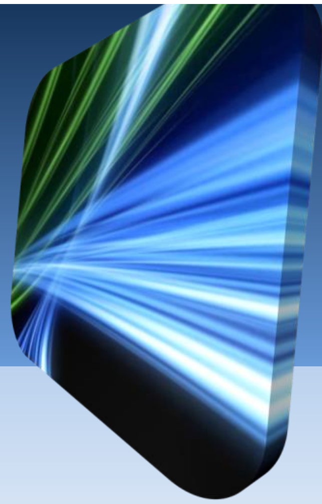
Trending Climate Change & Predicting Weather Using Fourier Transform Spectroscopy

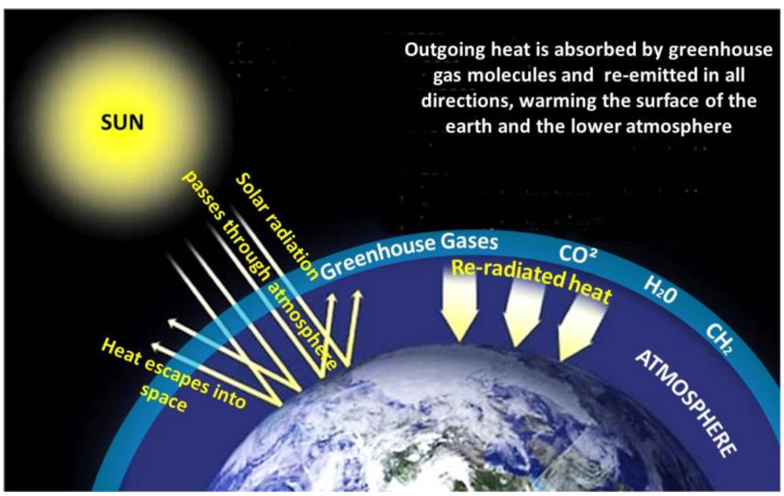


Technical Meeting
IEEE Fort Wayne Section, Indiana
IPFW Engineering & Technology Bldg.

Joe Predina (Logistikos Engineering LLC)
October 21, 2014

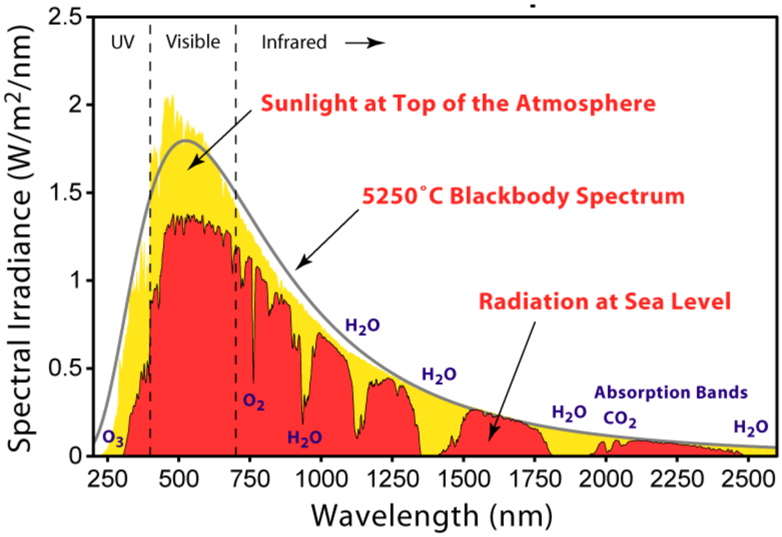
LOGISTIKOS
ENGINEERING LLC. AEROSPACE SYSTEM ENGINEERING SERVICES

Spectroscopy Can Address Many of the Un-answered Questions Related to Global Warming & Climate Change



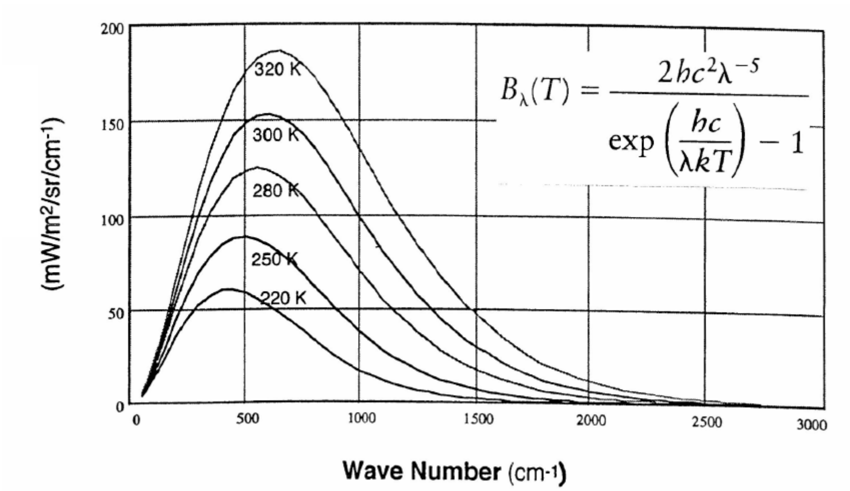
2

Solar Radiation Interacts With Earth's Atmosphere in Many Ways



3

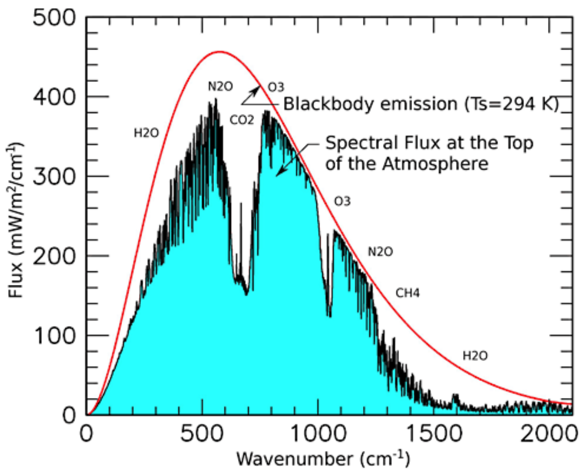
Radiance for a Black Body



Emissivity of a material will alter magnitude of the wave that gets launched

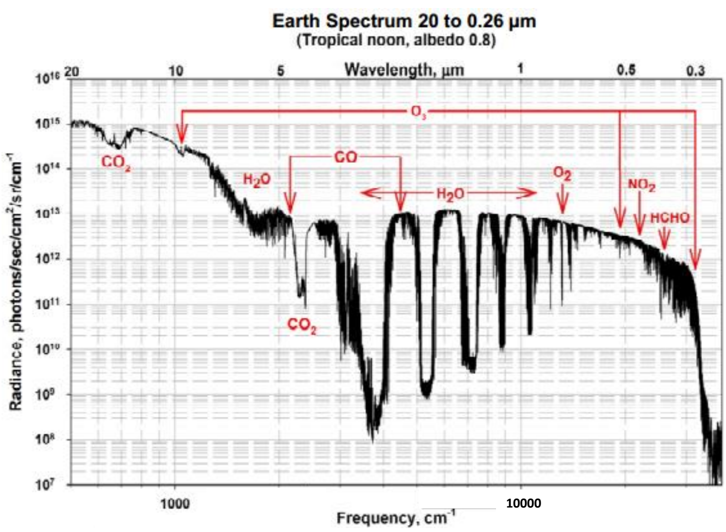
4

Earth's Self Emission of Energy to Space Occurs At Infrared Wavelengths via Radiation



