Information content of the Cross-trace Infrared Sounder (CrIS) instrument and recent data denial experiments relevant to operational use of sounder data.

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Motivation for this work

- Major investments have been made to provide SW-IR (2000-2800 cm^{-1}, 3.5-5.0 μm) observations
  - We have had hyperspectral SW-IR in-orbit since 2002
  - We have successfully used the SW-IR in retrieval applications
  - My colleagues have tested the SW-IR in data assimilation
  - **See Erin Jones, 9.01: Assimilation of CrIS SW in NOAA GDAS**
- From Mar. 26, 2019 to June 25, 2019 we lost the S-NPP MW-IR
  - We developed NUCAPS LW+SW systems to analyzed the relative information content of the mid-wave band (not shown here today).
- Also, comparing CrIS information with AIRS and IASI?
  - Can we improve the temporal continuity of multi-satellite observations in weather and climate applications?
  - **See Nadia Smith, 10.03: Continuity in Sounding Products**

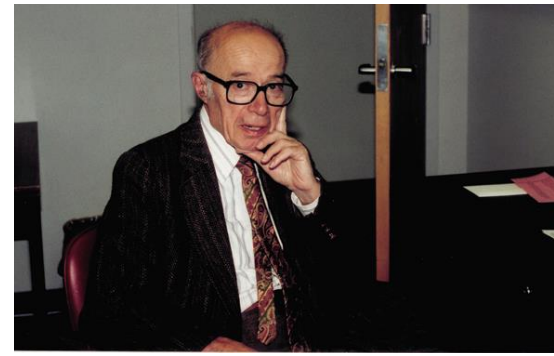
Project initiated to explore SW-IR options for operational CrIS & future instruments

	Size (cm)	Mass (kg)	Power (W)
AIRS	116 x 159 x 95	177	200
IASI	120 x 110 x 130	236	210
CrIS	80 x 47 x 66	147	106
SW-IR SmallSats	6U (10 x 20 x 30) Are plausible	4	29

- Low power {and lower noise} detectors can drive the entire design of instruments *and satellites.*
- Low mass, power, and size will have significant implications for schedule and the cost of launch of future instruments.

1980's began the launch of microwave and infrared sounders for weather forecasting

- 1977 Lewis Kaplan published idea that SW-IR (2000-2800 cm^{-1}) has unique sounding properties.
  - **See Kaplan, Chahine, Susskind Searl 1977 Applied Optics v.16 p.322-324.**



- 1989 Dave Wark wrotes the NOAA specifications for a hyperspectral infrared sounder

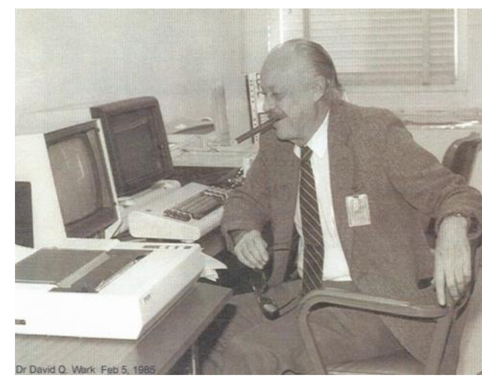


Table 2. Numbers of channels required by NOAA in the sixteen spectral intervals of the AIRS instrument. (DS) indicates double sampling.

Band	Spectral range (cm^{-1})	Spectral range (Lm)	No. of channels Available	No. of channels Required
	Long-Wave Spectrometer			
1.	595.4- 686.6	14.56-16.79 (DS)	342	132
2.	686.2- 777.4	12.86-14.57 (DS)	299	298
3.	776.8- 868.6	11.51-12.87 (DS)	268	94
4.	867.8- 959.4	10.42-11.52	120	23
5.	958.5-1050.1	9.52-10.43	109	37
6.	1050.1-1141.2	8.76- 9.52	99	24
7.	1139.9-1231.2	8.12- 8.77	92	29
8.	1231.2-1322.4	7.56- 8.12	85	32
	Short-Wave Spectrometer			
1.	1322.4-1526.3	6.55- 7.56	172	172
2.	1524.0-1729.6	5.78- 6.56	151	150
3.	1726.6-1930.0	5.18- 5.79	133	132
4.	1930.0-2131.6	4.69- 5.18	119	78
5.	2131.6-2335.8	4.28- 4.69	109	43
6.	2330.4-2537.4	3.94- 4.29 (DS)	204	63
7.	2537.4-2739.0	3.65- 3.94	91	52
8.	2739.0-2940.4	3.40- 3.65	85	42
	"Visible"		Not specified	1

Makes use of Kaplan's idea of using SWIR CO_2 band

Pro's and con's of SW vs. LW-IR

	LW-IR	SW-IR
Interfering gases in CO_2 bands	**H2O, O3, HNO3**	**None**
Use of N_2O for T(p) sounding	**No**	**YES**
Vertical sounding range	**1 hPa to surface**	20 hPa to surface
Influence of solar radiation	**negligible**	**Must handle non-LTE and surface reflection**
Planck function linearity (sensitivity to thermal structure)	1-2%/K Not sensitive to T	**~3-4%/K at 280 K** **~4-6%/K at 200 K**
Instrument Noise sensitivity to scene temperature	**NEΔT is constant (not really true!!)**	**Noise is strong function of scene T**
FWHM of T(p) Kernel Fnct's	**4 km**	**2 km**
Future instruments: Detector technology and optics.	**Higher Power** **Requires Cold T's**	**More COTS options**

NOTE: All of the issues for the SWIR have been solved by the AIRS science team & implemented in NUCAPS AIRS, IASI, and CrIS systems.

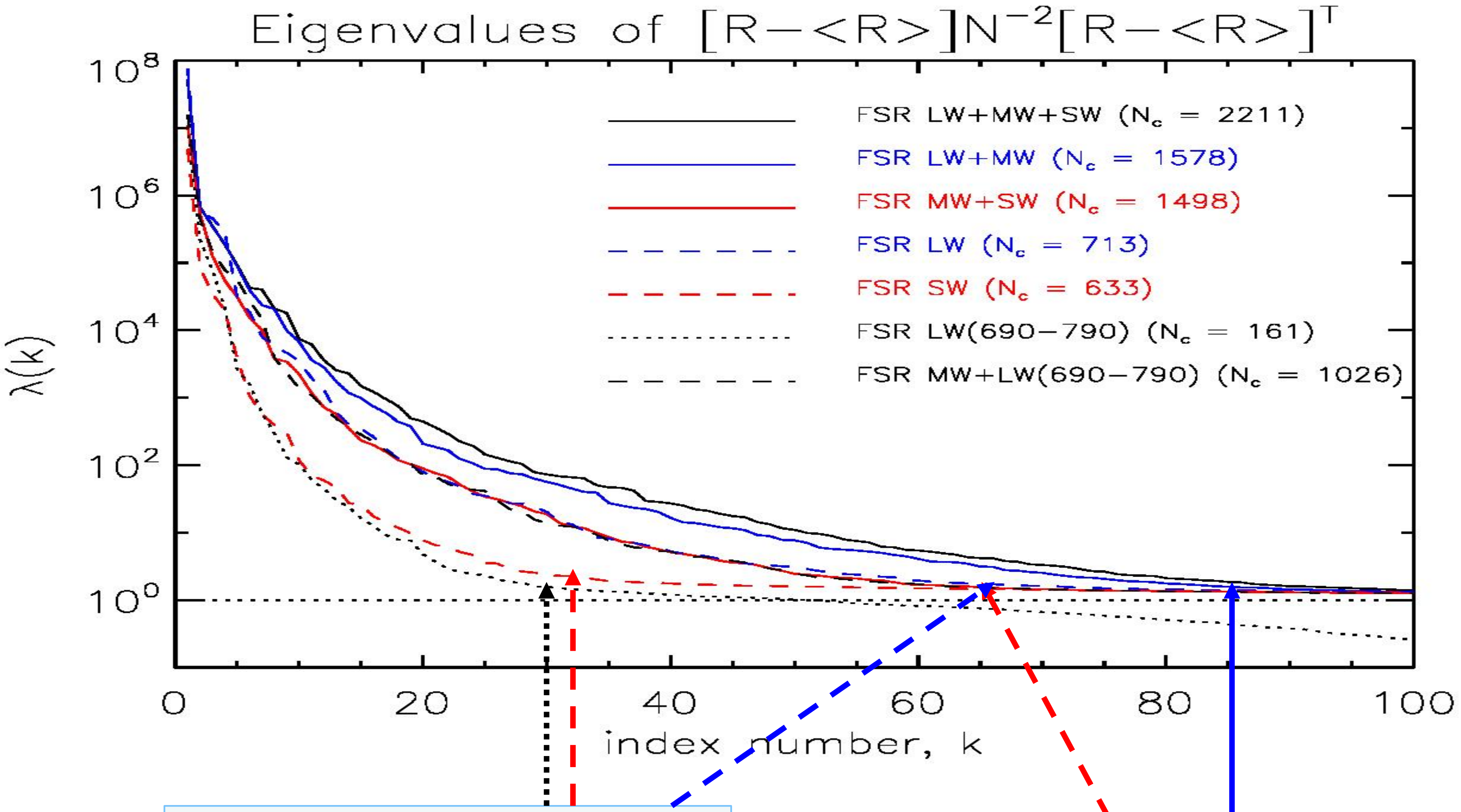
Quick look Information Content (IC) Analysis of CrIS measurements

- Used Singular Value Decomposition (SVD or EOF) of CrIS NSR and FSR observed radiances for various band configurations
  - Did this in S/N space (i.e., radiance/NEΔN)
  - Number of significant eigenvalues is the degrees of freedom (d.o.f.) or IC of the radiances:

