Motivation for an experiment: can we utilize the CrIS short-wave infrared channels in data assimilation?

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Help from: Colby Francoeur, Nadia Smith, Rebekah Esmaili (all STC)

Topics for today

- I am discussing *the motivation behind* an experiment to assimilate the short-wave infrared radiances (SWIR ≅ 2000-2800 cm^{-1}) from the Cross-Track Infrared Sounder (CrIS)
  - **Topic #1: History of the SWIR instruments**
  - **Topic #2: The Pro's and Con's of using the SWIR**
- The experiment is designed to answer the following questions:
  - Can the SWIR add additional information?
    - **Topic #3: Radiance vs. Brightness Temperature DA**
    - **Topic #4: Spectral Purity**
    - **Topic #5: non-LTE**
  - Can the SWIR replace the LWIR for the next generation of sounding instruments?
    - **Topic #6: What is the future for IR sounding instruments?**

TOPIC #1: A LITTLE HISTORY OF HYPERSPECTRAL SOUNDING INSTRUMENTS

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

- 1977 Lewis Kaplan published idea that SWIR (2000-2800 cm^{-1}) has unique sounding properties.
  - **See Kaplan, Chahine, Susskind Searl 1977 Applied Optics v.16 p.322-324.**
- 1989 Dave Wark writes 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

1990's: The AIRS Science Team is formed and implements the NOAA requirements

- Advanced the design of microwave + infrared advanced sounding instruments.
- Developed advanced forward models for the microwave and infrared.
  - ***Major investment in low noise, high spectral resolution SWIR***
- Developed an algorithm approach that merged numerous concepts, ***including the use of the SWIR for sounding.***

David Wark, Bill Smith Phil Rosenkranz Larrabee Strow Catherine Gautier Larry McMillin Alain Chedin
Hank Revercomb Roberto Calheiros Joel Susskind Moustafa Chahine Mitch Goldberg George Aumann

The first (and only) AIRS instrument was launched on the NASA EOS Aqua Platform May 4, 2002

AMSR-E

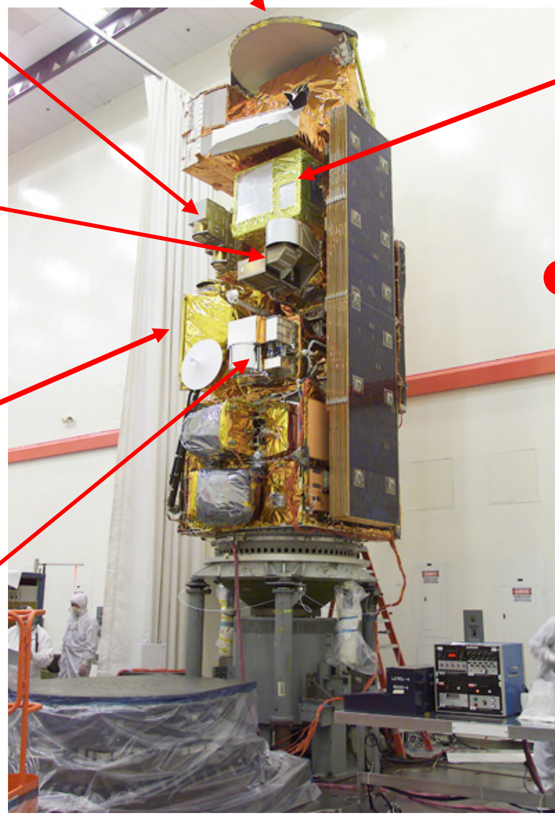
AMSU-A1(3-15

AMSU-A2(1-2)

AIRS

HSB

MODIS

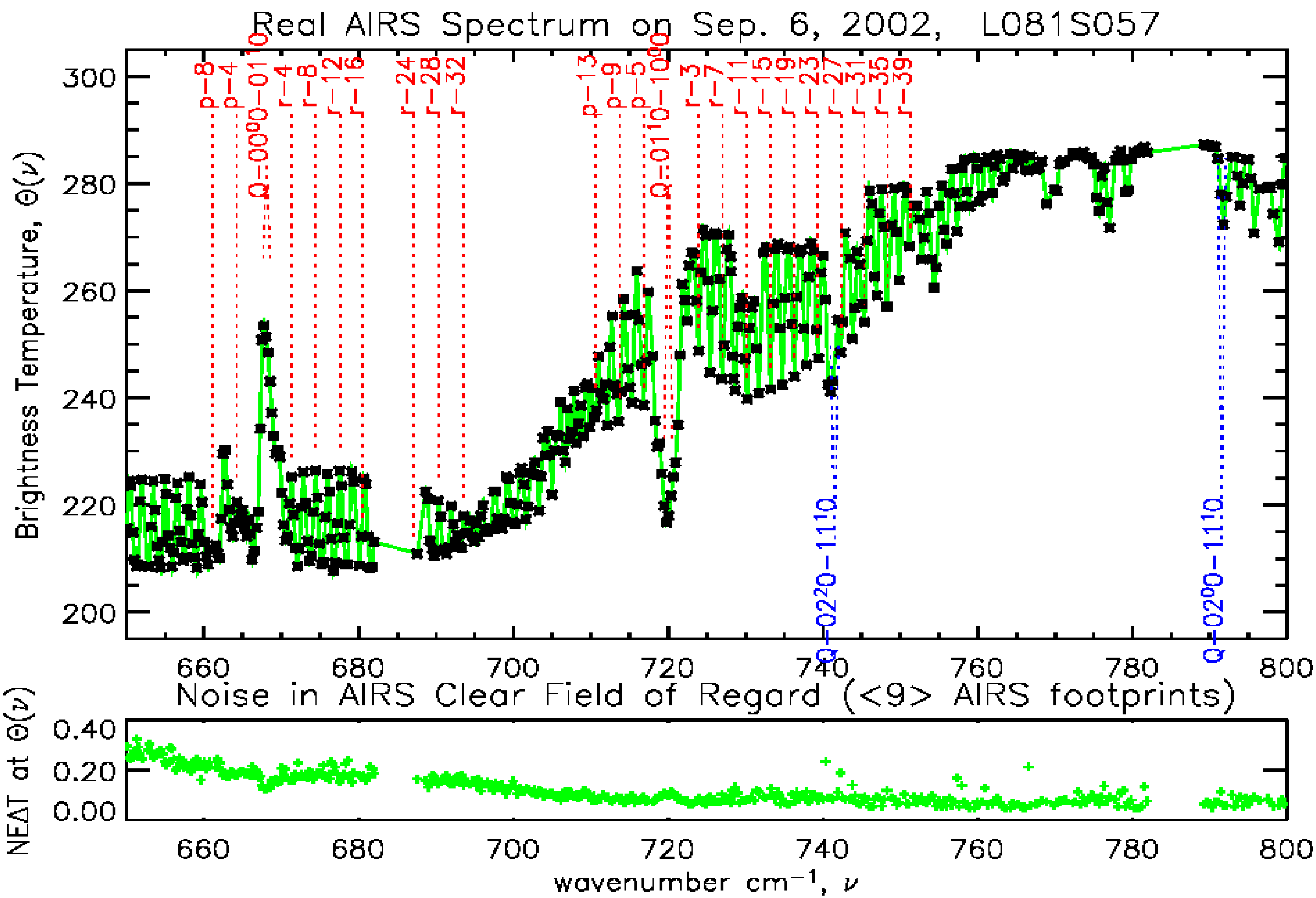


Aqua Acquires 325 Gb of data per day

Delta II 7920

AIRS Version.5, fully exploiting the SWIR and the basis for NUCAPS, has been operational at NASA since 2007

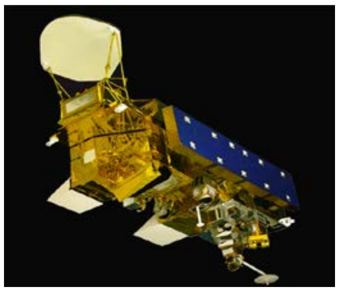
Example of 15 μm band radiance measurement from AIRS 1st operational day, Sep. 6, 2002



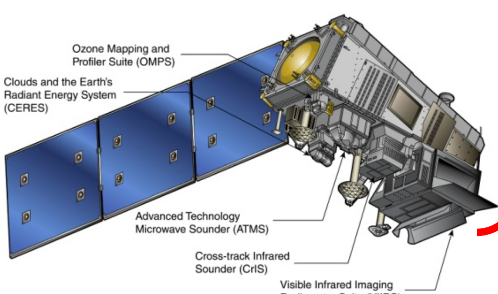
The NOAA-Unique Combined Atmospheric Processing System (NUCAPS) was envisioned in late 1990’s.