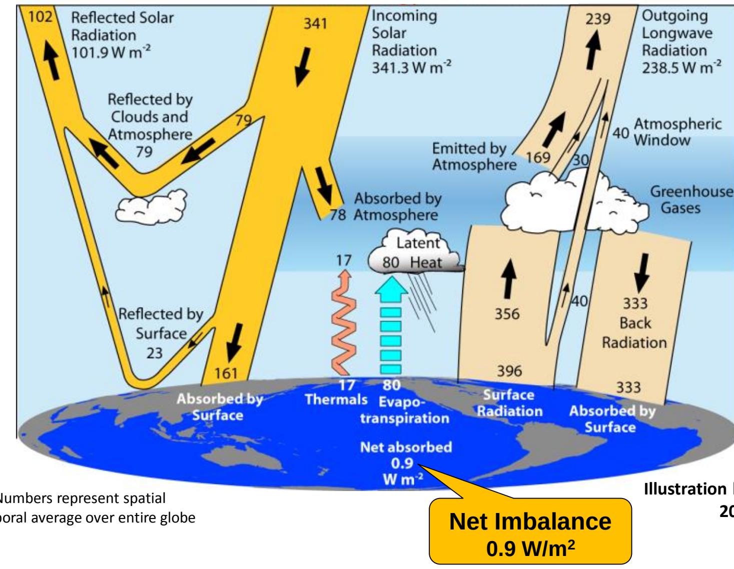
5

High Resolution Broadband Spectrometer Shows Much Structure in the Reflected Solar & Emissive Infrared



6

Radiation Exchange Between Earth, Sun & Space Is Enormous But Imbalance Driving Climate Change Is Small



Note: Numbers represent spatial & temporal average over entire globe

Illustration by Trenberth 2010

Atmospheric Gases Absorb Solar & Terrestrial Energy
(*i.e.,* warm the atmosphere)

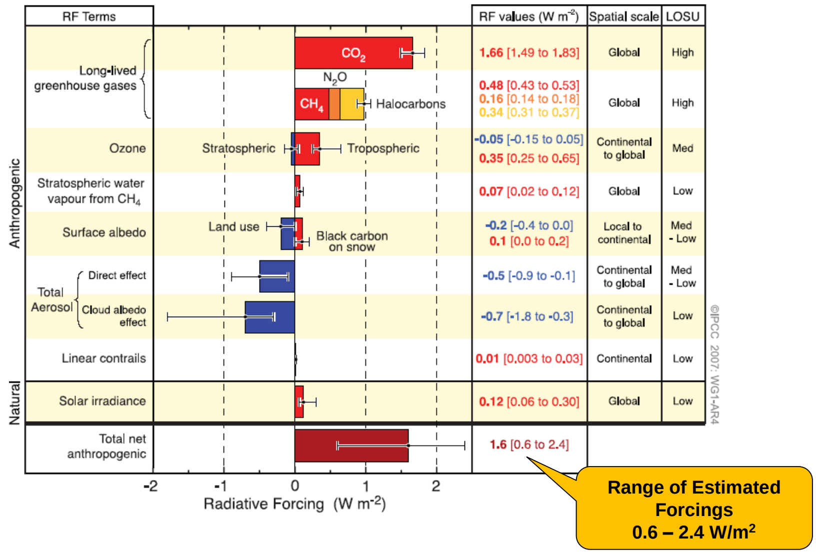
99.9% of the Earth's atmosphere does not absorb significant solar or infrared radiation.

Gas	Symbol	Fraction	ΔWatt/m²	Comments
Nitrogen	N_2	78.084%	≈ 0	Provides Thermal Inertia
Oxygen	O_2	20.9476%	≈ 0	Provides Thermal Inertia
Water	H_2O	0.5%	±	Self regulates, Feedback
Carbon Dioxide	CO_2	0.038%	1.4	Fossil Fuels, Biosphere
Methane	CH_4	0.00018%	0.7	Agriculture, wetlands, landfills
Ozone	O_3	0.002%	0.25	Chlorofluorocarbons, pollution
Nitrous Oxide	N_2O	0.000032 %	0.15	Agriculture

These "trace" gases absorb an additional 150 Watts/meter² to increase average temperature 60 F

- Without these trace gases the Earth's average temperature would be -0.5 F.
- Atmosphere absorbs 2.75 W/m² more in 2003 than in 1880 (Hansen 2005)

Climate Models Have Large Uncertainty in Radiative Forcing Estimates……..Need Satellites to Resolve



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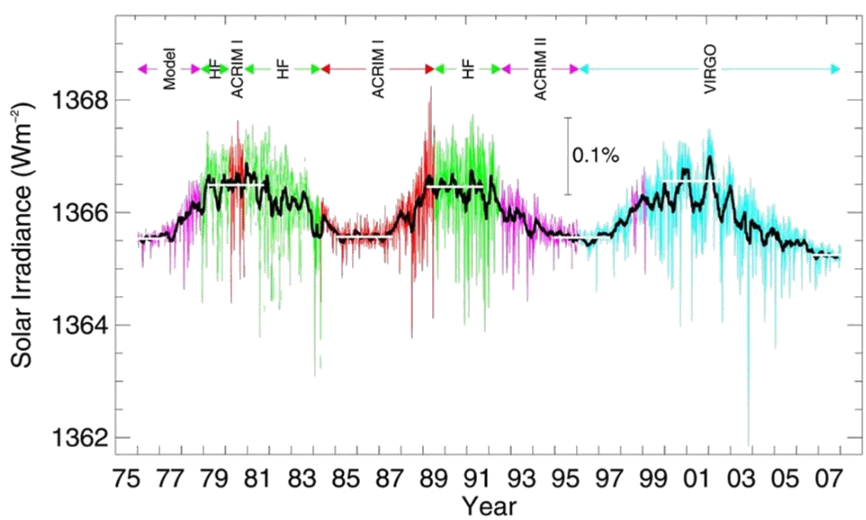
Solar Irradiance Reported for Last Three Solar Cycles

(from Fall 2008 AGU Meeting)



10

However, Satellite Sensors Differ Considerably in Their Reported Observations of Total Solar Irradiance