    $\lambda(k,k) = E(k,n)*\check{R}\check{R}^T(n,n)*E^T(n,k)$

    where, $\check{R} \equiv (R(n)-\langle R\rangle(n))/NE\Delta N(n)$
- For S-NPP {and NOAA-20} FSR used 4 focus days for training of eigenvectors
  - 6/15/2017, 9/14/2018, 12/15/2018, 2/25/2019

Information content in the CrIS Instrument bands



~35 dof for SW (red dash)
~65 dof for LW (blue dashed)
~30 dof for LW (690-790, black dots)
~65 dof for MW+LW (690-790, black dash)

~65 dof for MW+SW (red solid)
~85 dof for LW+MW (blue solid)
~100 dof for LW+MW+SW (black)

Summary of Degrees of Freedom

Degrees of Freedom (d.o.f.) of signal is where signal approaches the noise floor ($\lambda \approx 1$) in the previous figure

System	Line on plot	# of channels	d.o.f.
LW+MW+SW	Solid Black	2211	100
LW+MW	Solid Blue	1578	85
MW+SW	Solid Red	1498	65
LW-only	Dashed Blue	713	65
MW-only	(Backup Slides)	865	60
SW-only	Dashed Red	633	35
LW (690 to 790 cm-1)	Dotted Black	161	30
MW + LW (690-790 cm-1)	Dashed Black	1026	65

D.o.f. does not inform us of where the information content is. For example, the MW band has high information content relevant to T(p) if water vapor is known, but in practical terms the LW & SW has better T(p) sensitivity (T(CO2) is spectrally more pure) and MW has better q(p) sensitivity once T(p) is known.

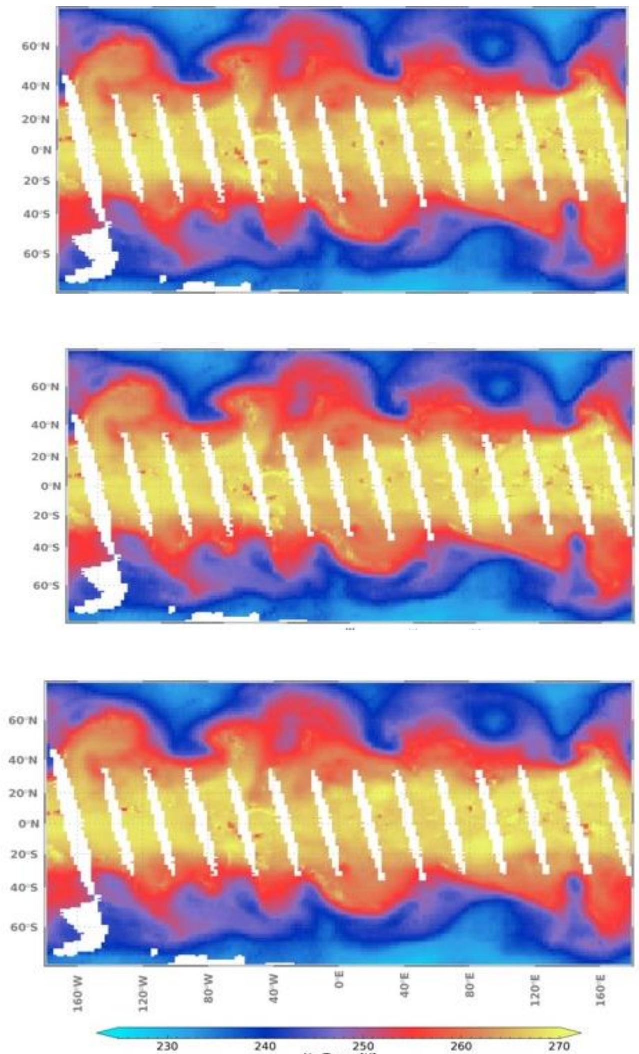
Things to notice about d.o.f.

- SW adds a tiny amount of information to LW+MW
  - LW+MW has ~15 dof less than LW+MW+SW
  - Implies SW and LW has a lot of overlapping information
- MW+SW has ~15 dof less than LW+MW
  - *These results suggest that the MW+SW will be slightly degraded w.r.t. to MW + LW*
- LW has ≈2x more dof than SW
  - LW has additional ozone and water vapor signals, stratospheric and mesospheric T(p) signals
  - *The T(p) sounding of the LW is in 690-790 cm^{-1} region*
  - *LW(690-70) has ≈ same IC as SW-only*
- *MW+SW, LW-only, and MW+LW(690-790) all have ~65 d.o.f.*
  - *Implies that MW+SW and MW+LW in data assimilation could potentially have similar impact*

Use NUCAPS to evaluate impact of SW vs. LW in statistical/physical retrieval system.

- NOAA-Unique Combined Atmospheric Processing System (NUCAPS) is the operational retrieval at NOAA
- Created regressions from 4 focus days of ATMS and CrIS full spectral resolution (FSR) observations
  - All regressions trained with subset of scansets (every 15th) from all granules on 6/15/2017, 9/14/2018, 12/15/2018, 2/25/2019.
  - T(p) and q(p) “truth” from co-located ECMWF
- Ran NUCAPS for a full independent focus day: Oct. 30, 2017
  - **NUCAPS system uses ATMS information (both in regression and physical T/q steps).**
- The physical retrieval was modified to remove all long-wave CrIS data (MW+**SW**) run
  - Required turning off the CO_2, ozone,& nitric acid retrieval.
- Also removed SW-IR (**LW**+MW) for comparison
  - Required turning off the carbon monoxide retrieval.

Example T/q products from the 3 runs

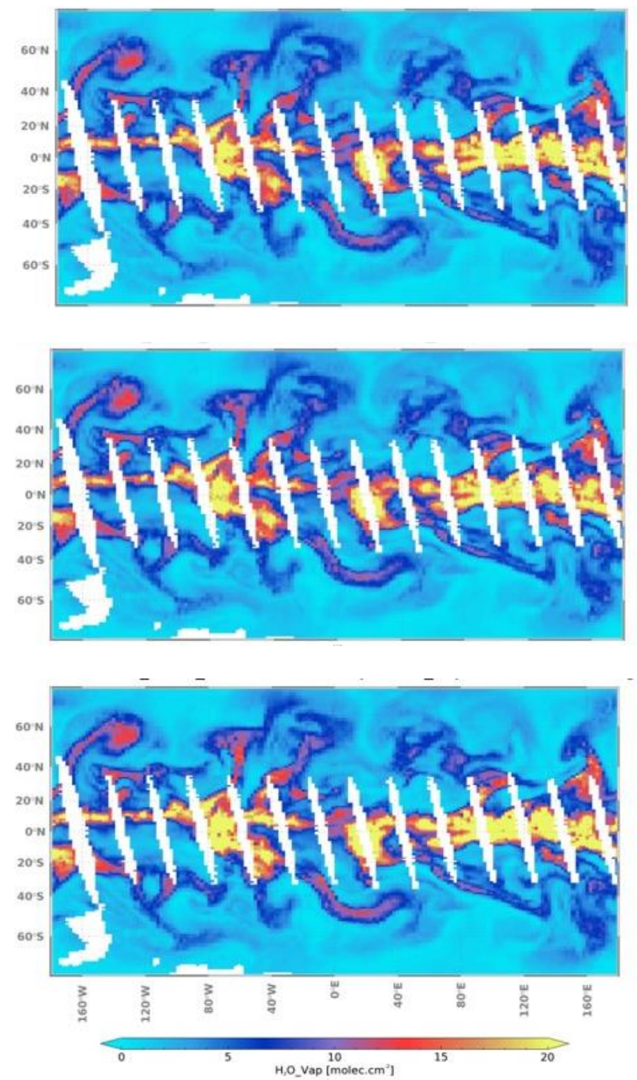


T(500 hPa)

LW+MW**+SW**
(baseline)

LW+MW
(i.e., no SW)

MW**+SW**
(i.e., no LW)



H_2O(500 hPa)

Statistics: BIAS vs. ECMWF (NUCAPS retrieval with CrIS + ATMS)

Black: MW + **SW**

Blue: **LW**+MW

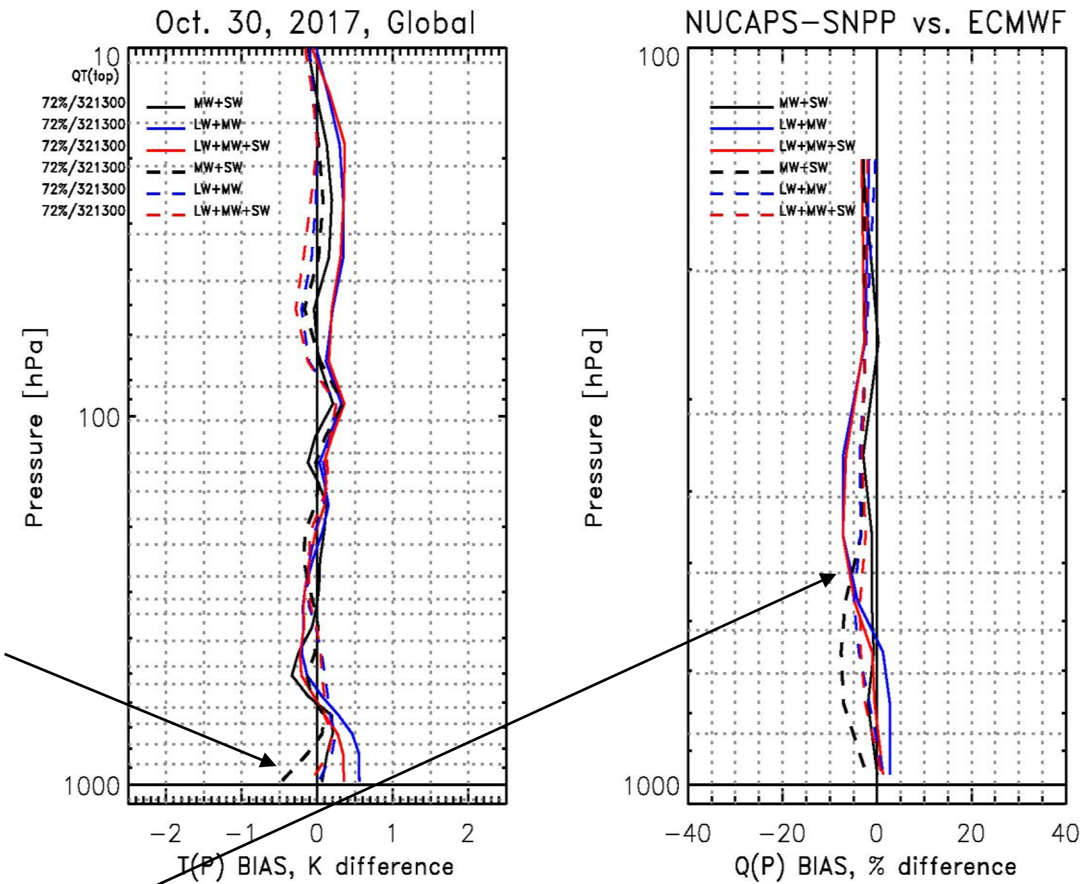
Red: LW+MW+SW

Results:

Very similar biases for the 3 systems

T(PBL) in MW+SW regression (dashed) has cold bias that is removed with physical.