NUCAPS leverages the lessons learned by NASA AIRS Team

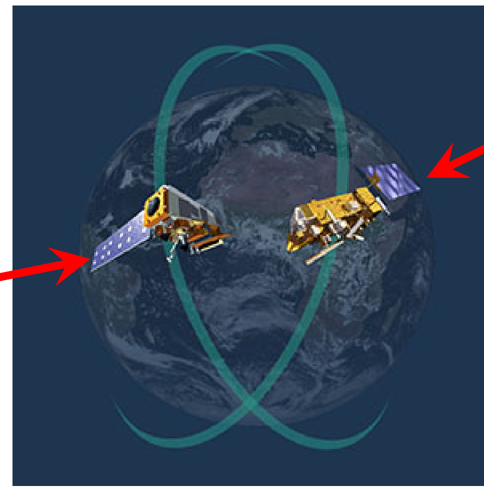
NASA/Aqua
1:30 pm orbit
(May 4, 2002)

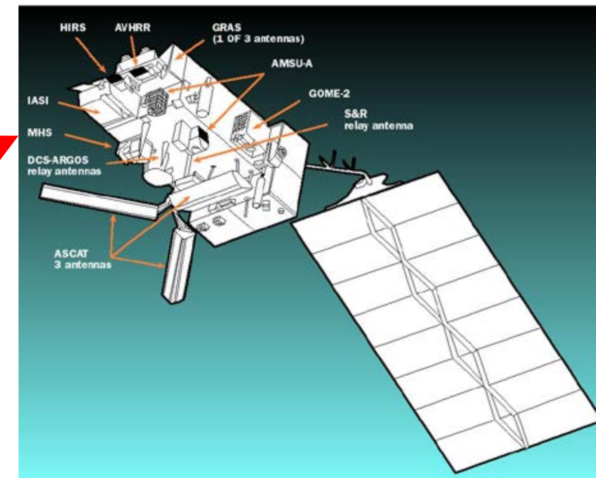


Suomi-NPP & JPSS
1:30 pm orbit
(Oct. 28, 2011, Nov. 18, 2017, 2021)

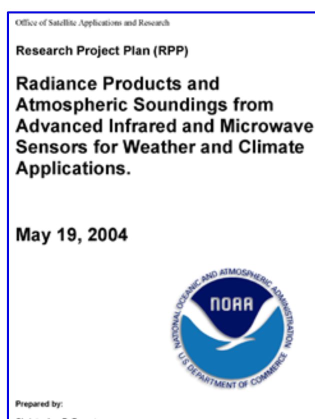


9:30 and 1:30 orbits provide information at critical times in the diurnal cycle





EUMETSAT/METOP-A,B, C
9:30 am orbit
(Oct. 19, 2006, Sep. 17, 2012, Nov. 7, 2018)


Office of Satellite Applications and Research

Research Project Plan (RPP)

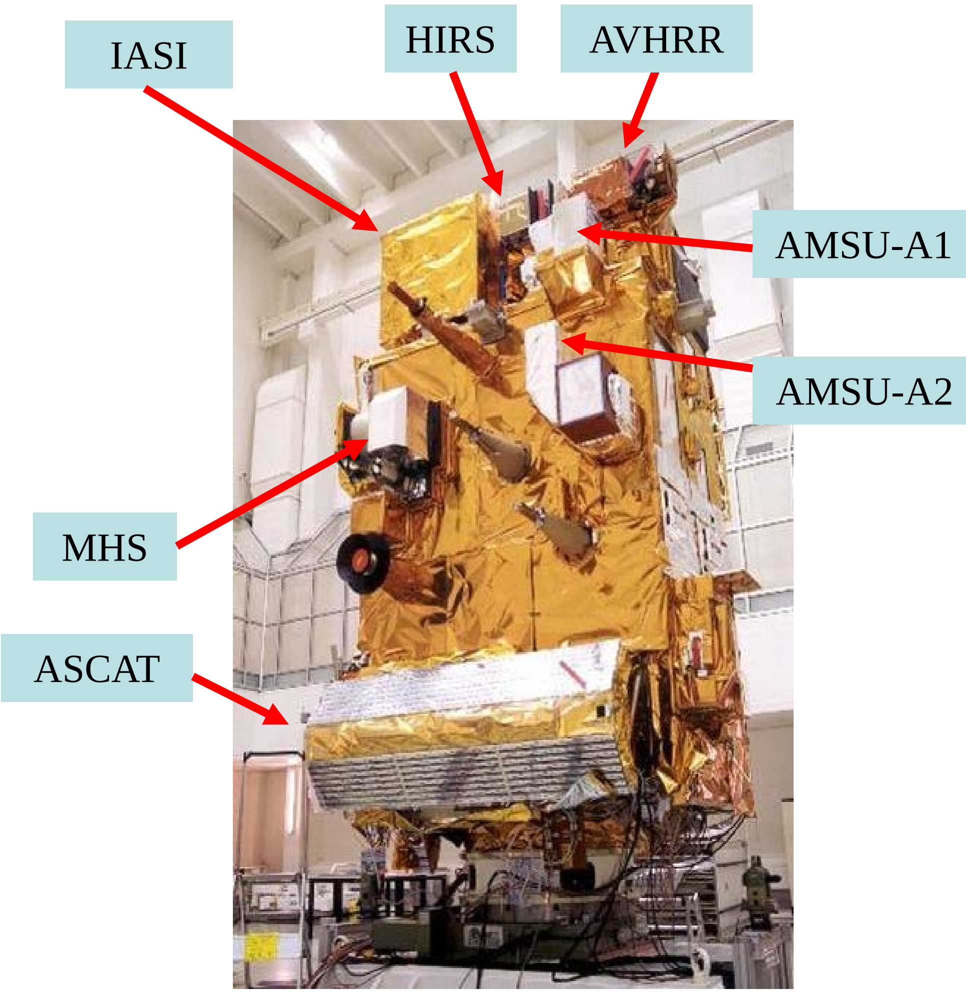
Radiance Products and Atmospheric Soundings from Advanced Infrared and Microwave Sensors for Weather and Climate Applications.

May 19, 2004

Prepared by:
Christopher D. Barnet

Discussions at 1999 ITOVS and OSA meetings led to the 2004 NOAA Research Plan to implement NUCAPS