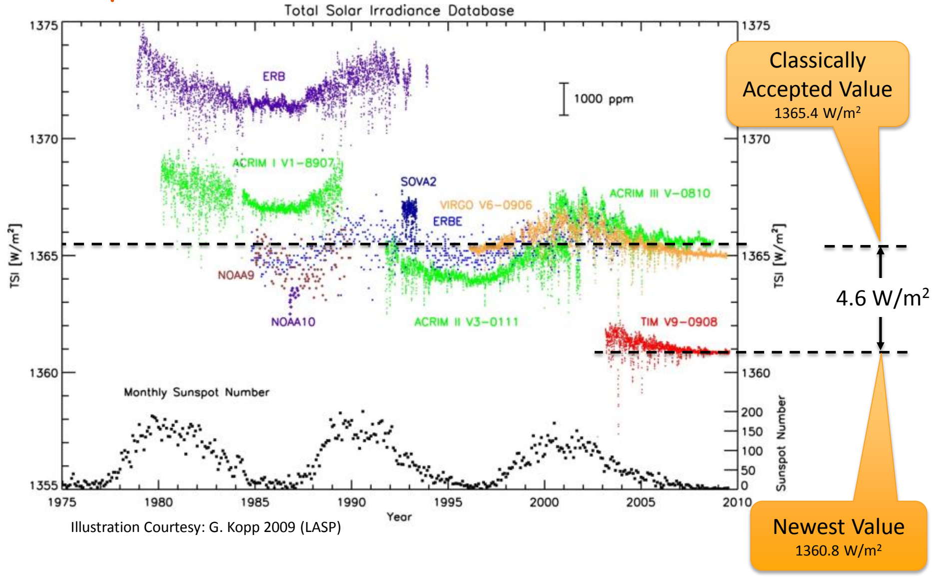
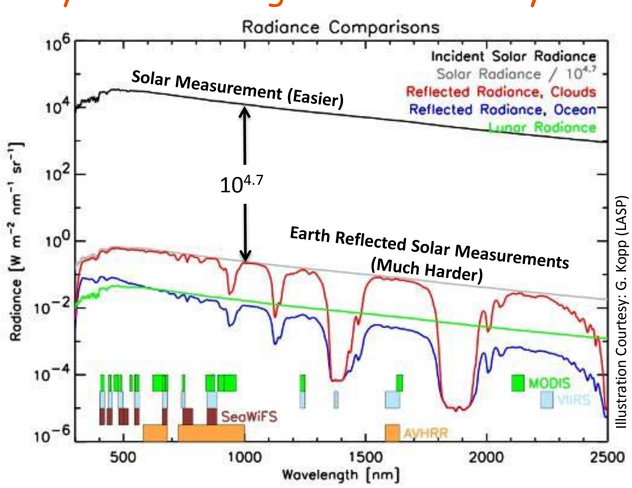


Illustration Courtesy: G. Kopp 2009 (LASP)

11

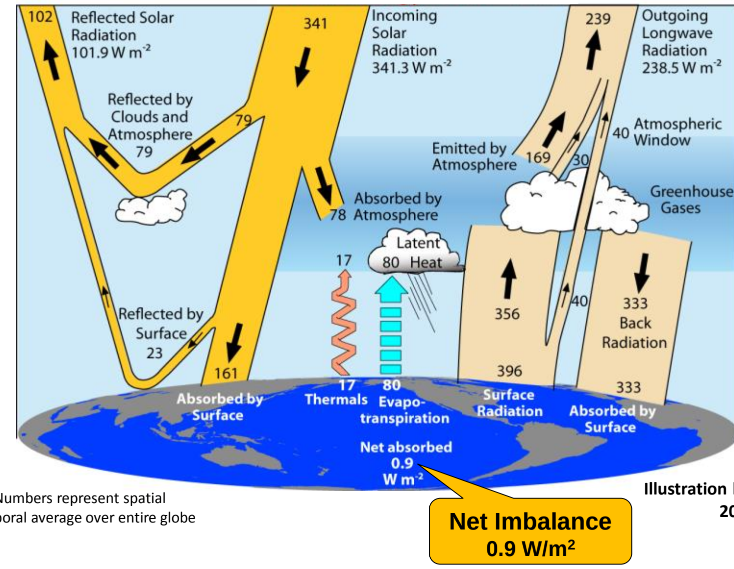
Solar Radiance & Earth Reflected Radiance Differ Enormously & Measuring this Accurately Is Difficult



How can accurate measurements be made from space to trend climate forcings?

12

Adjustments to Climate Models (Such as This One) Continue as Better Data Becomes Available

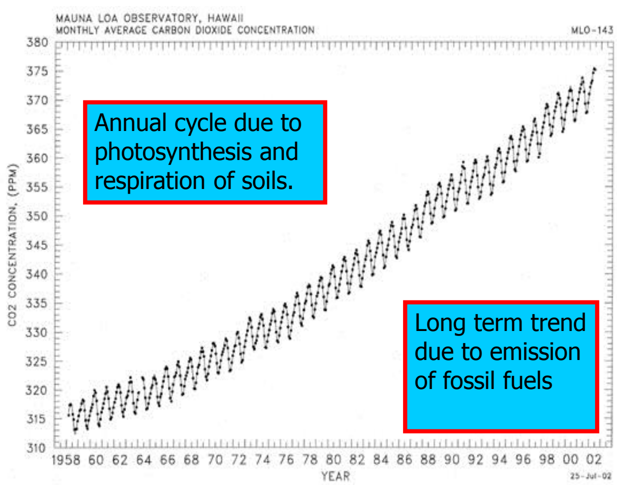


Note: Numbers represent spatial & temporal average over entire globe

Illustration by Trenberth 2010

13

Increase of atmospheric CO_2 Has Been Accurately Measured for Many Decades



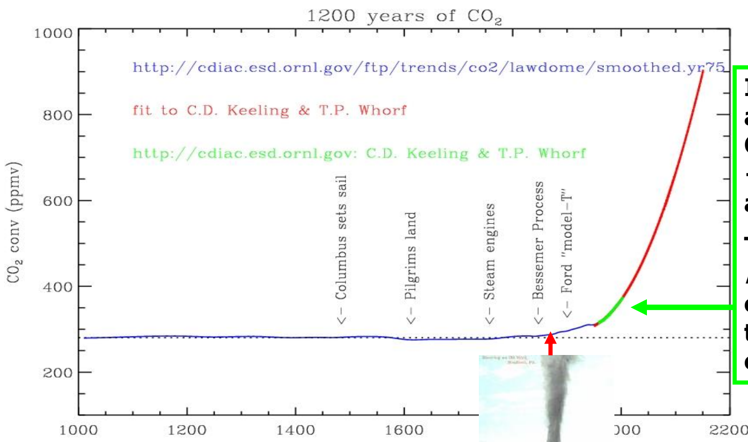
Charles David Keeling

1928-2005

2002 Nat'l Medal of Science

14

Atmospheric CO_2 has risen 35% in last 150 years and is projected to rise to 200% in the 21st century.



Increase in atmospheric CO2 is currently +2.5 ppm/year and rising.

That is 4.4 *billion* tons of carbon added to the atmosphere each year.

8/28/1859
Edwin Drake's 1st oil well

15

Solar Cycles Don't Explain Longer Term Earth Temperature Trend

Solar radiance maxima is approx. every 11 years (2000,1989,1981) and has been decreasing since 2002.

20th century warming was 0.75 K/century and is accelerating.

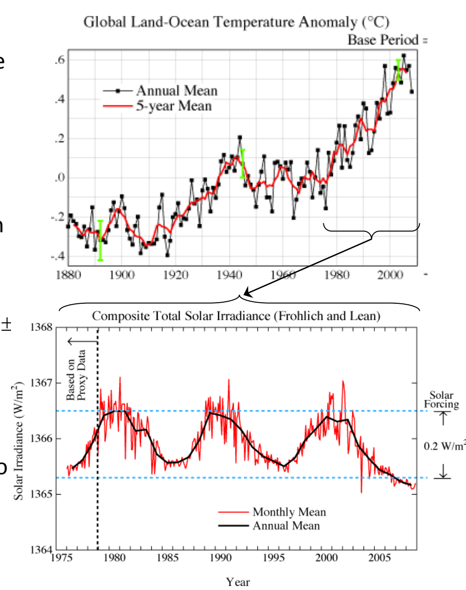
- Top 5 warmest years on record since 1880's are: 2005, 1998, 2007, 2002, 2003, and 2006.