The q(p) bias is improved in MW+SW run over the regression and other systems



Solid lines are physical retrieval
Dashed lines are the regression first guess
Statistics are on a common ensemble
(i.e., used LW+MW+SW QC)

Statistics: SDV vs. ECMWF (NUCAPS retrieval with CrIS + ATMS)

Black: MW + **SW**

Blue: **LW**+MW

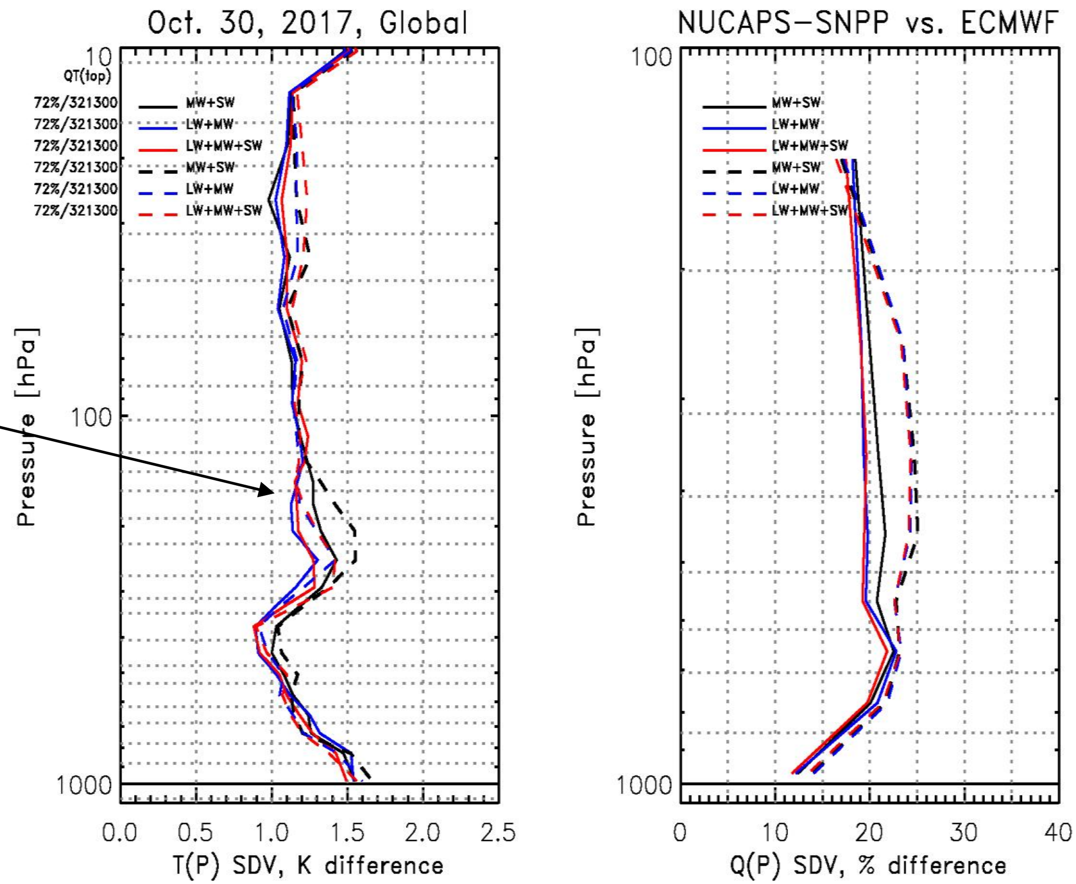
Red: LW+MW+SW

Results:

T(200 hPa) in MW+**SW** regression (dashed) has issue at 200 hPa (loss of CrIS) but Physical (solid) recovers most (caused by polar cases, not shown)

Overall the loss of LW has ~0.2K degradation in mid-trop T(p) and ~3% in q(p)

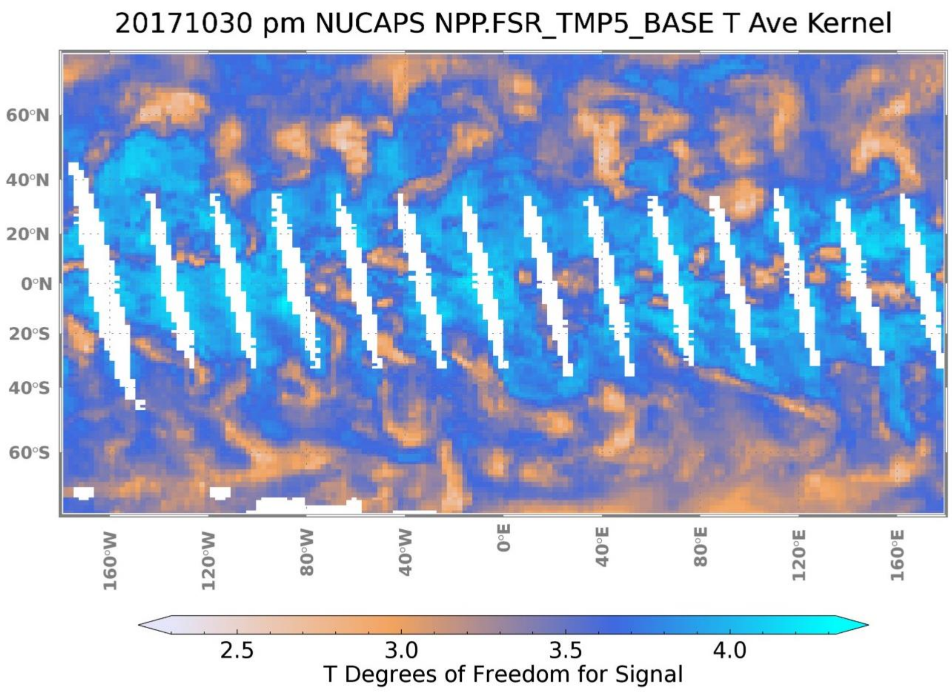
A few % degradation in moisture is due mostly to degradation in T(p)



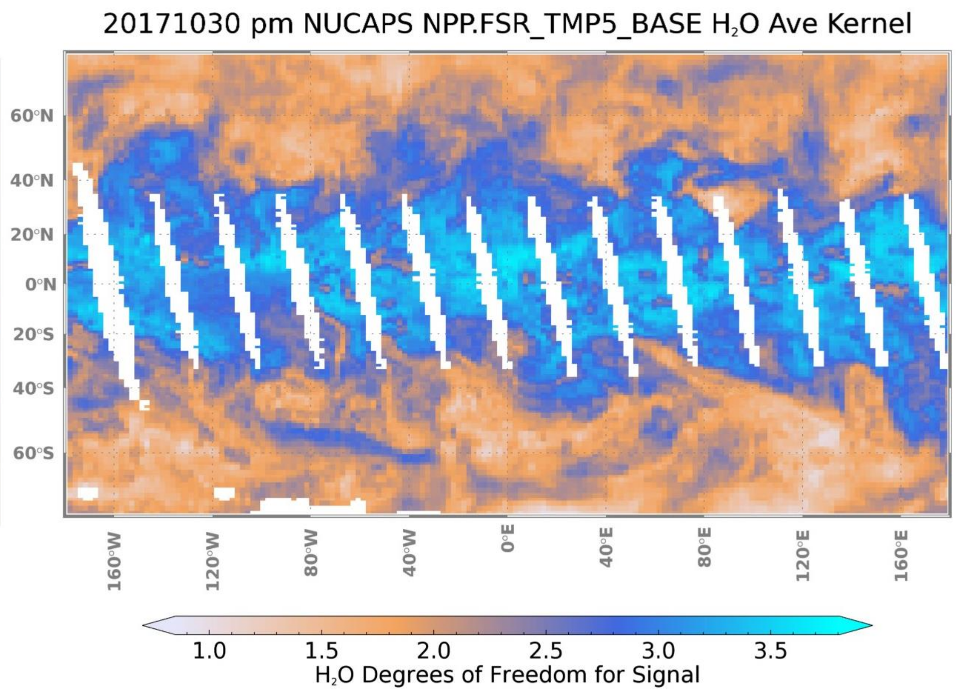
Solid lines are physical retrieval
Dashed lines are the regression first guess
Statistics are on a common ensemble
(i.e., used LW+MW+SW QC)

NUCAPS baseline run – LW+MW+SW
Degrees of Freedom for Signal (Daytime scenes)