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

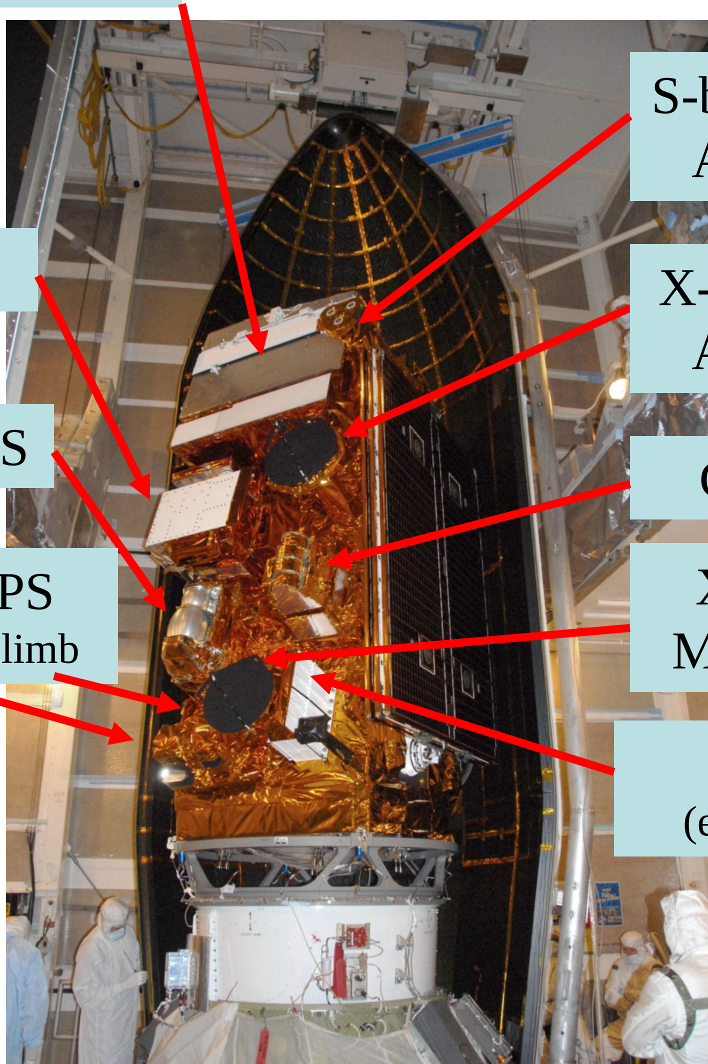


Soyuz 2/Fregat launcher,

Baikonur, Kazakhstan

NUCAPS, using IASI SWIR, has been operational since Dec. 2008

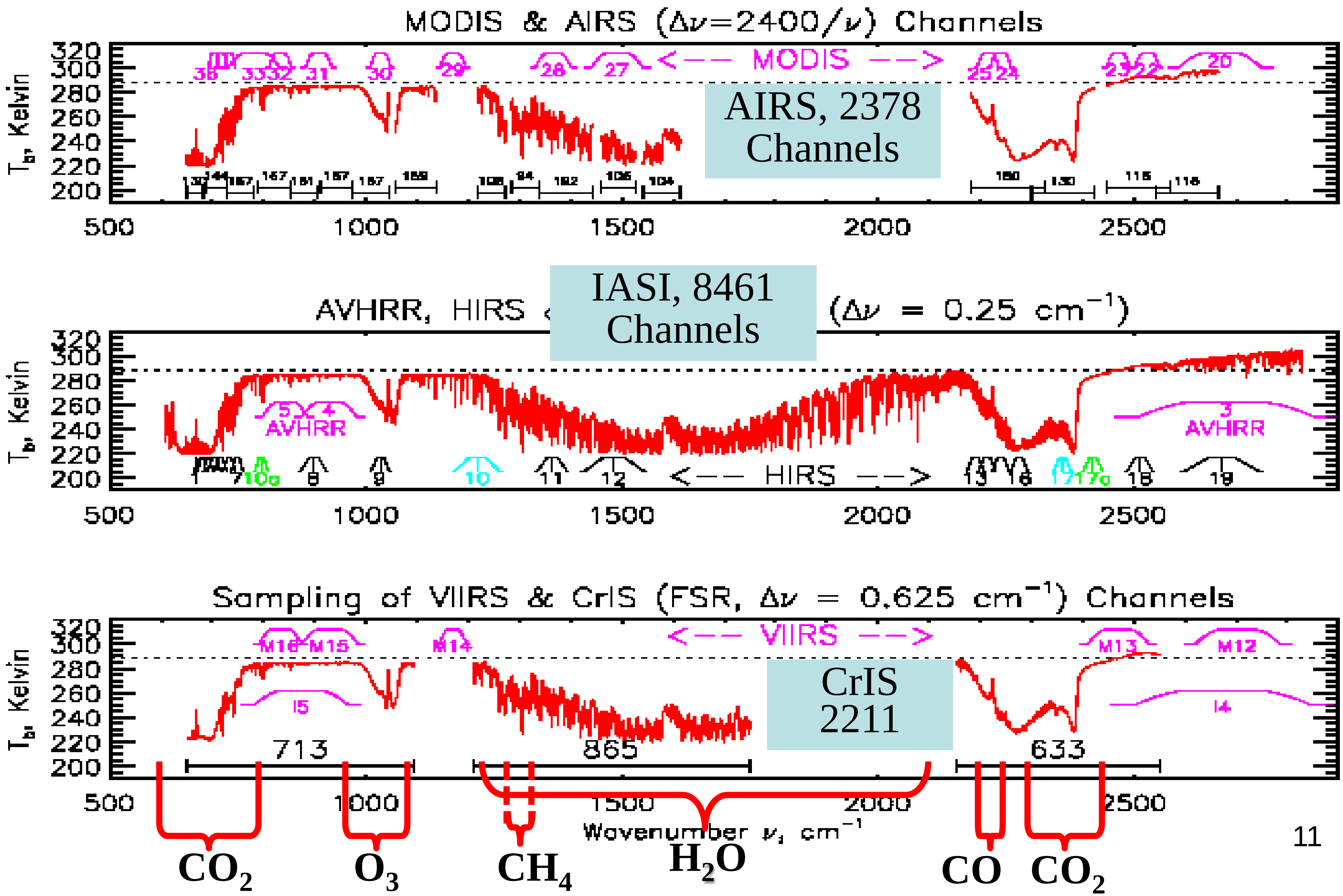
First CrIS/ATMS was launched on the NPP Satellite on Oct. 28, 2011



Delta-II-7920

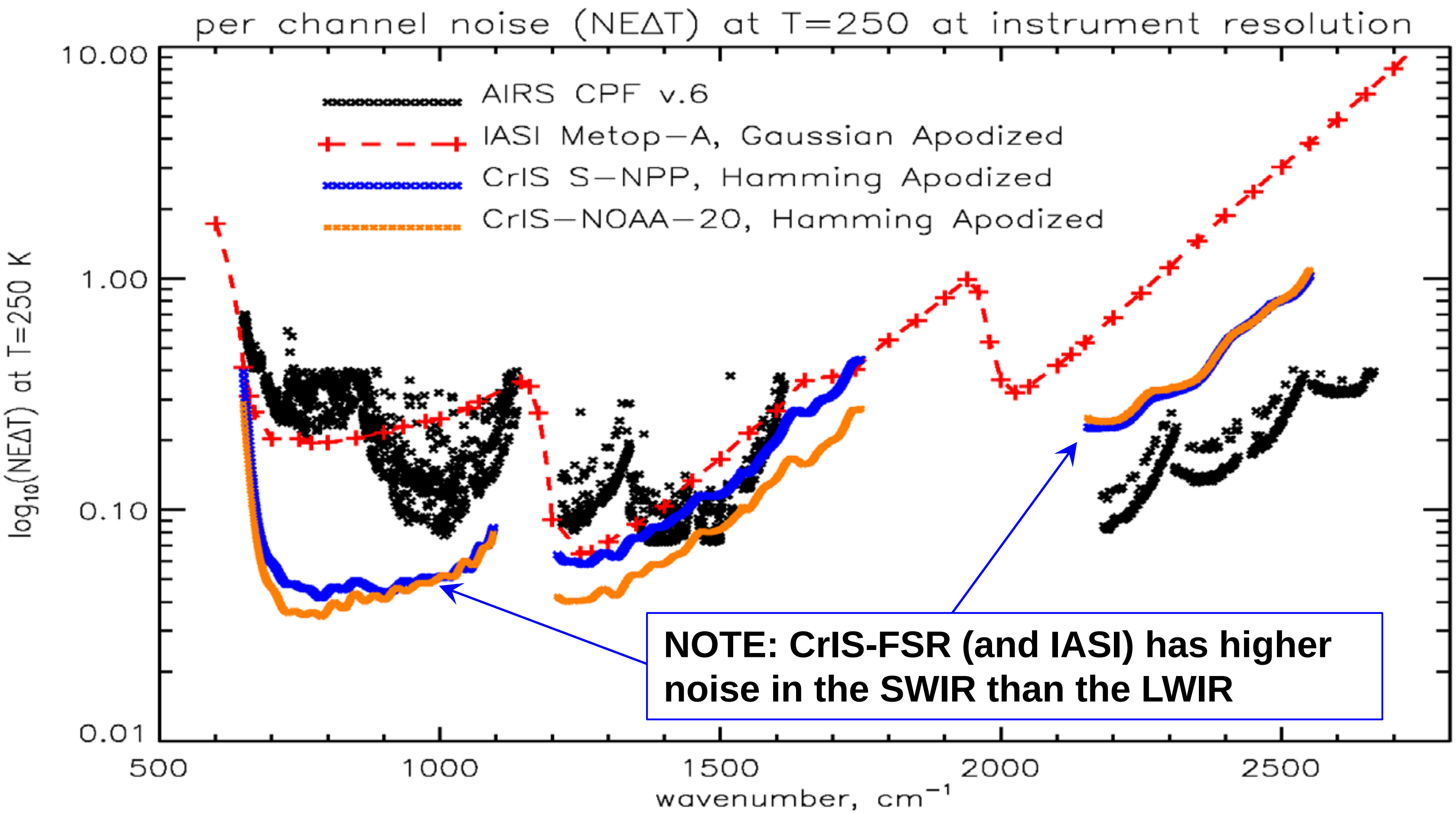
Vandenburg AFB

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)