Solar irradiance cannot explain stratospheric cooling and global tropospheric warming seen in last 30 years (GHG's can!)

Solar irradiance was important in previous centuries

- Recent studies show that the solar cycle drives a ± 0.1 K temperature cycle.
- Little ice age and medieval warm periods were **redistribution** of global energy
- Present day warming is global and monotonic.

The myth survives even though scientists have persuasively discredited the solar contribution to late 20th century warming. Why?



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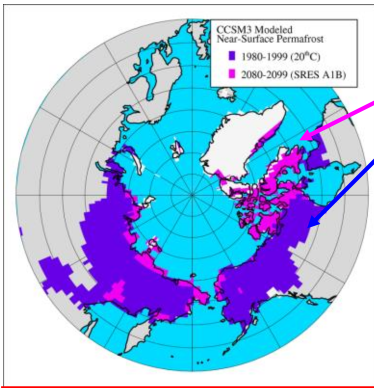
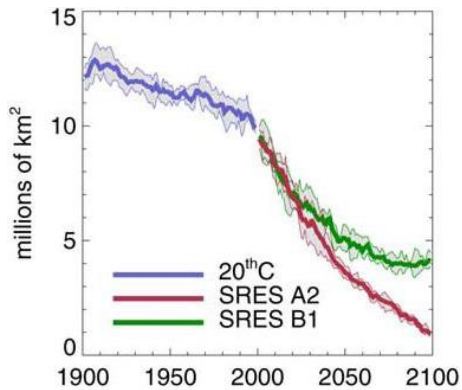
Significant amounts of Siberian and Alaskan permafrost *could* melt within 100 years. *Very likely* in 300 years.



Permafrost in 2100 for A1B scenario

Current Permafrost

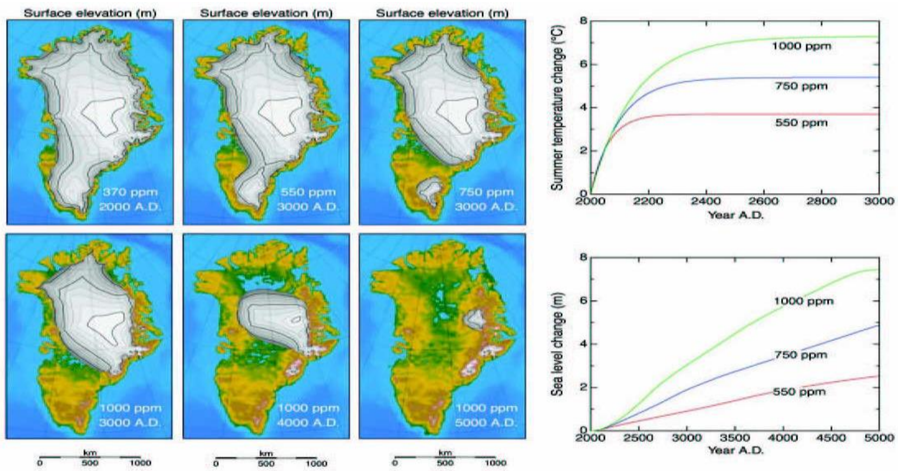


Permafrost is composed of ices that are millions of years old and contain *tremendous* amounts of methane.

Northeast US climate impact assessment (all values are changes from <1961-1990>)

	Low Emission	High Emission (track we are on)
Atmospheric CO2 in 2100	550 ppmv	940 ppmv
2040 Winter Temperature 2070 2100	2.5 to 4.0 F 4.0 to 5.0 F 5.0 to 8.0 F	2.4 to 4.0 F 4.0 to 7.0 F 8.0 to 12 F
2040, Summer Temperature 2070 2100	1.5 to 3.5 F 2.0 to 5.0 F 3.0 to 7.0 F	1.5 to 3.5 F 4.0 to 8.0 F 6.0 to 14 F
Number of Days > 100 F	3 to 9	14 to 28
Sea Level Rise	7 to 14 inches	10 to 23 inches
# heavy rains (>2” in 48h)	+8%	+12 to +13%
Length of growing season	2 to 4 weeks	2 to 6 weeks
First leaf bloom date	1 day/decade earlier	2 day/decade earlier

Even if we stabilize at 550 ppm,a significant amount of Greenland will *ultimately* melt.



Greenland glacier is 3-km thick at center: as ice melts, elevation is lowered, air is warmer. But, melting will take <u>many</u> centuries if the glacial models are correct.

19

65 Million Year Temperature Reconstruction

Temperature derived from sediment cores from Deep Sea Drilling Project and Ocean Drilling Program.

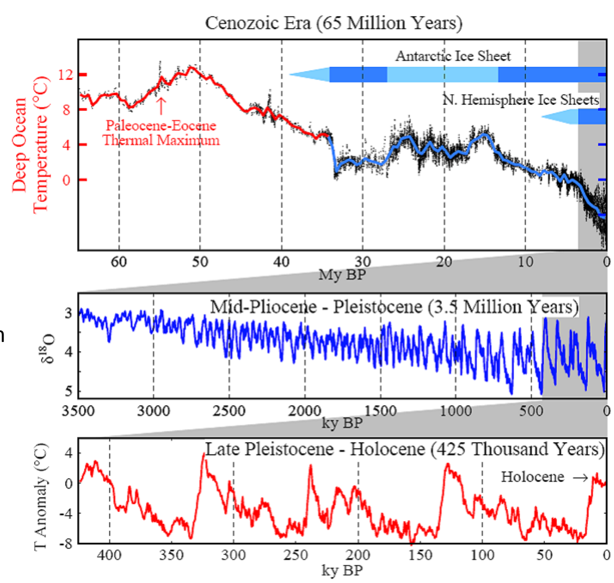
30 Mya: Drake passage, uplift of Himalaya's, Andean Mountains (increase weathering, draw down CO2)

25 Mya: Expansion of grassland habitats, draw down of CO2.

15 Mya: Columbia River volcanism (increase CO2)

5.5 Mya: closure of Panama
3 Mya, NOTE change from 41 ky to 100 ky cycles

1.0 Mya: transition from 41 Kyr(tilt) to 23+100 ky (precession) cycles.



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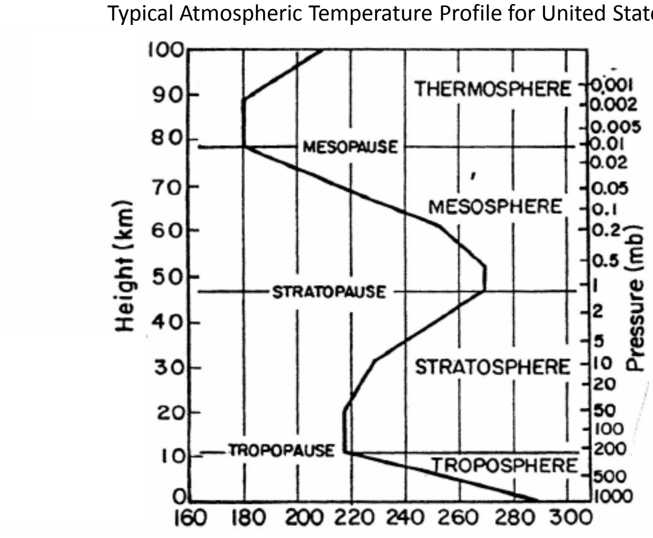
Satellite Spectroscopy Will Provide Many Answers to Help Quantify How Fast Climate is Changing