Temperature DOF



H_2O Vapor DOF

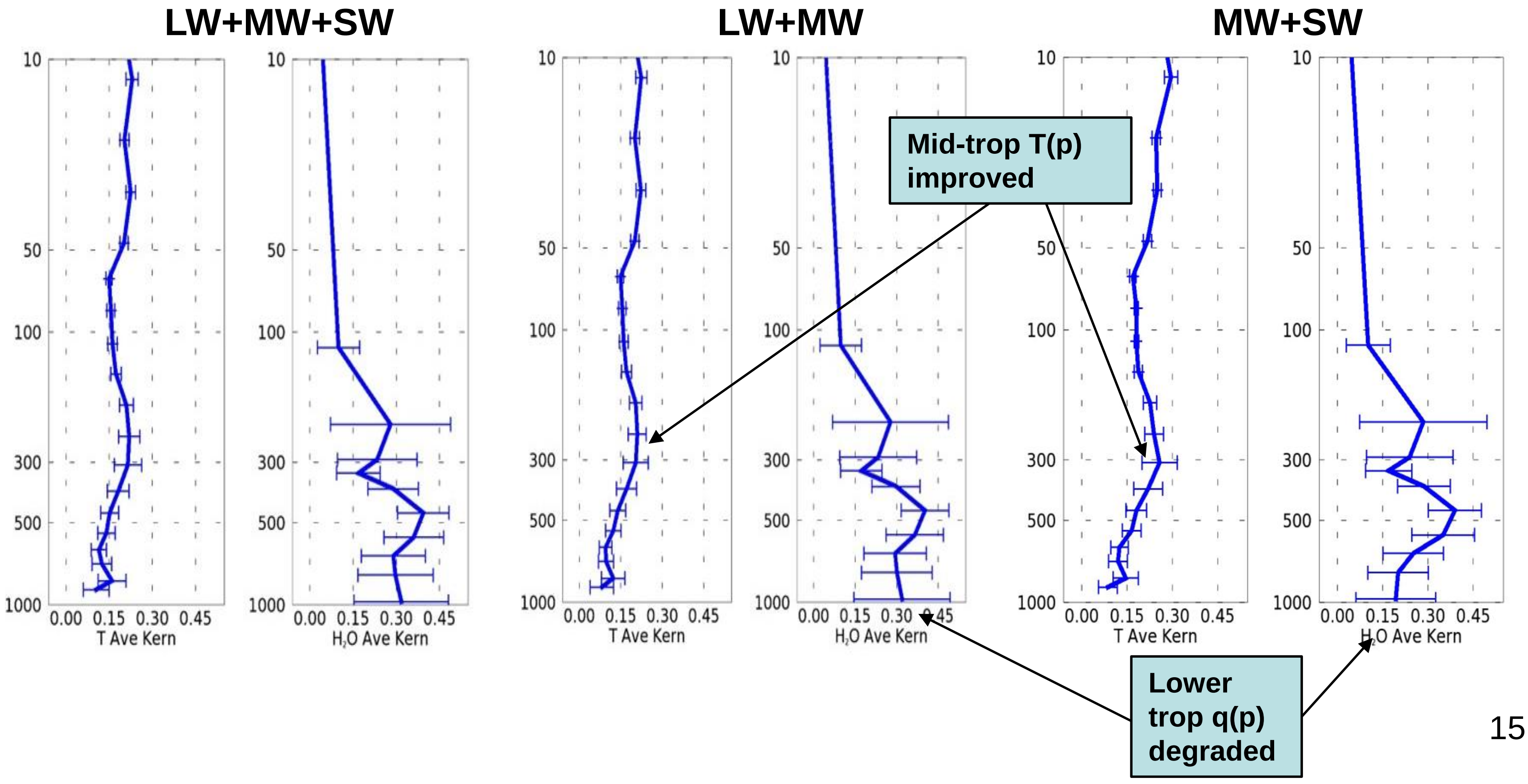


Degrees of freedom in the physical retrieval for daytime scenes

The 3 systems have very similar d.o.f. (not shown here).
NOTE: cloud clearing makes the d.o.f. spatially variable

Information Content Analysis of Physical Retrieval: Retrieval Averaging Kernels

- Here we show the mean and sdv of the global ensemble of averaging kernels for the 3 systems



Next Steps

- There results are very encouraging
  - SW-only cloud clearing works well.
    - This is 1st time this has been demonstrated
  - Need to optimize (and understand) the details of these new systems
    - LW+MW+SW has been optimized over the last 2 decades
    - This is literally the 1st run of MW+**SW** and **LW**+MW systems
- We are developing other configurations
  - We expect that the SW-only will degrade
    - ATMS will be the majority of q(p) information, but SW T(p) should dominate.
    - Probably will need to reject the intermediate difficulty scenes (yield ~ 50%)
  - Will run a version of MW+SW and SW-only without ATMS to highlight the loss of CrIS LW information
    - We expect this system to be significantly degraded
      - Especially in scenes that have evolving weather
      - But will allow better understanding of the LW and SW T(p) skill

QUESTIONS?

The NUCAPS system can be used to explore the value of new instrument concepts.

It is valuable (*and educational*) to test our understanding of the information content of the current space-borne systems by running alternate configurations.

The CrIS LW and SW bands appear to contain *mostly* redundant information

But there are small differences between LW and SW
- ability to detect trace gases
  LW: CO_2, O_3, HNO_3
  SW: CO
- LW has stratospheric signals

One of the biggest outcomes of this experiment might be communication

- Data assimilation and retrievals are the same math, but there are many differences, for example:
    - *Retrievals do not "inflate" the observation error.*
    - *Retrievals can explicitly add "geophysical errors."*
    - *Retrievals never convert observations to brightness temperature because observed radiances can go negative!*
- Instrument noise can be difficult to characterize exactly, but it is usually more linear in radiance space.
    - Retrievals handle spectral correlations, noise as a function of scene temperature, and other effects.
- **Having retrieval, instrument, and DA folks in the same room, *looking at details of how things are done*, matters!**

Simplified view of how things are done

Variable	Retrievals	Data Assimilation
Observations	Radiance, $R_{obs}(n)$	Brightness Temp., $\Theta_{obs}(n)$
Forward Model	SARTA $R_{calc}(n,X)$ X=state	CRTM $R_{calc}(n,X)$ X=state
Conversion	$G(n,X) \equiv \delta B_{\upsilon}/\delta T(n, \Theta_{calc}(n))$	$\Theta_x \equiv B_{\upsilon}^{-1}(n, R_x)$
Signal, S	$[R_{obs}(n) - R_{calc}(n,X)] / G(n,X)$ $\cong \Theta_{obs}(n) - \Theta_{calc}(n)$	$\Theta_{obs}(n) - \Theta_{calc}(n)$
Noise, N	$NE\Delta N(n) / G(n,X)$ $\cong NE\Delta T(n, X)$	$NE\Delta T(n)$
S/N	**$[\Theta_{obs}(n) - \Theta_{calc}(n)] /$ $NE\Delta T(n, X)$**	**$[\Theta_{obs}(n) - \Theta_{calc}(n)] /$ $NE\Delta T(n)$**

- **When minimizing the cost function, we are effectively minimizing the square of S/N**

- **Saying it is *radiance assimilation* is misleading, it really is *brightness temperature assimilation*.**

But nothing in life is free.

- The instrument NEΔT increases non-linearly for cold scene temperatures

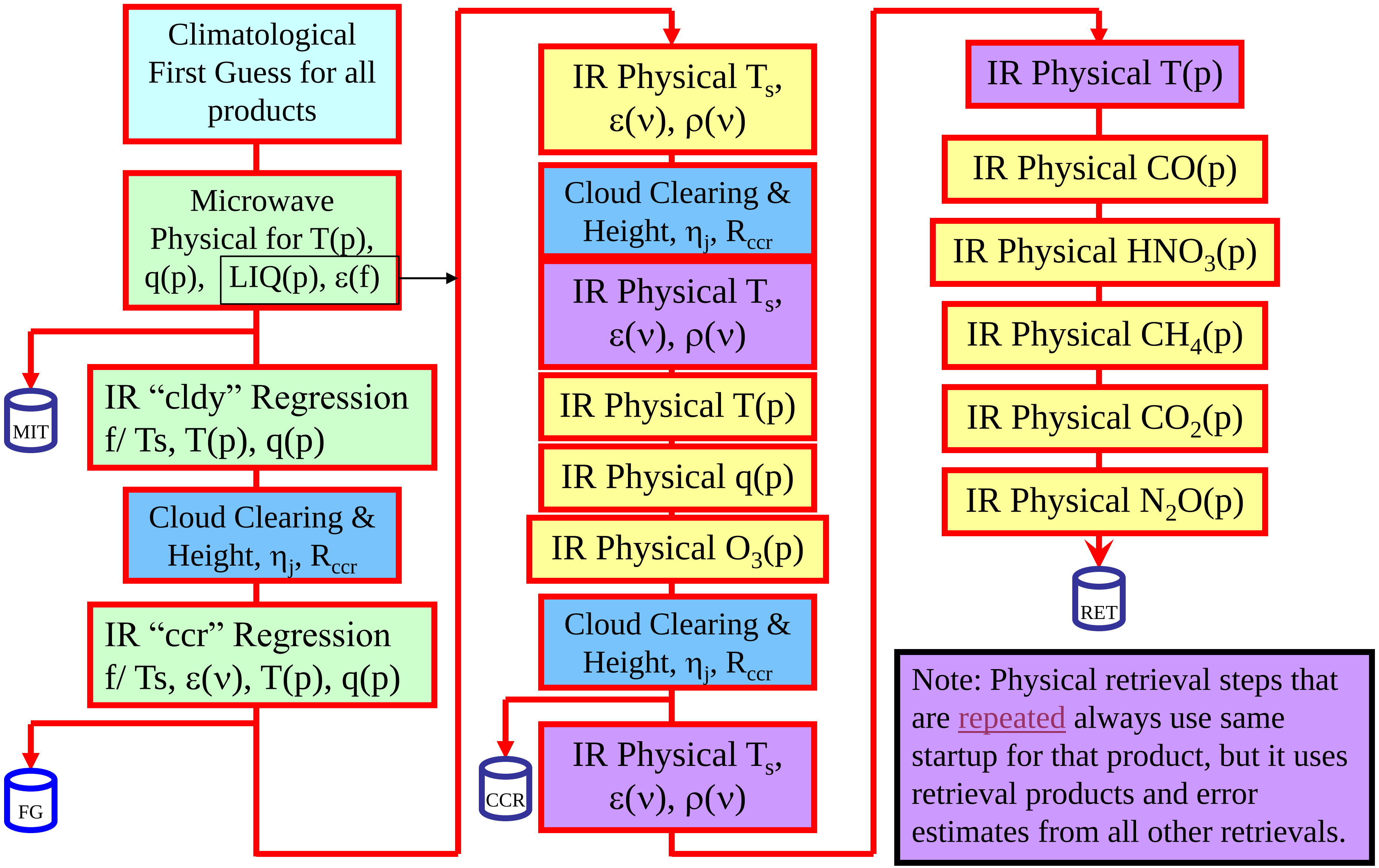
Scene BT	LW NEΔN	LW NEΔT	MW NEΔN	MW NEΔT	SW NEΔN	SW NEΔT
200 K	0.05	0.09	0.03	0.65	0.0046	9.7
250 K	0.05	0.04	0.03	0.12	0.0046	0.5
300 K	0.05	0.03	0.03	0.04	0.0046	0.07