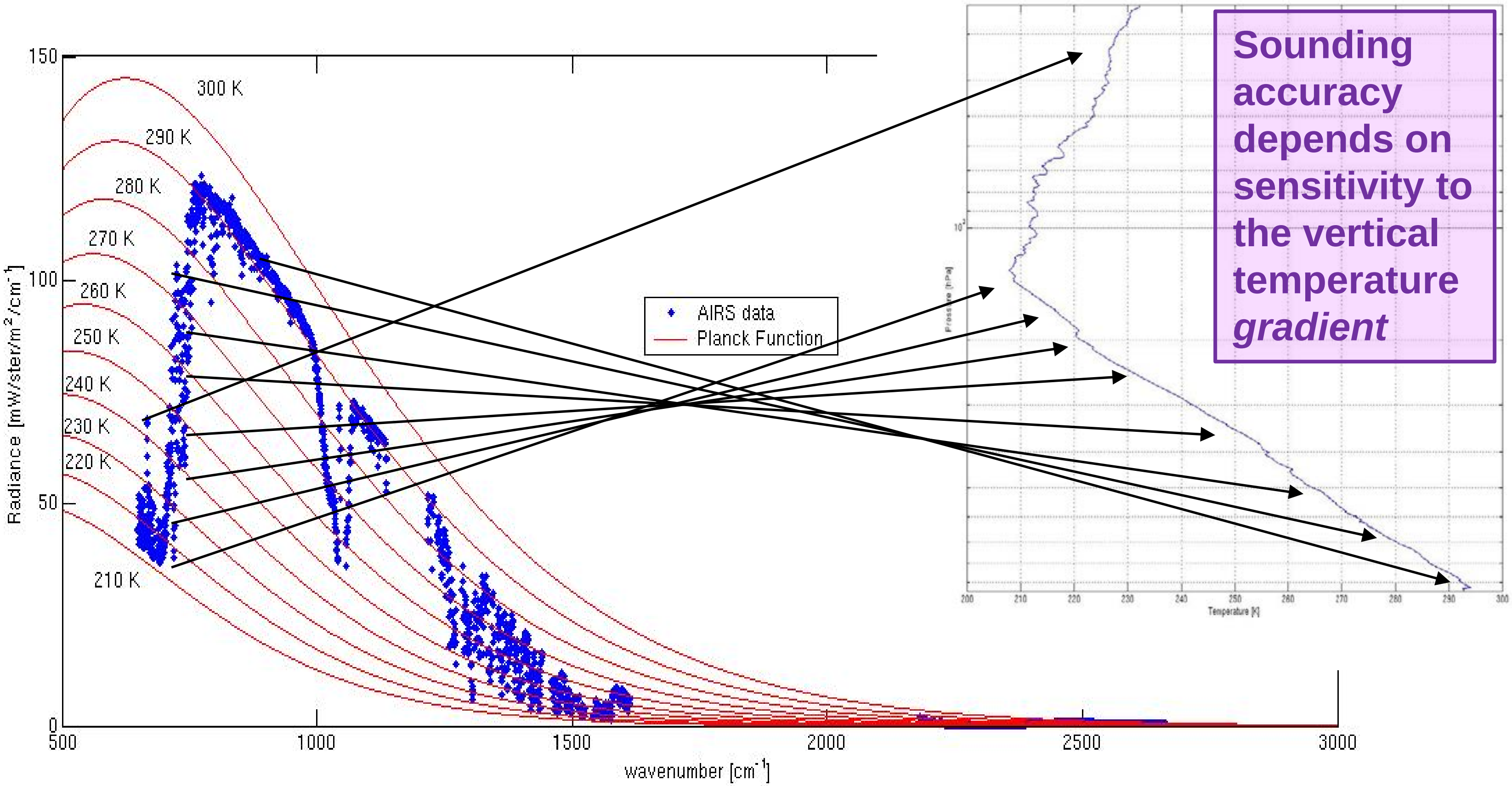


So where are we today?

- It has been 42 years since Kaplan, Chahine and Susskind noted the advantage of the SWIR in sounding.
- It has been 30 years since Dave Wark wrote the hyperspectral sounding requirements.
- It has been 16 years since the AIRS ST demonstrated the benefits of the SWIR.
- It has been 14 years NOAA laid out a plan to exploit 30+ years of hyper-spectral assets with the lessons learned from the AIRS ST.

TOPIC #2: SO LET'S TALK ABOUT THE PRO'S AND CON'S OF USING THE SWIR

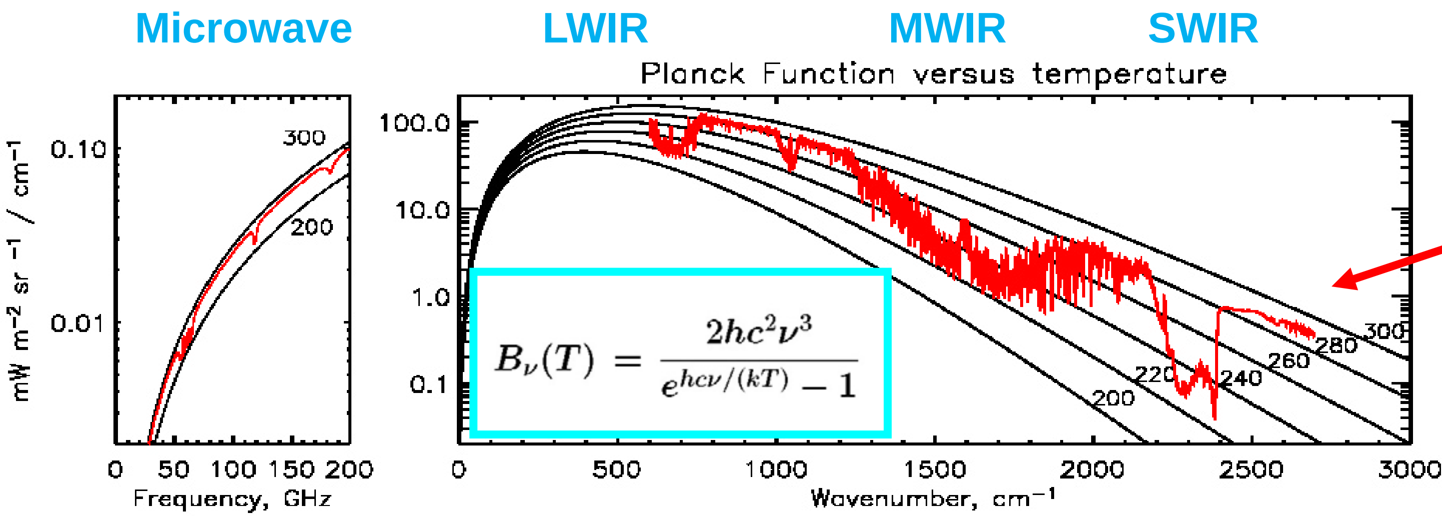
The Advantage of High Spectral Resolution is improved Vertical Resolution (selectivity)



Sampling over rotational bands

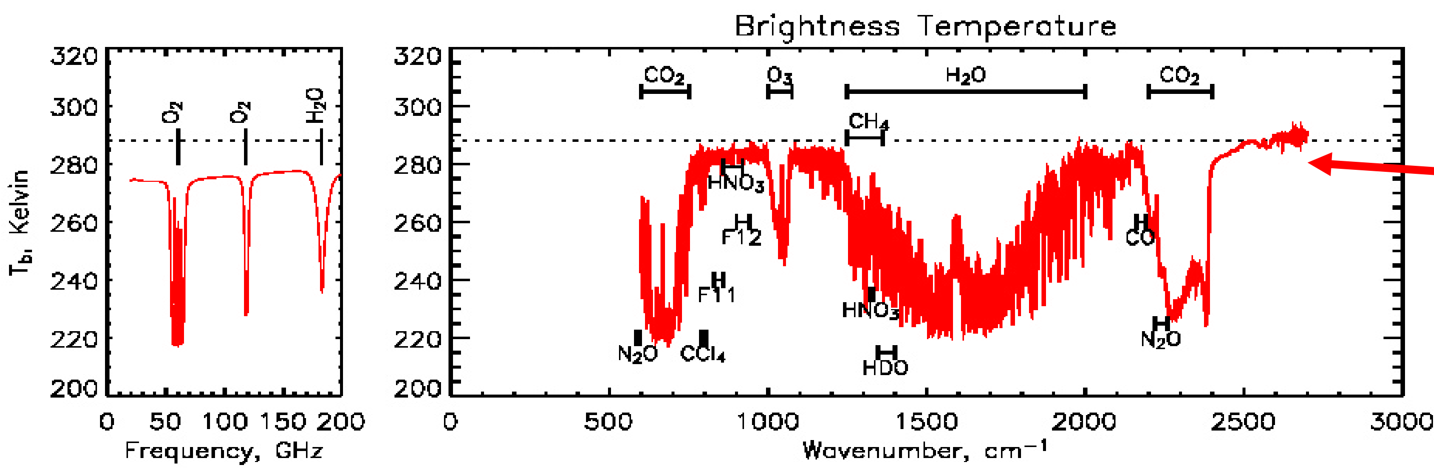
These instruments really measure radiance

that is, energy/time/area/steradian/frequency-interval



$$B_\nu(T) = \frac{2hc^2\nu^3}{e^{h c \nu/(kT)} - 1}$$

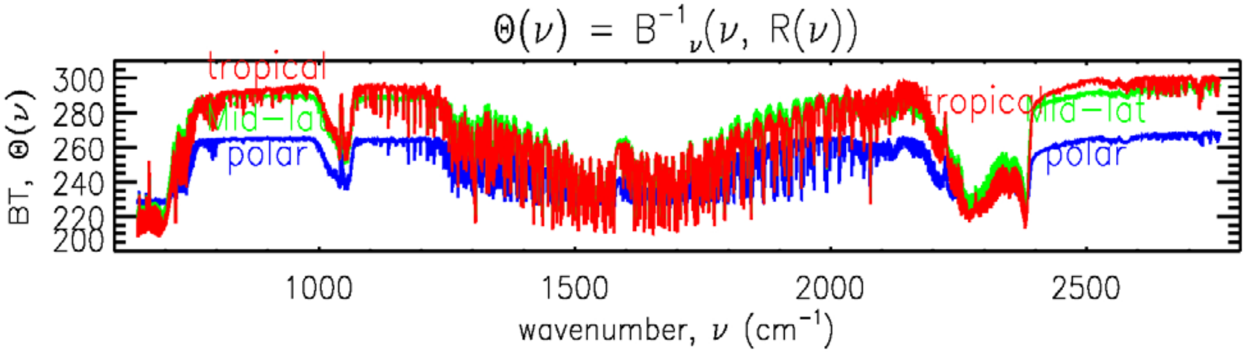
This is what we really measure.



