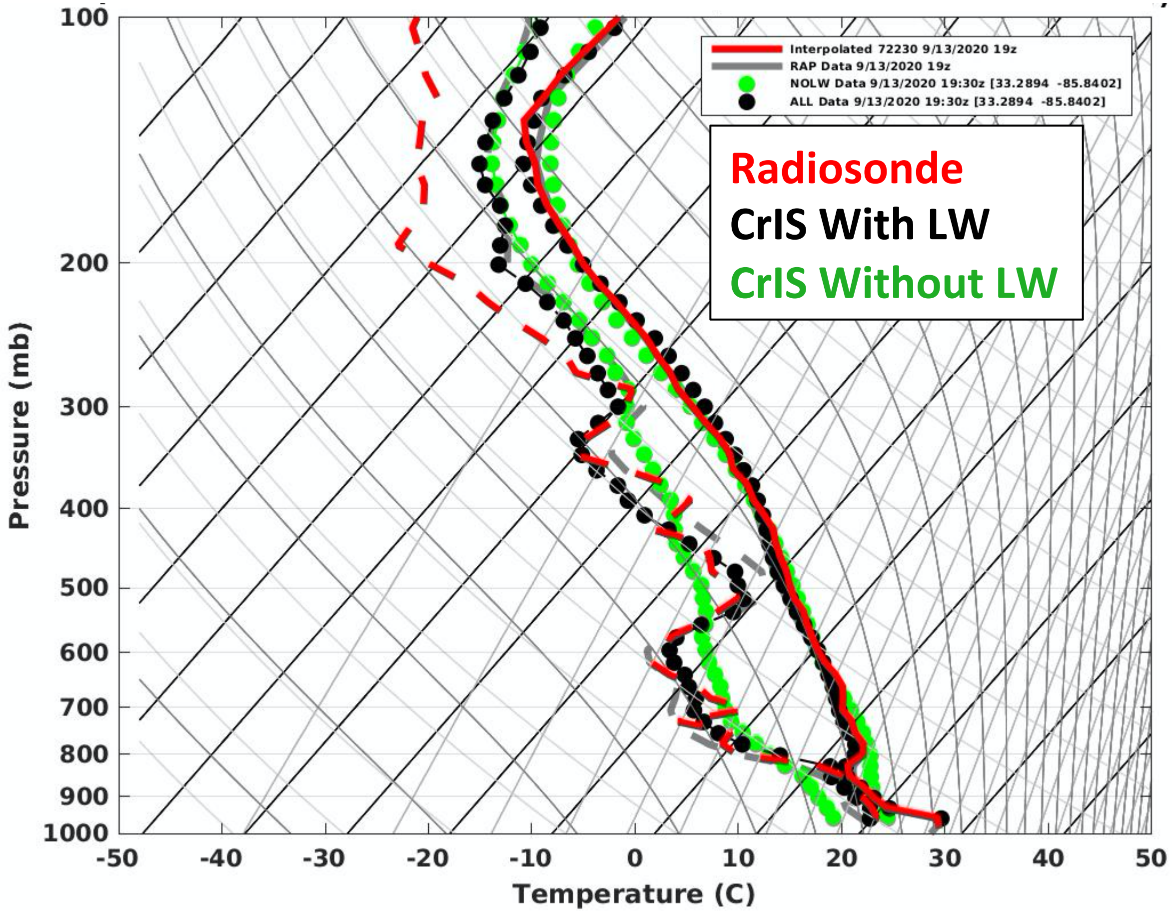
MW + SW Theoretical Vs. Empirical Results