It Will Also Help to Better Predict What the Weather Will Be Like Locally in the Next 5 Days

Our Goal Is to Profile the Temperature of the Atmosphere at Various Altitudes Using Spectroscopy

Typical Atmospheric Temperature Profile for United States



Temperature (Kelvin)

22

Measuring Atmospheric Temperature Not Possible at Solar Wavelengths Due to High Solar Reflection

TABLE 3.3. Albedo (%) of Various Surfaces Integrated over Solar Wavelengths[a]

Bare soil	10–25
Sand, desert	25–40
Grass	15–25
Forest	10–20
Snow (clean, dry)	75–95
Snow (wet and/or dirty)	25–75
Sea surface (sun > 25° above horizon)	<10
Sea surface (low sun angle)	10–70

23

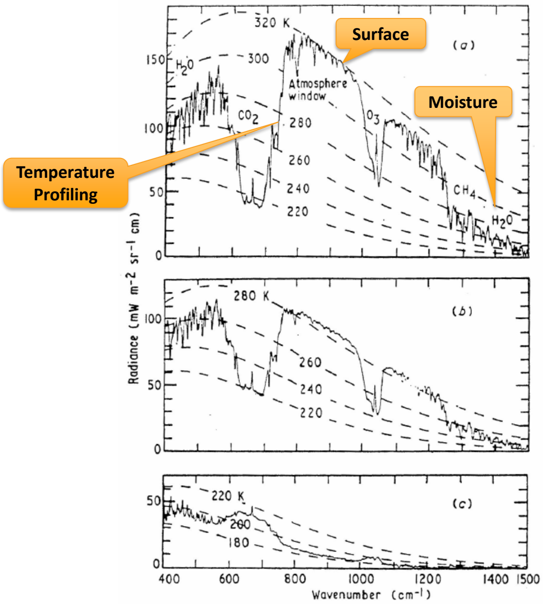
Scattering of Solar Energy by Clouds Prevents Use of Other Spectroscopic Wavelengths

Calculated Radiative Properties of a 2-km-thick Stratus Cloud[a]

Wavelength (μm)	*Absorbed* (%)	*Scattered* (%) *Out top*	*Scattered* (%) *Out bottom*
0.55	0.2	79.8	20.0
0.765	0.5	80.6	18.9
0.95	8.1	76.3	15.5
1.15	17.9	70.4	11.7
1.4	47.4	49.9	2.7
1.8	61.9	37.6	0.5
2.8	99.6	0.4	0.0
3.35	99.4	0.6	0.0
6.6	99.05	0.95	0.0
Total	10.0	73.8	16.6

24

Most Promising Range of Wavenumbers for Atmospheric Temperature & Moisture Observation



650 cm^{-1} – 1450 cm^{-1}
(15.4 um – 6.9 um)

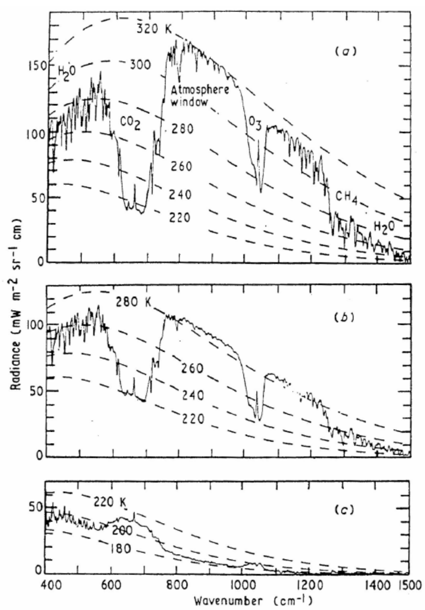
Sahara Dessert

Mediterranean

Antarctic

25

Spectroscopic Satellite Observations Can Determine Earth Surface Temperature



Sahara Dessert

Mediterranean

Antarctic

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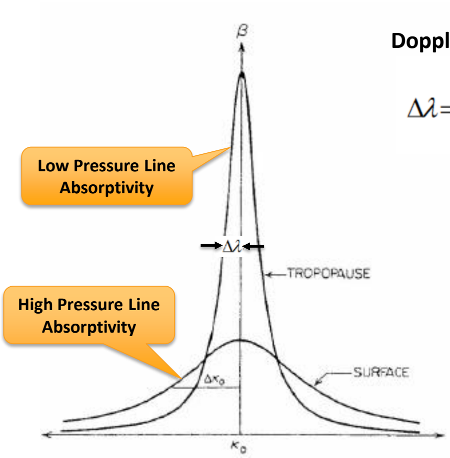
Atmospheric Gas Absorption Line has Narrow Width at Low Pressure…………..Dominated by "Doppler Broadening"



Doppler Broadening

$$\Delta\lambda = \frac{2\lambda}{c}\sqrt{\frac{2kT}{m}}$$

Mechanism of Doppler Broadening

In thermal equilibrium, the atoms in a gas, each of mass *m*, are moving randomly about with a distribution of speeds that is described by the Maxwell-Boltzmann distribution function, with the most probable speed given as

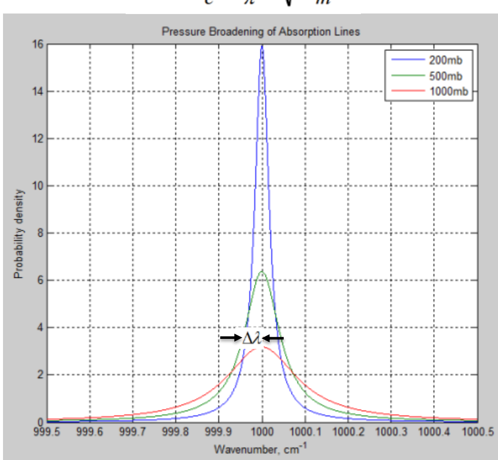
$$v_{mp} = \sqrt{2kT/m}$$

The wavelengths of light absorbed or emitted by the atoms in the gas are Doppler-shifted according to (nonrelativistic)

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c}$$

Shape of Gas Absorption Lines Can Be Changed By "Pressure Broadening & Temperature"

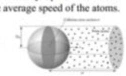
$$\Delta\lambda = \frac{\lambda^2}{c}\frac{n\sigma}{\pi}\sqrt{\frac{2kT}{m}}$$