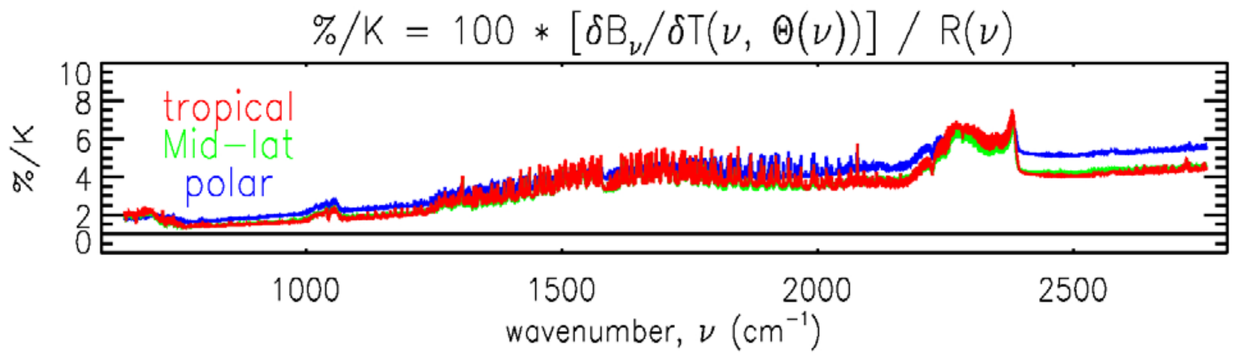
This is how we usually show it.

To Convert to Brightness Temperature ≡ Find Temperature where the Planck Function is equal to measured radiance at a given frequency.

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

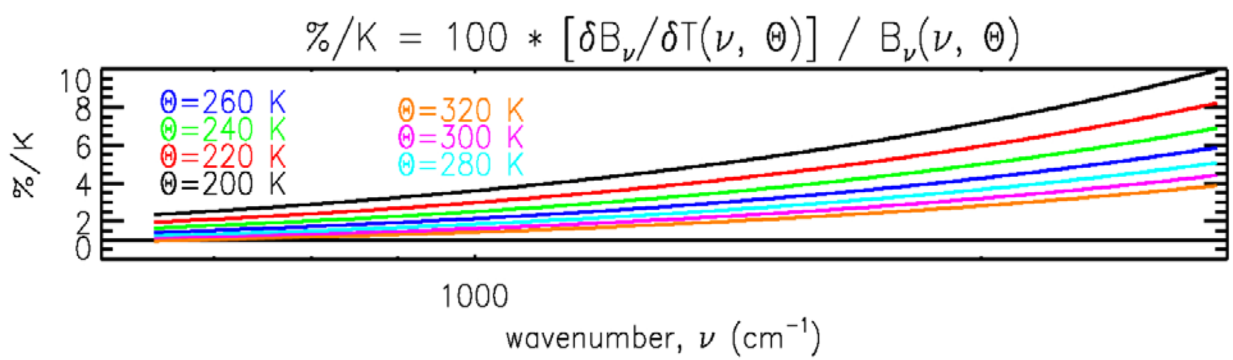


Example Brightness Temperature for Polar, Mid-Lat, and Tropical cases



% change in radiance for a 1 K change in T

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



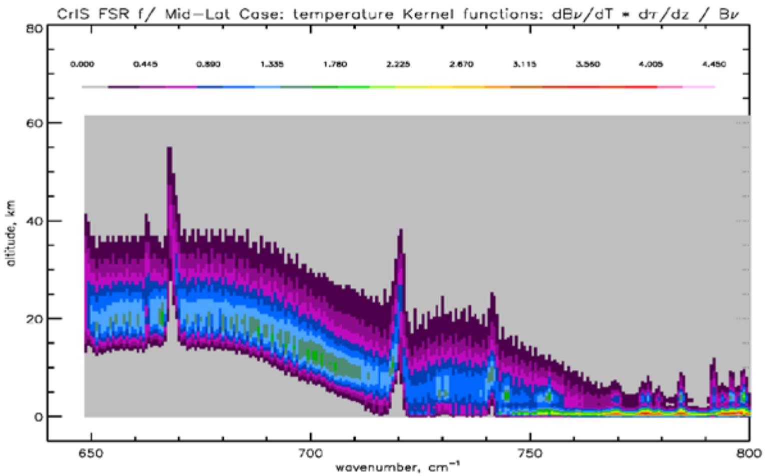
This is due to the derivative of the Planck function

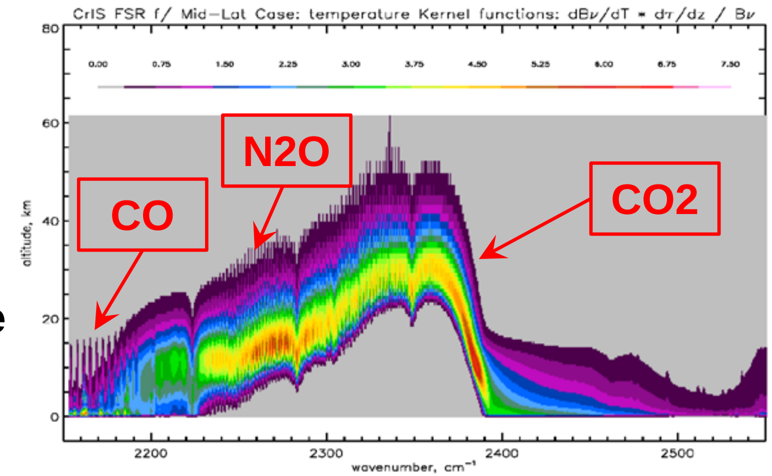
Cold scenes are significantly more sensitive.

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

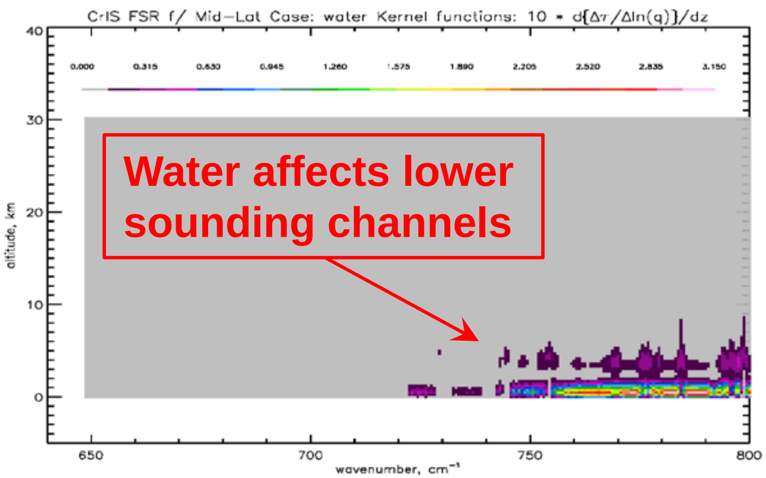
LWIR (15 μm, 650-800 cm^{-1})

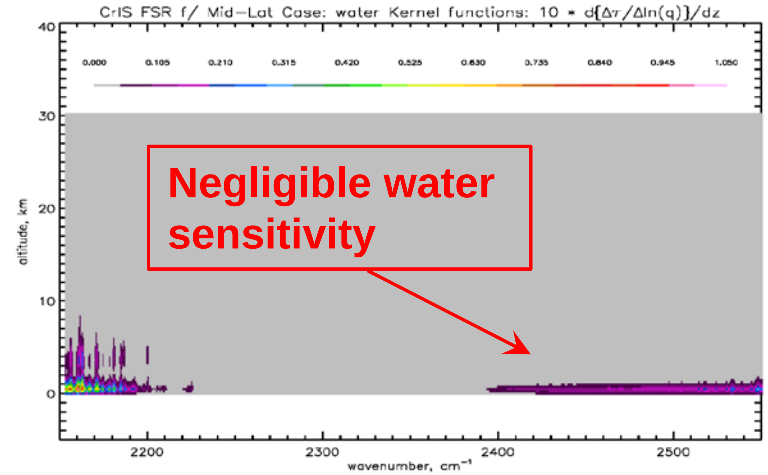
SWIR (4 μm, 2200-2700 cm^{-1})





Sensitivity to Temperature





Sensitivity to Water

Pro's and con's of SWIR vs. LWIR

	LWIR	SWIR
Interfering gases in CO2 bands	**H2O, O3, HNO3**	**None**
Exploit the use of N2O 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	**1st order linearity**	Highly nonlinear
Instrument Noise sensitivity to scene temperature	**Can Assimilate BT's (not really true!!)**	Noise is stronger 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 items in SWIR column been resolved by the AIRS science team & implemented in NUCAPS-IASI and NUCAPS-CrIS systems.