- Note that for a constant NEΔN
  - LWIR NEΔT varies by 3x
  - MWIR NEΔT varies by 16x
  - SWIR NEΔT varies by 100x

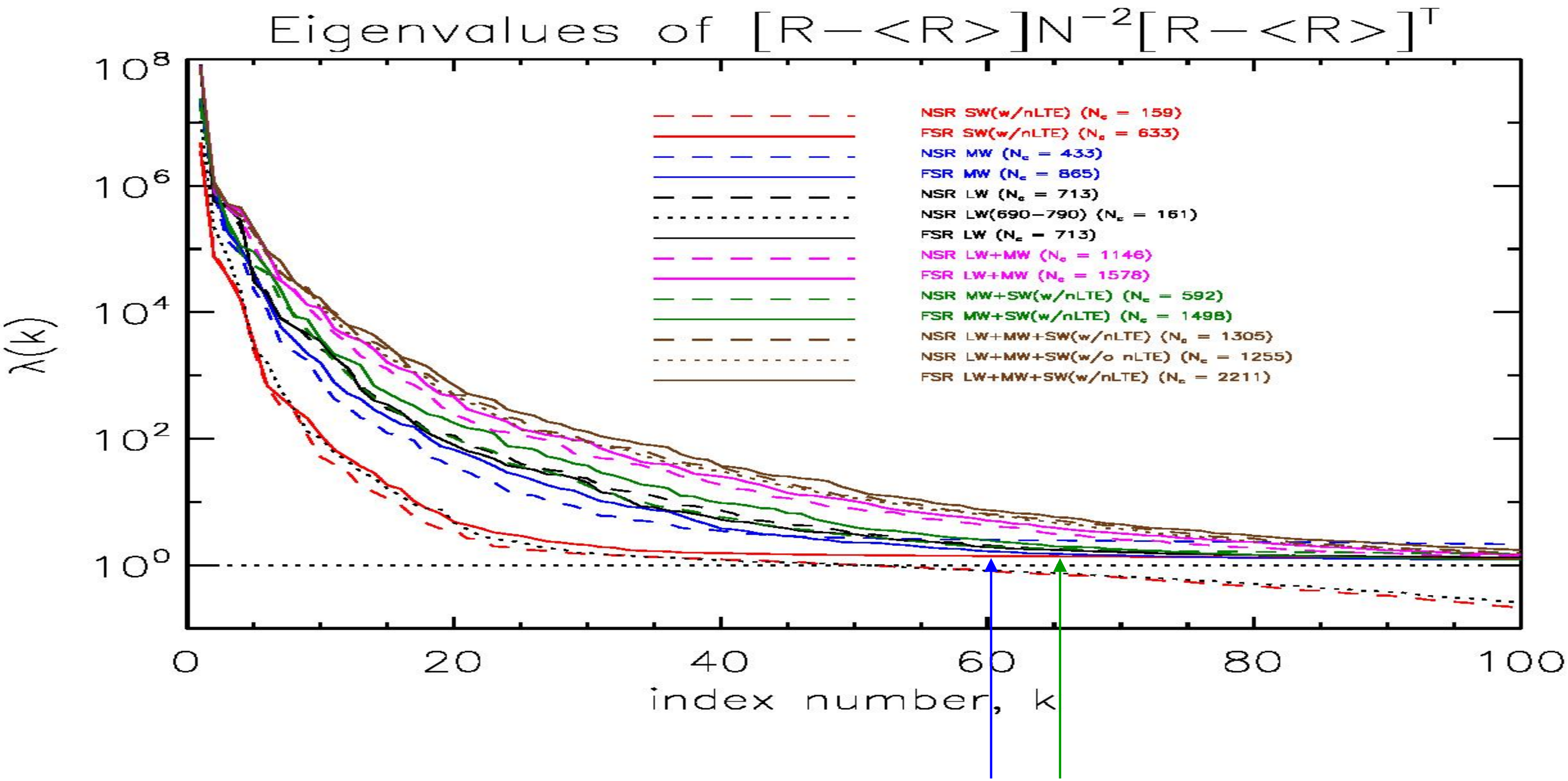
Note: This issue has recently been raised by Larrabee Strow & CrIS SDR Team

- ***In the SWIR it is critical to use radiance, not brightness temperature, as the operator***

Simplified Flow Diagram of the NUCAPS Algorithm (based on AIRS v5.9)