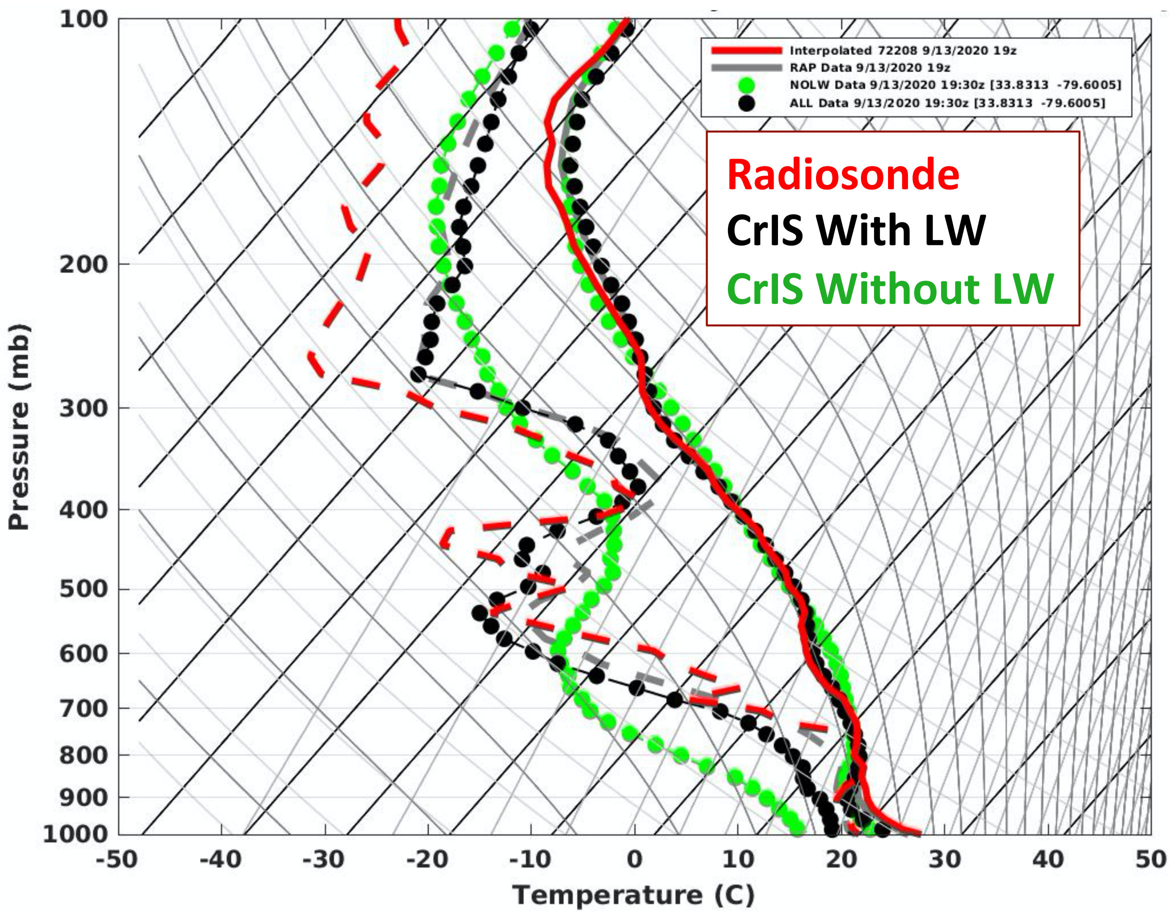
- **The errors in the theoretical estimations of a MW+SW instrument capability by including H_2O temperature profile Jacobians are confirmed by comparing actual CrIS profile retrievals for September 13, 2020 with analyses of radiosonde**



Theoretical Estimation of a MW+SW Instrument Capability is Confirmed By CrIS Profile Retrievals

Radiosonde Comparisons - With LW Vs. Without LW Band





CrIS Vs. Radiosonde Profile Comparisons Illustrate Decreased Temperature and Water Vapor Profile Vertical Resolution Resulting From the Exclusion of Longwave Band Radiance Observations

CrIS Band Information Content and degrees of Freedom

- Shannon information content and degrees of freedom (i.e., number of independent pieces of information)
  - Considered 1x, 2X, and 4x CrIS NEdN noise performance.
- Figure on the right shows results
  - Green cases indicate best band combinations and noise levels for NWP profile assimilation.
  - Red cases indicate poorest band combinations and noise levels for NWP profile assimilation.

CrIS Information Content

	Temperature			Humidity		
	X 1	X 2	X4	X 1	X 2	X4
All	34.4	25.4	18	32	24.6	18.4
LW + MW	33.6	24.8	17.6	32	24.5	18.4
MW + SW	19.7	14	9.6	29.6	22.4	16.5
LW	32.4	23.7	16.7	14.5	11.4	8.7
MW	14.7	11	7.9	29.1	22	16.7
SW	13.9	9	5.5	4.2	2.8	1.8
NCEP100	22.3	16.2	11.1	14.9	11	7.6
NCEP431	26.8	19.7	13.9	22	16.7	12.2

CrIS Noise Factor

CrIS Degrees of Freedom

	Temperature			Humidity		
	X 1	X 2	X4	X 1	X 2	X4
All	10	8.1	6.5	6.5	5.1	4.1
LW + MW	9.8	7.9	6.4	6.4	5.1	4
MW + SW	6.3	5	3.9	5.5	4.3	3.4
LW	9.6	7.8	6.3	2.8	2.4	2
MW	4.1	3.4	2.8	5.2	4.1	3.3
SW	5.5	4.2	3	1.3	1	0.8
NCEP100	6.8	5.6	4.5	3.2	2.7	2.3
NCEP431	7.9	6.4	5.2	4.5	3.4	3

CrIS Noise Factor

Theoretical studies show that the longwave plus midwave band combination is most important for providing profile information for numerical weather forecasting

Conclusions

- The results show that when the Rodger's optimal estimation information theory is applied properly for specifying the spectral requirements for a new satellite sounding instrument, the sounding capabilities of a MW+SW band instrument are greatly inferior to satellite instruments that include the LW band.
- This theoretical result is shown to be consistent empirical results obtained from current satellite hyperspectral observations.
- It is shown that failure to apply Rodger's information content theory in its linear form properly, for the purpose of specifying a future infrared sounding instrument's measurement requirement, can lead to the misguided belief that the traditional LW-band is no longer needed for NWP applications of satellite sounding radiance data.

W. L. Smith *et al.*, "Hyperspectral Satellite Radiance Atmospheric Profile Information Content and Its Dependence on Spectrometer Technology," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 14, pp. 4720-4736, 2021, doi: 10.1109/JSTARS.2021.3073482.