TOPIC #3: RADIANCE VERSUS BRIGHTNESS TEMPERATURE DATA ASSIMILATION

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

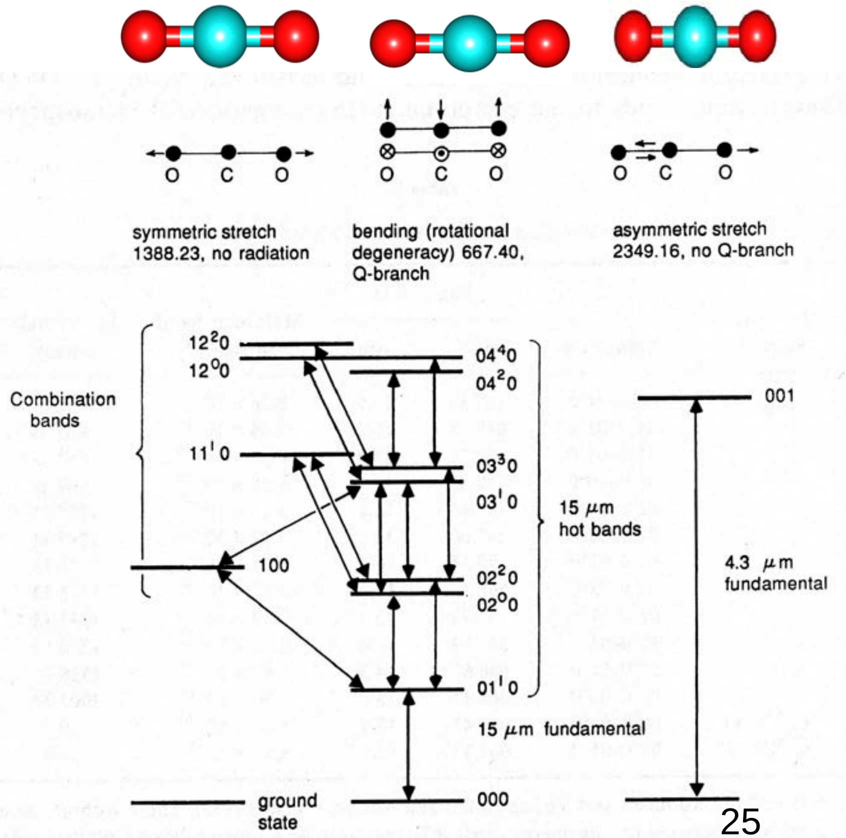
Note: This issue has recently been raised by Larrabee Strow & CrIS SDR Team

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

TOPIC #4: SPECTRAL PURITY

Molecular Vibrational Modes (Example: CO_2)

- CO_2 has 4 modes of vibration. Each is quantized.
  - ν_1 is symmetric stretch (not active in infrared due to lack of dipole moment) but does interact via Fermi resonance with υ_2
  - ν_2 is a bending that is doubly degenerate
  - ν_3 is an asymmetric stretch
- Energy of vibrational mode is given by
  - $E_{vib} = \Sigma\, hc \cdot \nu_k \cdot (i_k + ½)$ for $i_k = 0, 1, 2, \ldots$



Isotope	transition	band	S	d
$^{12}C^{16}O^{16}O$	$00^00 \rightarrow 01^10$	667.38	194	1.56
	$01^10 \rightarrow 02^20$	667.75	15	0.78
	$01^10 \rightarrow 10^00$	720.81	5	1.56
	$01^10 \rightarrow 00^00$	618.03	4	1.56
	$02^20 \rightarrow 03^30$	688.11	0.85	0.78
	$10^00 \rightarrow 11^10$	647.06	0.7	1.56
$^{13}C^{16}O^{16}O$	$00^00 \rightarrow 01^10$	648.48	2.01	1.56
$^{12}C^{18}O^{16}O$	$00^00 \rightarrow 01^10$	662.37	0.77	1.56

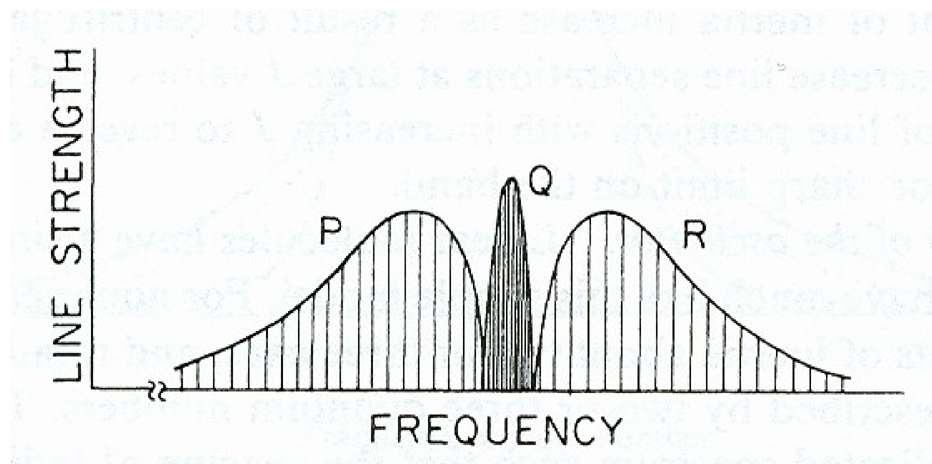
Rotational Modes

- The energy of rotation is quantized and given by
  - $E_{rot} = hc \cdot B \cdot j \cdot (j+1)$, j = 0, 1, 2, 3, …
- But as the molecule rotates it also has centrifugal forces
  - $E_{rot} = hc \cdot (B \cdot j \cdot (j+1) - D \cdot j^2 \cdot (j+1)^2$

P-branch lines form when Δj = +1

Q-branch lines form when Δj = 0

R-branch lines form when Δj = -1



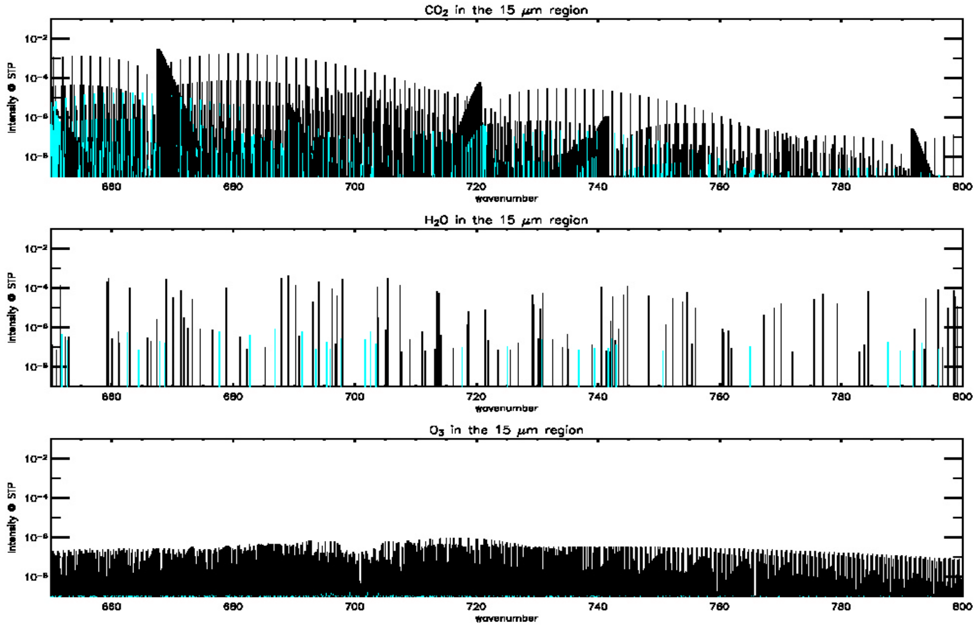
All the Physics is Contained in a quantity called the Absorption Coefficient

- The absorption coefficient is a complicated and highly non-linear function of molecule *i* and line *j*
- Line Strengths, S_{ij}, result from many molecular vibrational-rotational transitions of different molecular species and isotopes of those species(blue).

$$\kappa_i(\nu, p, T, \theta) \simeq \sum_{j=1}^{J} \frac{N_i \cdot S_{ij}}{\pi} \frac{\gamma_{ij}}{(\nu - \nu_{ij})^2 + (\gamma_{ij})^2} \cdot \sec(\theta)$$

Where width of line, γ_{ij}, is a function of the molecule structure (natural broadening), temperature (doppler broadening) and pressure (collisional broadening)

$$\gamma_{ij} \simeq \gamma_{ij}^{0} \cdot \frac{p}{P_0} \cdot \sqrt{\frac{T}{T_0}}$$