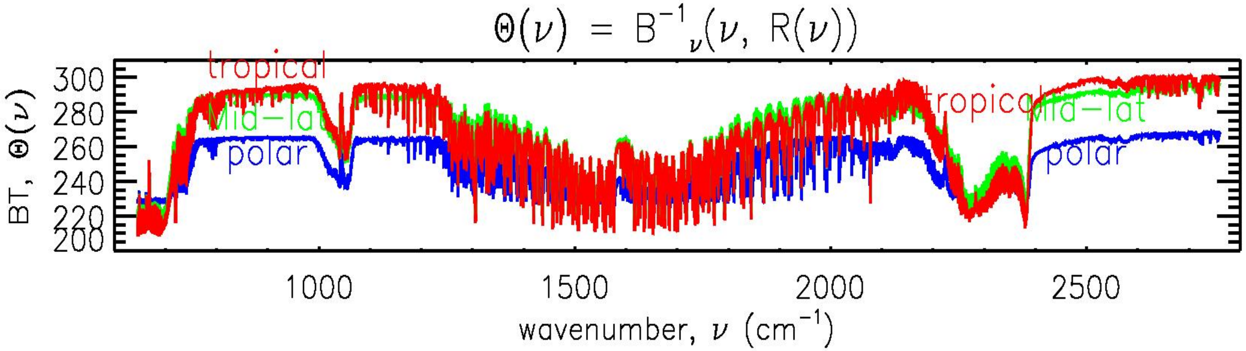


And for completeness – a plot with the CrIS MW band w.r.t. other bands

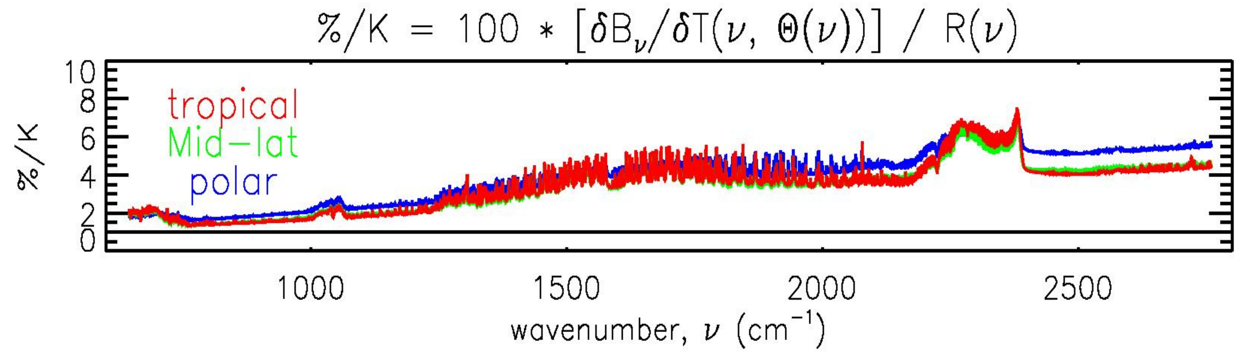


~60 d.o.f. for MW band
~65 d.o.f. for MW+SW band

The SWIR is ~3x more sensitive due to the non-linearity of Planck function

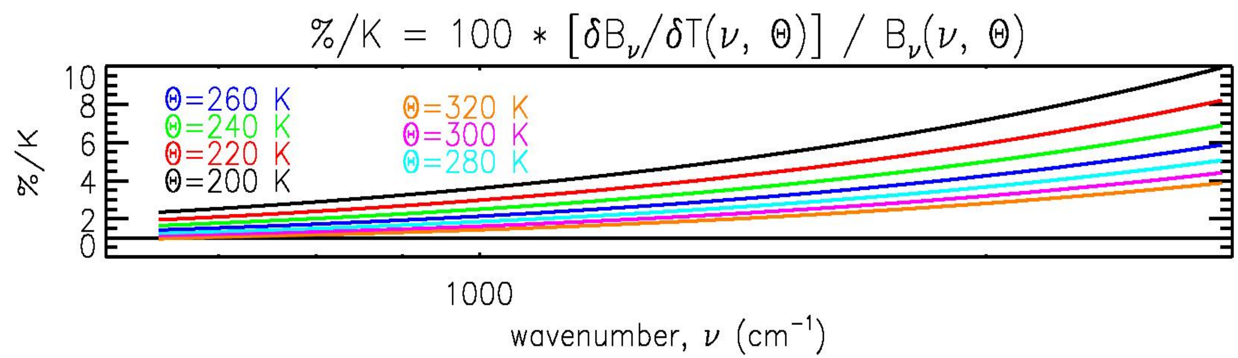


Example Brightness Temperature for Polar, Mid-Lat, and Tropical cases



% change in radiance for a 1 K change in T

SWIR changes 4-6%/K
LWIR changes 1-2 %/K



This is due to the derivative of the Planck function

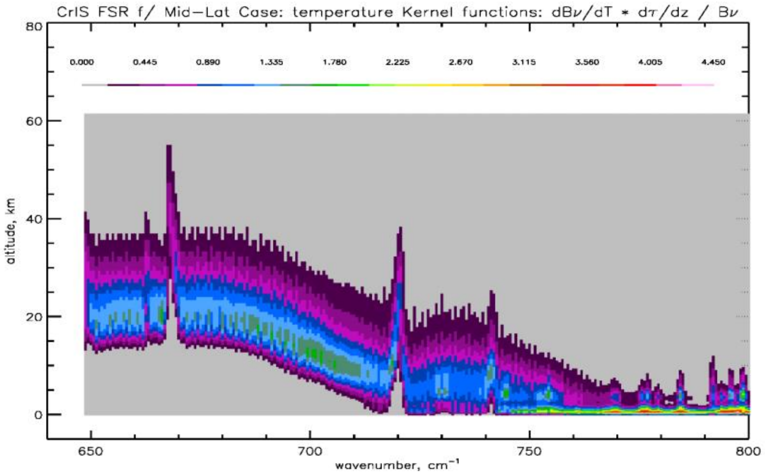
Cold scenes are significantly more sensitive.

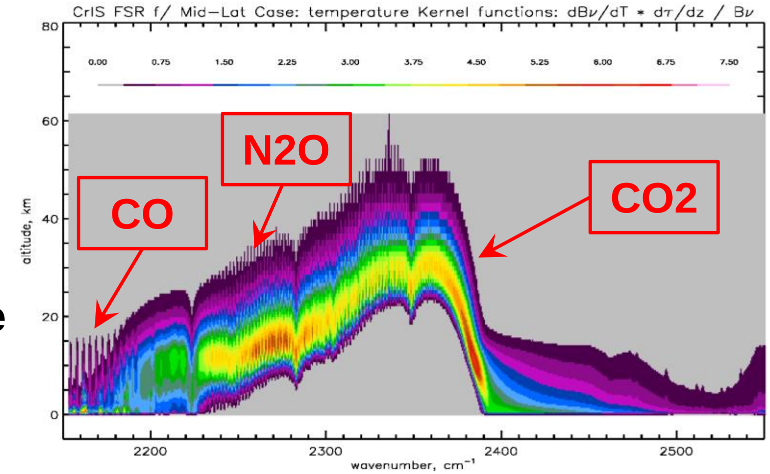
The CrIS FSR LWIR & SWIR Temperature (top) and Moisture Channel Kernel Functions

LWIR (15 μm, 650-800 cm^{-1})

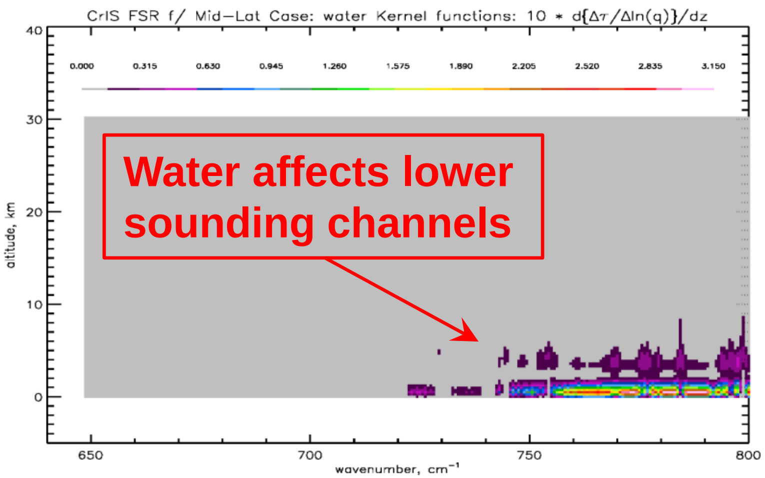
SWIR (4 μm, 2200-2700 cm^{-1})