Mechanism of Pressure Broadening

An estimate of pressure broadening due to collisions with atoms of a single element can be obtained by taking the value of Δt_o to be the average time between collisions. This time is approximately equal to the mean free path between collisions divided by the average speed of the atoms. The mean free path is

$$l = \frac{vt}{n\sigma vt} = \frac{1}{n\sigma}$$



and the speed is given by

$$v_{mp} = \sqrt{2kT/m}$$

So we find that

$$\Delta t_o = \frac{l}{v} = \frac{1}{n\sigma\sqrt{2kT/m}}$$

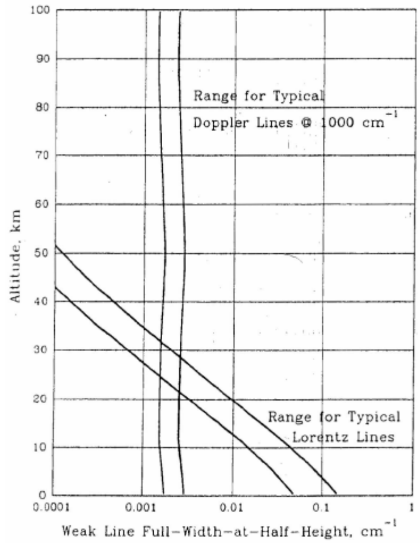
where *m* is the mass of an atom, σ is its collision cross section, and *n* is the number density of the atoms. Thus the **width of a spectral line due to pressure broadening** is on the order of

$$\Delta\lambda = \frac{\lambda^2}{c}\frac{1}{\pi\Delta t_o} \approx \frac{\lambda^2}{c}\frac{n\sigma}{\pi}\sqrt{\frac{2kT}{m}}$$

The width of the line is proportional to the number density *n* of the atoms.

Pressure Broadened Line Absorption Will Dominate for Altitudes of Greatest Interest

Variation of typical weak Lorentz and Doppler broadened lines through the Earth's atmosphere



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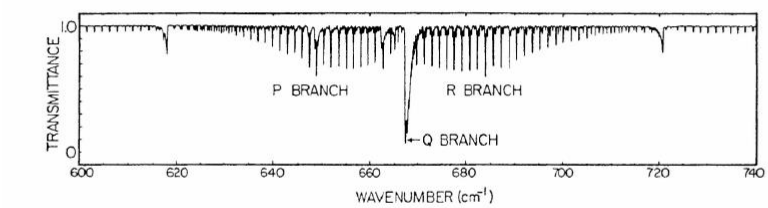
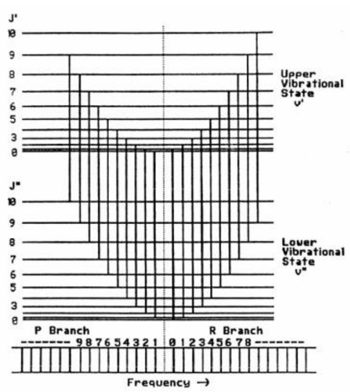
Many Discrete Vibration Modes Exist for CO2

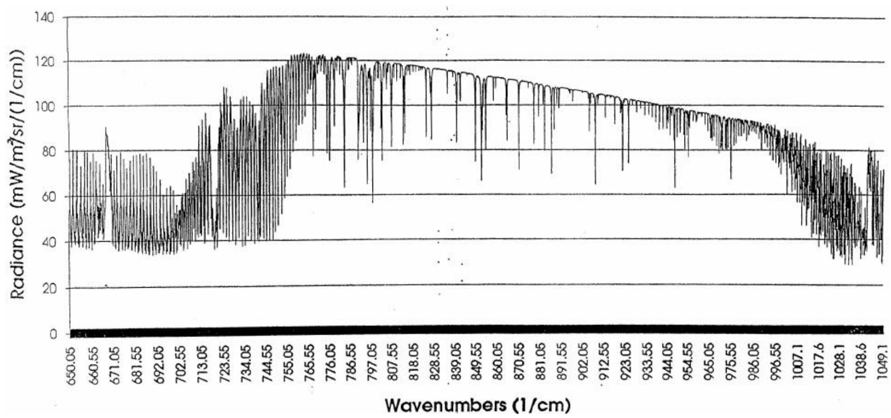




CO_2 Energy level diagram for two vibration states illustrates that large number of discrete transitions possible

30

Satellite Observation
When High Resolution Spectrometer Is Used
(0.1 wavenumber resolution)



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Example of How Atmospheric Temperature Changes Atmospheric Transmittance ($750\ cm^{-1}$ - $790\ cm^{-1}$)

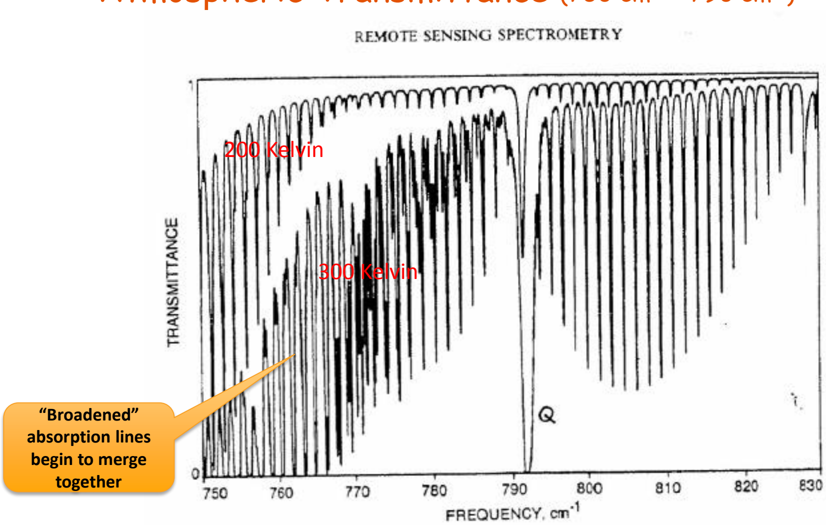

Figure 3.7. Example of the temperature dependence of a rotation–vibration band of carbon dioxide (CO_2). The gas abundance is the same in both cases; only the temperatures differ: *upper*, 200 K; *lower*, 300 K. Note also the strong Q branch in the middle of the figure.

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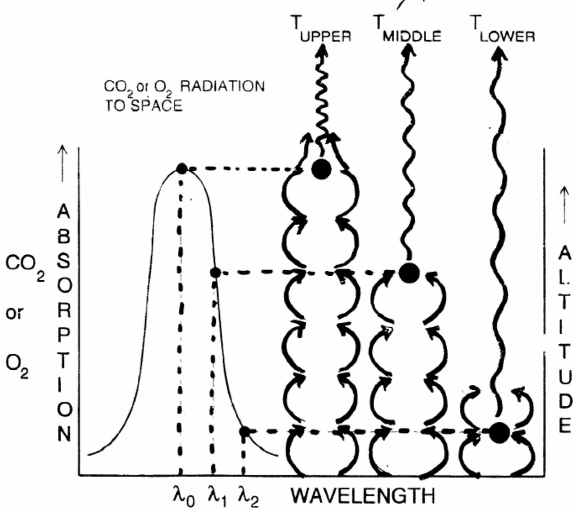
How We Measure & Profile Atmospheric Temperature

1) Absorption line properties
2) High Resolution Spectroscopy



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Sensitivity to Temperature Will Vary for Different Observation Wavelengths

Atmospheric Transmission

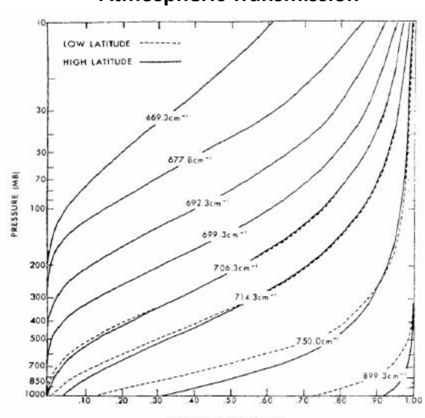
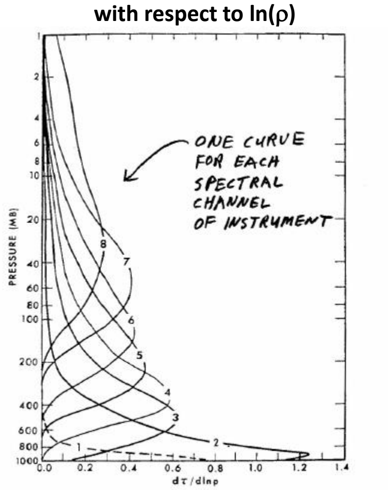


FIGURE 1.—Atmospheric transmission functions pertaining to the SIRS spectral intervals of observation for two different atmospheres.