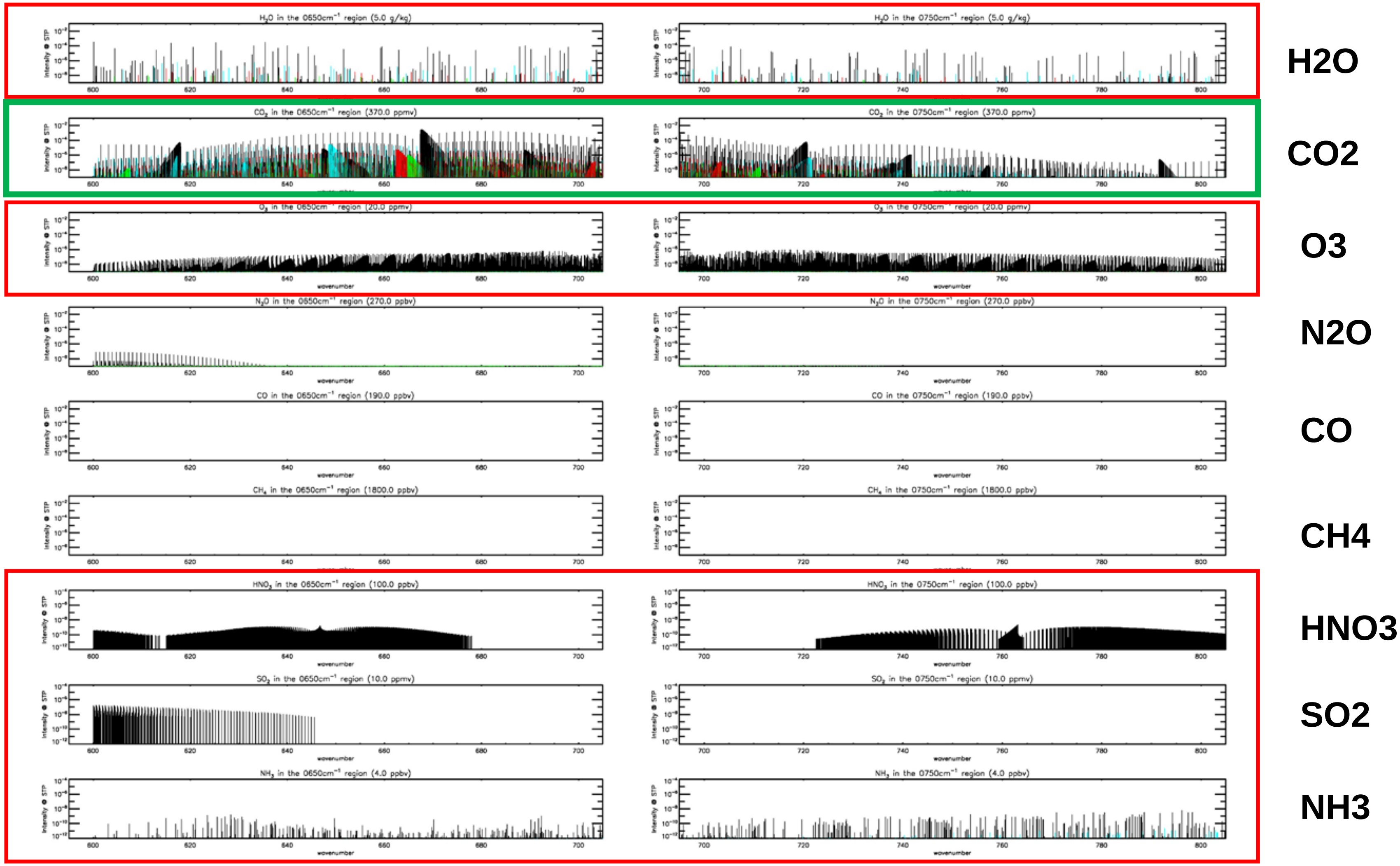
Line strength (at T=300K) of CO2, H2O, and O3 in the 15 μm band.

Line strength, S, is also a function of temperature

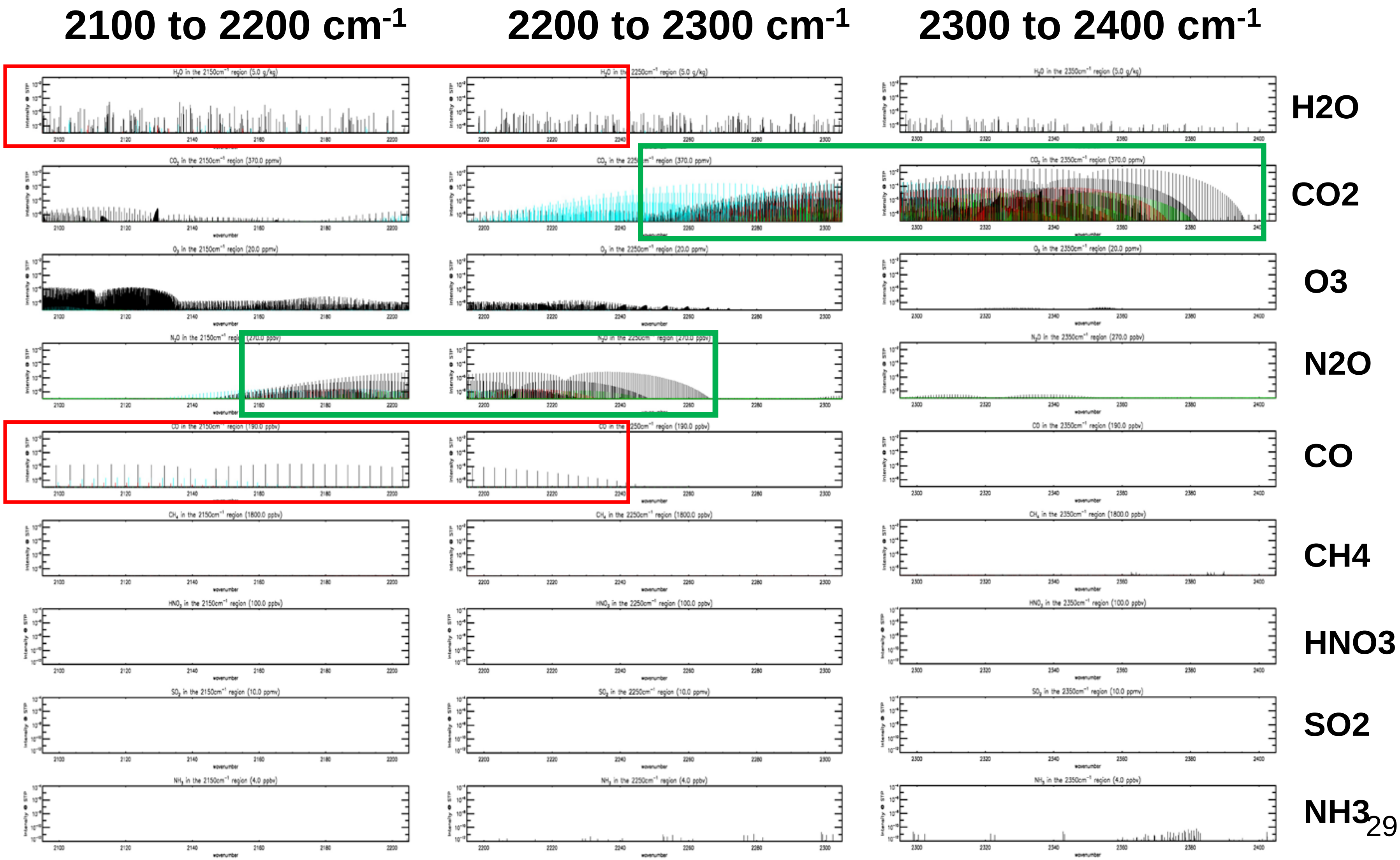
$$S(T) = S(T_0)\cdot(T/T_0)\cdot\frac{(1-\mathrm{EXP}(1-1.439\nu/T))^3}{(1-\mathrm{EXP}(1-1.439\nu/T_0))^3}$$

Example of vibration rotational line strengths in 15 μm band region

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



Example of vibration rotational line strengths in 4 μm band region



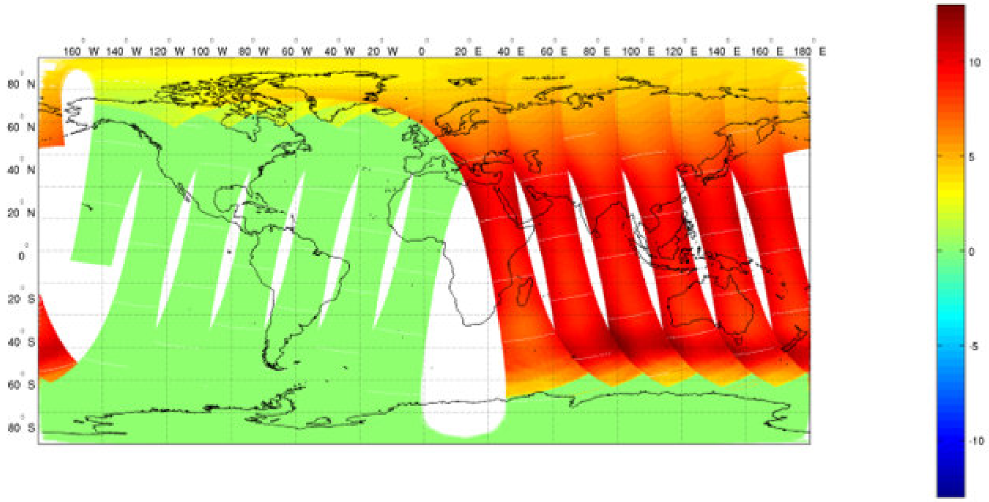
TOPIC #5: NON-LTE

How big is the non-LTE effect?