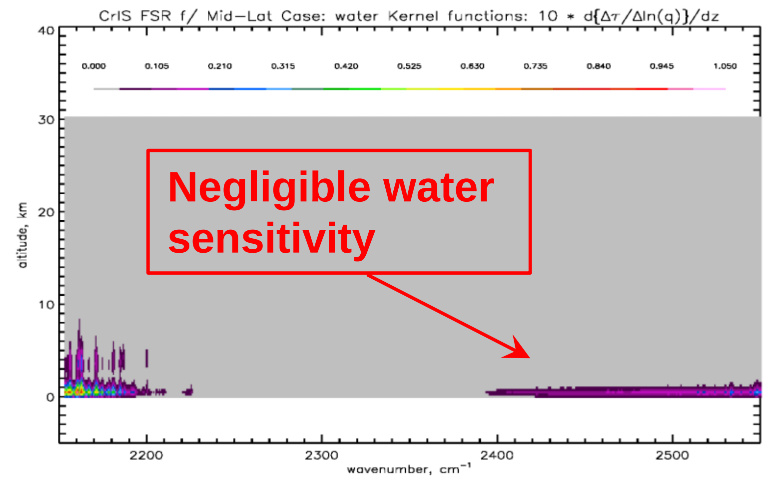
Sensitivity to Temperature





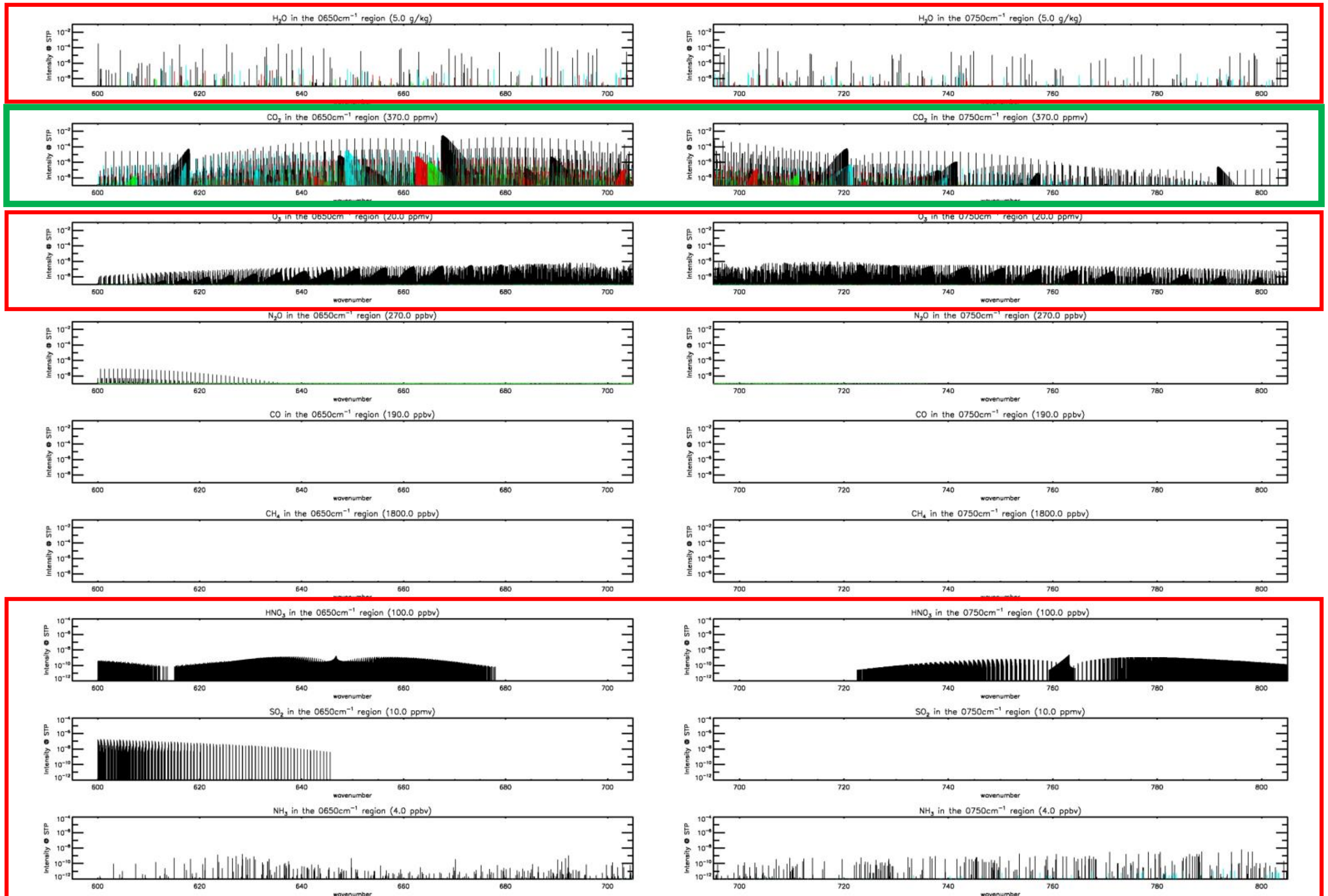
Sensitivity to Water





Purity of the spectrum: Absorption features in the 15 μm band

600 to 700 cm^{-1} | 700 to 800 cm^{-1}



H2O

CO2

O3

N2O

CO

CH4

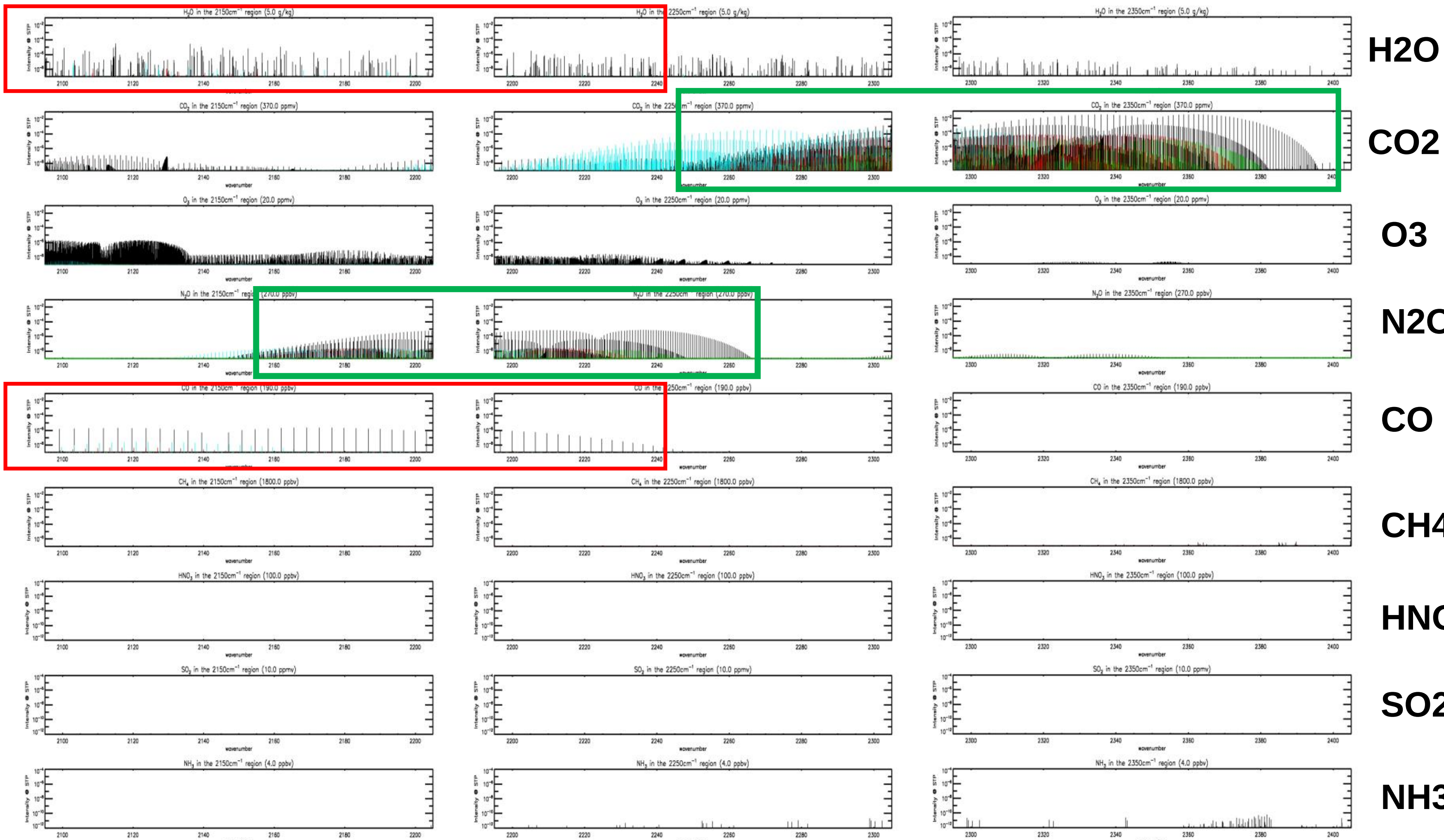
HNO3

SO2

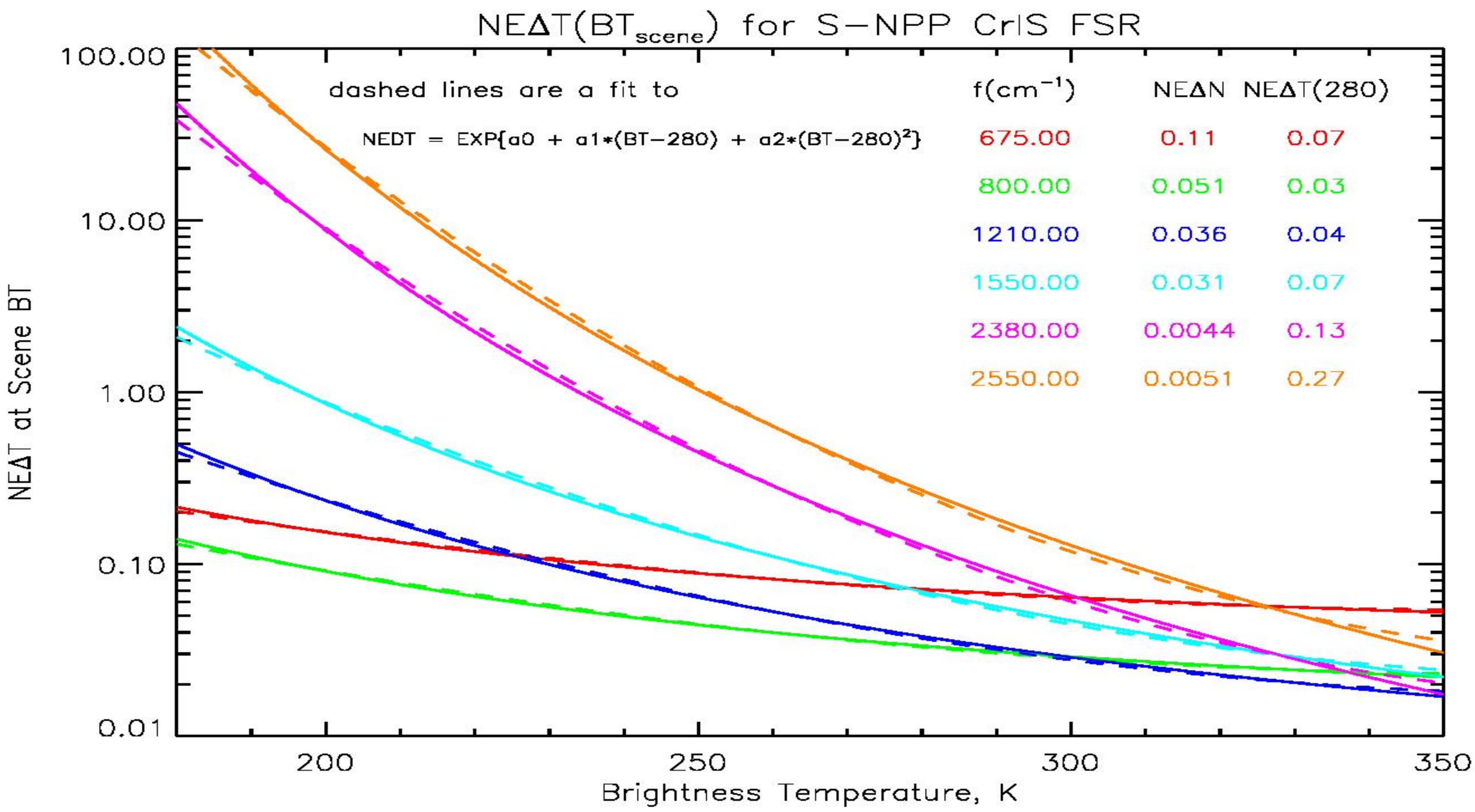
NH3

Purity of the spectrum: Absorption features in the 4 μm band

2100 to 2200 cm^{-1} | 2200 to 2300 cm^{-1} | 2300 to 2400 cm^{-1}

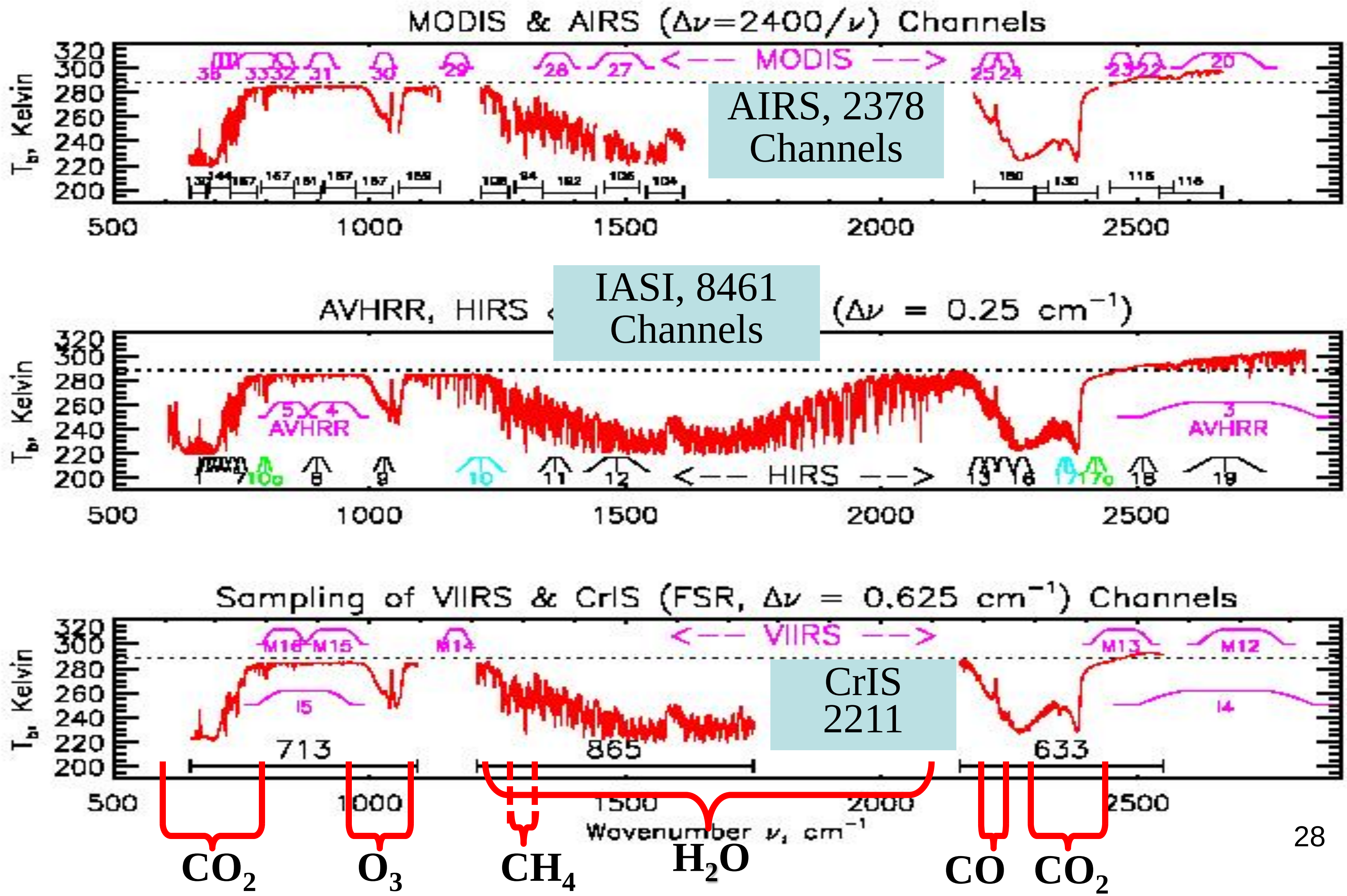


We will begin by installing a scene dependent NEΔT(BT)



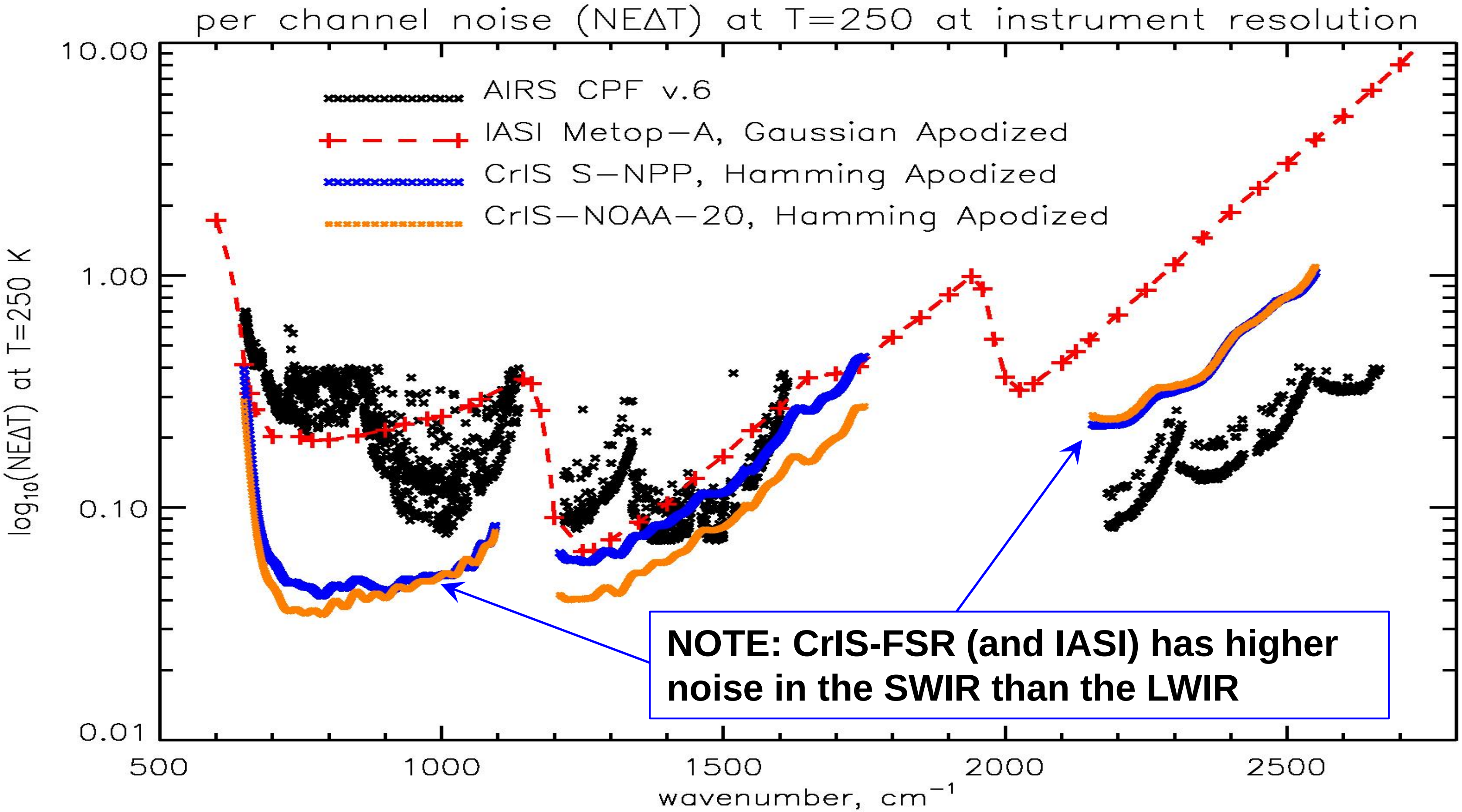