Derivative of Transmission with respect to ln(ρ)



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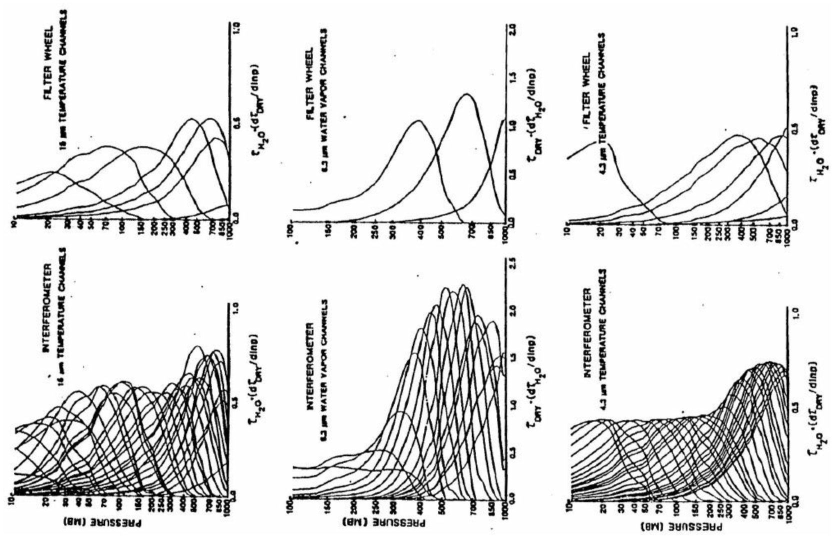
Top Row – Sensitivities for low resolution FW spectrometer
Bottom Row – Sensitivities for high resolution interferometer

Temperature Profiling | **Moisture Profiling** | **Temperature Profiling**



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Can Spectroscopic Satellite Observations Improve Our Response to These Types of Severe Weather Events?

Models need to be improved and observations need to be improved to better predict

- Hurricane landfall
- Expected changes of hurricane intensity

Spectroscopy introduces a new dimension to these observations that better tracks wind patterns above and around severe weather

Katrina, Aug 28, 2005

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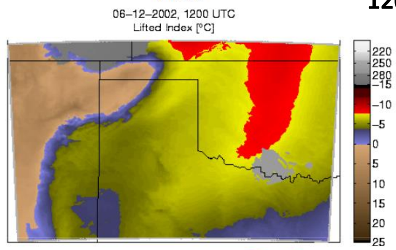
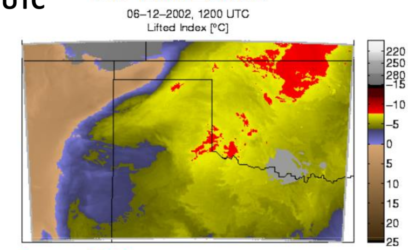
Severe Weather Prediction from Four Perspectives

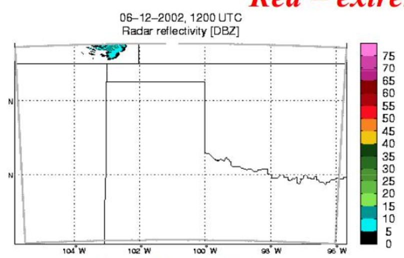
Jun Li, Jinlong Li, Jason Otkin, and Tim Schmit

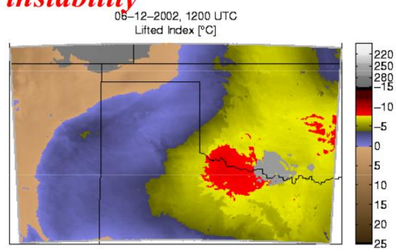
True | **1200 UTC** | **GIFTS/HES/IRS**





Red = extreme instability



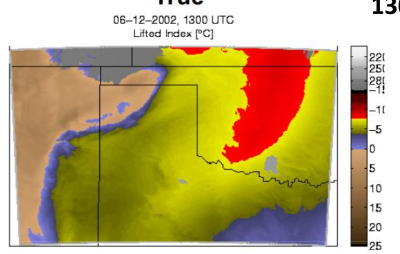


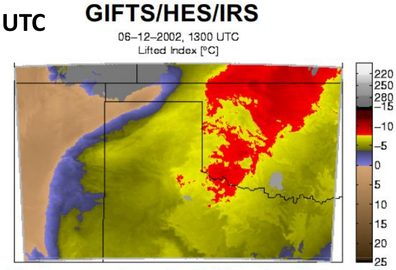
Simulated Radar | **ABI/GOES Sounder like**

37

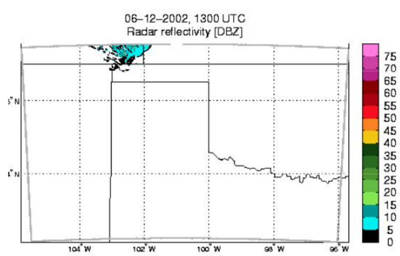
Beginning of Wide Area Instability Is Recognized by Hyperspectral Satellite Sensor