CRTM simulation of a channel pair difference

SWIR 2336.25 cm-1 minus LWIR 667.50

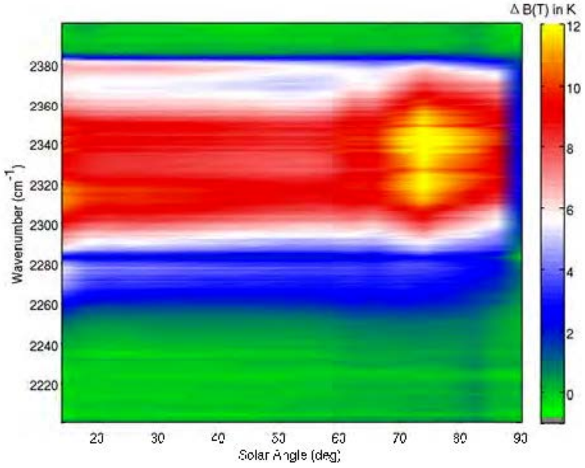
Non-LTE effect is ~5 to ~10 K in daytime



This figure stolen from Zhenglong Li (CIMSS)

Bias in AIRS SWIR region for daytime radiances versus solar zenith angle

Need to correct for non-LTE from 2255 to 2383 cm-1



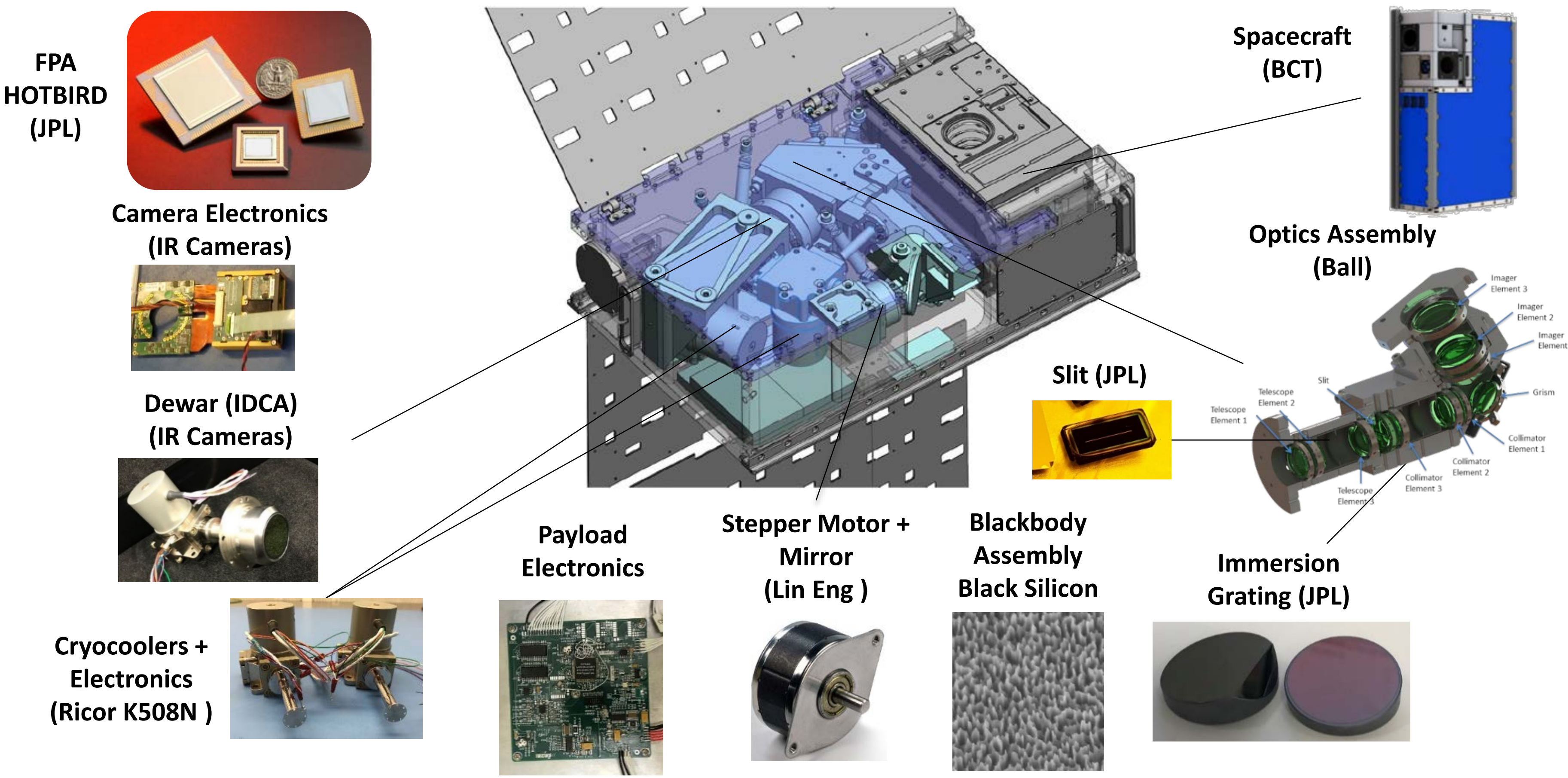
From DeSouza-Machado 2007 GRL, Fig. 3

We know how to correct for non-LTE.

- The use of the Planck function assumes a Boltzmann distribution in the population of energy states – called thermodynamic equilibrium or LTE
- Channels sensitive to high altitudes do not have enough molecular collisions to achieve equilibrium – called non-LTE
- AIRS Science Team dealt with this issue and employed an algorithm to correct for non-LTE effects (DeSouza-Machado 2007 GRL)
- NASA/AIRS ST and NOAA NUCAPS Teams have demonstrated that the SWIR + LWIR can be used for both day and night without introducing day-night artifacts.
- ***Non-LTE correction is in the CRTM (Chen 2013 JAOT)***

TOPIC #6: WHAT IS THE FUTURE OF INFRARED HYPERSPECTRAL

Example of technologies enabled by using SWIR: A NASA/JPL CubeSat Instrument called CIRAS



Entire *satellite* can fit in 6U (60x10x10 cm) enclosure!

Advantage of the SWIR might be most important for 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
CIRAS	10 x 20 x 30	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 launch of these instruments.

Summary of the experiment

- NOAA/OPPA has funded a study to study the impact of the CrIS SWIR in DA
  - We will account for non-LTE, solar surface reflection, scene dependent noise, etc.
- My NOAA co-authors will perform an OSSE.
  - The CrIS instrument is being used as a proxy for future instrument concepts, such as CIRAS.
  - CrIS-FSR is also operationally relevant to NCEP.
  - We will develop QC, thinning, and bias correction schemes suitable for SWIR.
  - We will also evaluate radiance data assimilation versus brightness temperature data assimilation.

QUESTIONS?

Documents available

cell: (301)-789-6934 email: chrisdbarnet@gmail.com

Google drive short link: **http://goo.gl/twuRtW**

NOTES from UMBC classes, theory of remote sounding (PHYS741) and numerical methods documentation (PHYS 640)

rs_notes.pdf (~17.5 MB, ~650 pages)

180702_cuny_barnet.pdf (10 MB, 140 slides)

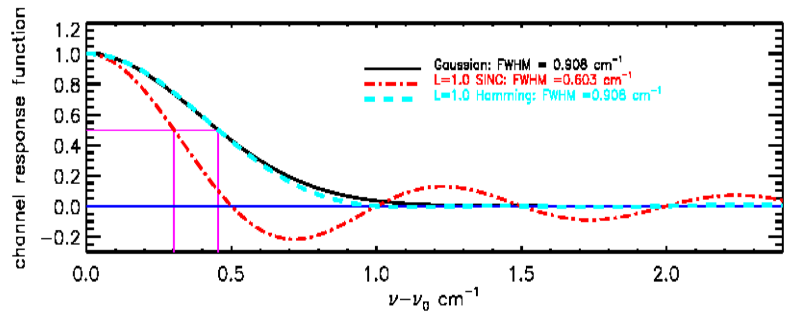
phys640_s04.pdf (~8.8 MB, 370 pages)

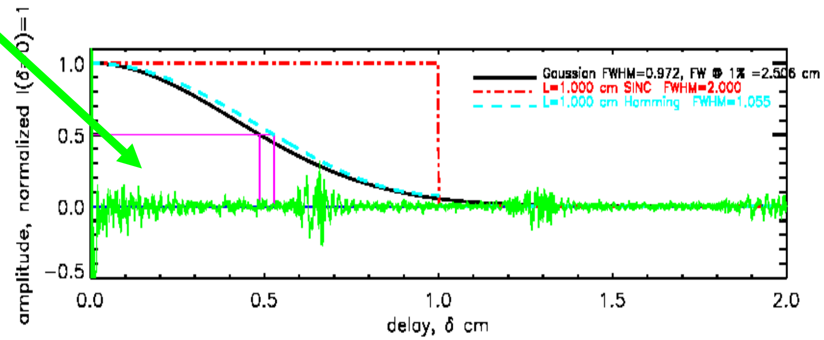
These are *living* notes, or maybe a scrapbook – they are not textbooks.

Those documents refer to other documents that are also on the google drive.

Apodization Alters the ILS and Spectally Correlates the Noise.

- Interferometers measure interferograms (green curve) signal as a function of optical delay, δ
- Performing a inverse cosine transform will yield the spectrum.
- Un-apodized transforms (red) have a SINC(x)=SIN(x)/x instrument line shape (ILS).
- AIRS has a Gaussian ILS (black)
- Apodization can produce a ILS that is localized and has small (< 1%) side lobes. But the tradeoff is that the central lobe is wider and the signal is spectrally correlated between neighboring channels





	Gaussian	**Hamming**	Blackman
FWHM / FWHM(SINC)	1.682	**1.5043**	1.905
Random Noise reduction	1.735	**1.586**	1.812
Maximum Side-Lobe	0.45%	**0.73%**	0.12%
% of signal in central Lobe	95.1%	**87.5%**	99.8%

Channel Spacing	Gaussian	**Hamming**	Blackman
±1	70.74%	**62.5%**	75.5%
±3	25.0%	**13.3%**	31.6%
±4	4.43%	**-**	6.57%
±5	0.38%	**-**	0.53%
±6	0.025%	**-**	-