$$NE\Delta N / (\delta B_{\upsilon}/\delta T(BT)) \cong EXP\{a_0 + a_1 * BT + a_2 * BT^2\}$$

Spectral Coverage of Thermal Sounders & Imagers (Aqua, Metop-A,B,C, Suomi-NPP, NOAA-20+)



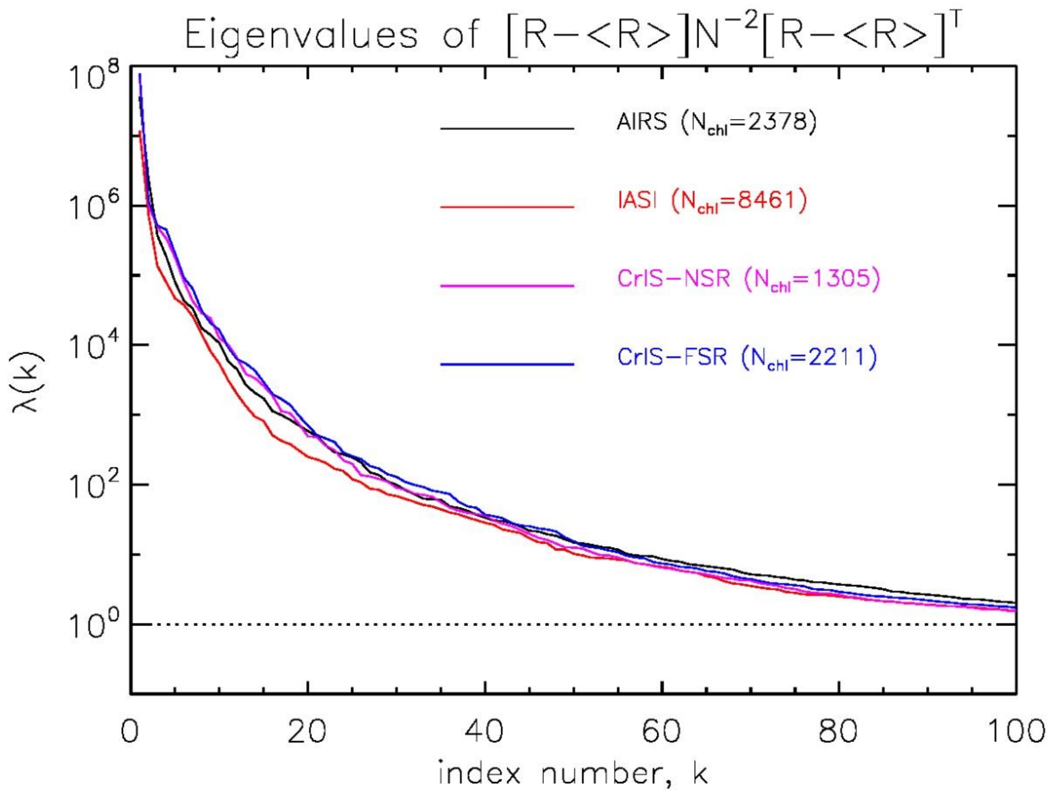
What is important for sounding is signal to noise

Per channel noise is shown as noise equivalent delta temperature (NEΔT) at a cold scene temperature (T=250 K)



The information content of modern sounding instruments is ***amazingly*** similar

- AIRS, IASI, and CrIS each have ~100 degrees of freedom
- Even though AIRS, IASI, and CrIS have different number of channels, ILS, noise, etc.



The 1st 100 significant eigenvectors of radiance covariance for a set of focus days normalized at λ(k=200)