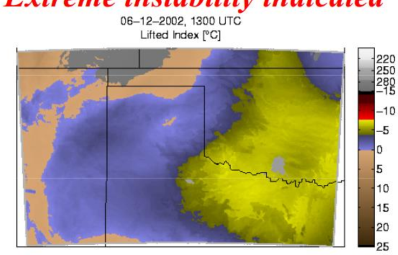
True | **1300 UTC** | **GIFTS/HES/IRS**





Extreme instability indicated

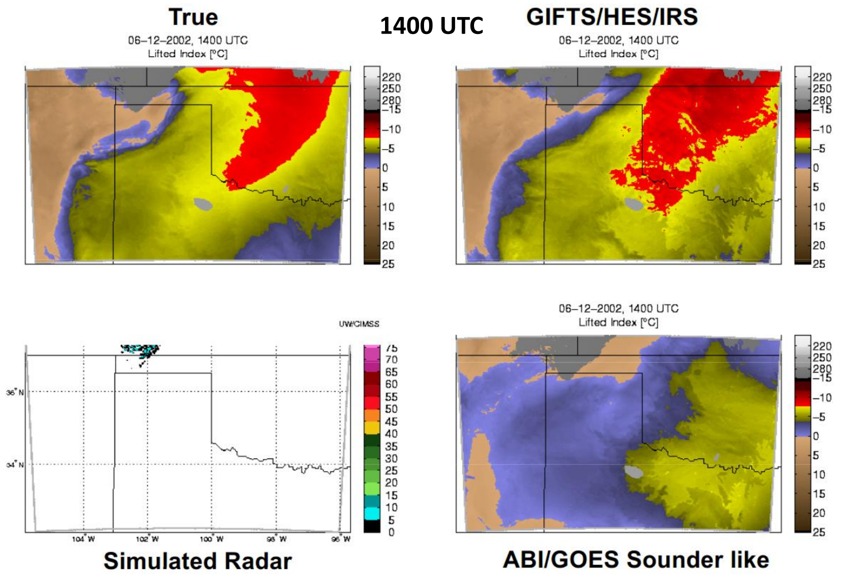




Simulated Radar | **ABI/GOES Sounder like**

38

1 Hour Later



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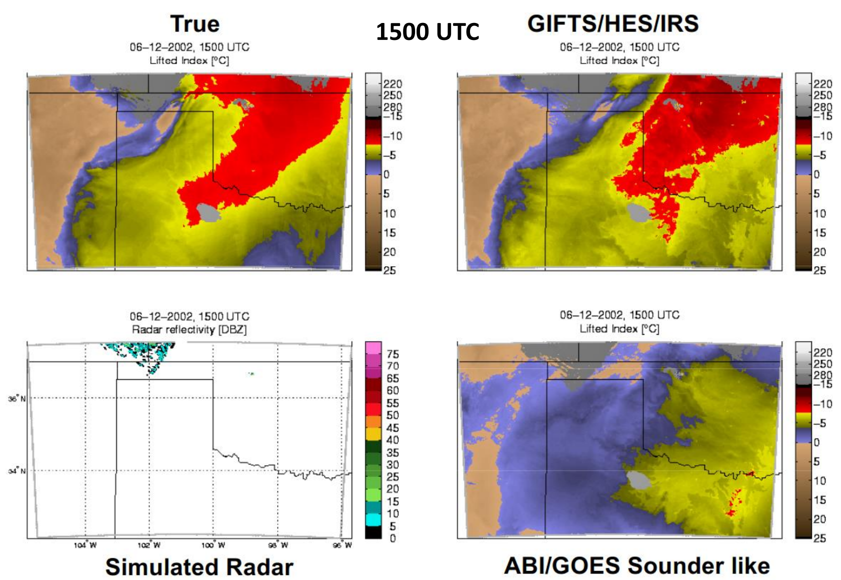
2 Hours Later



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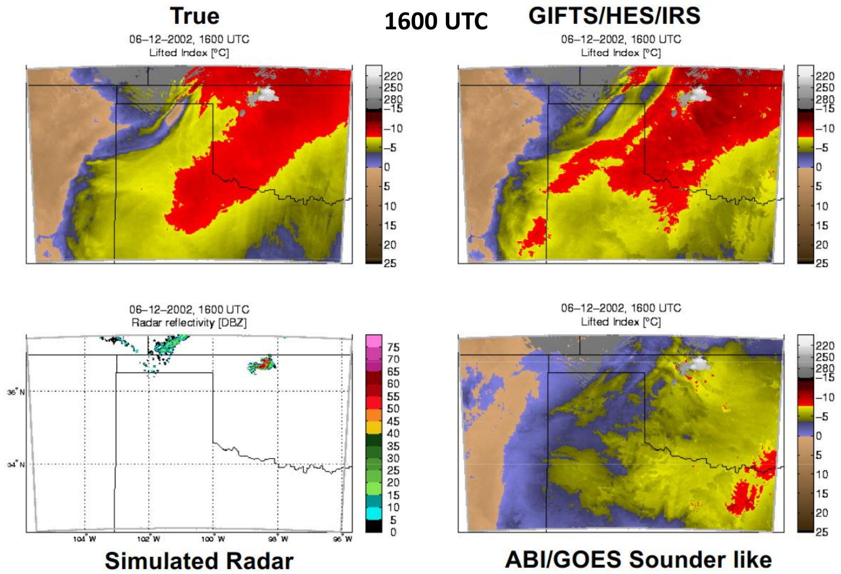
3 Hours Later



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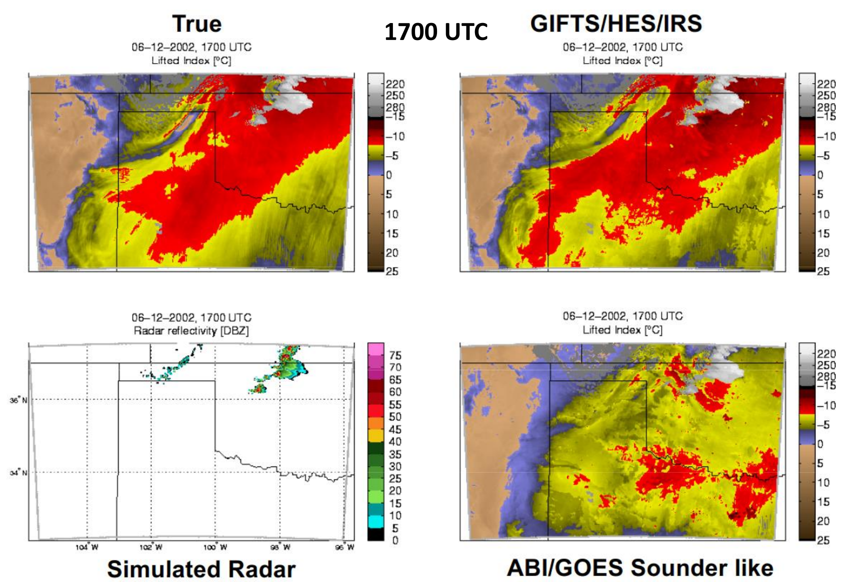
Start to See Extreme Instability 4 Hours Later



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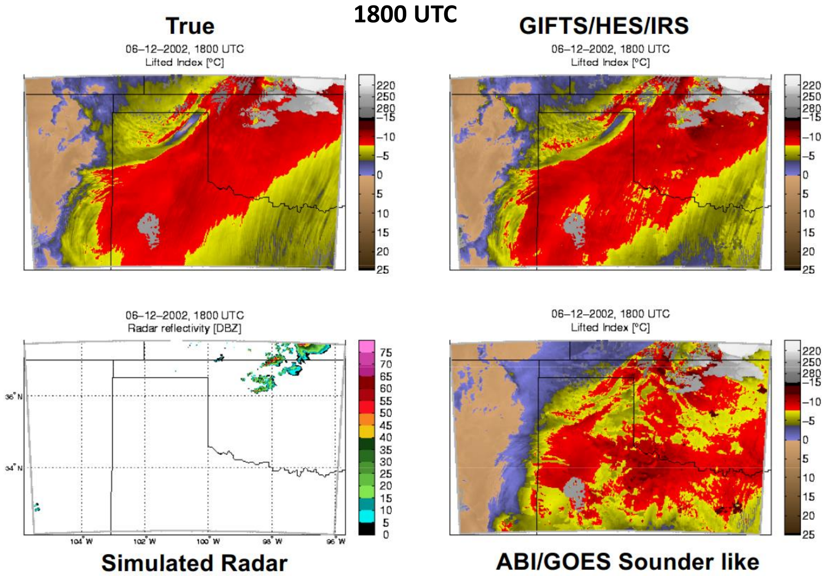
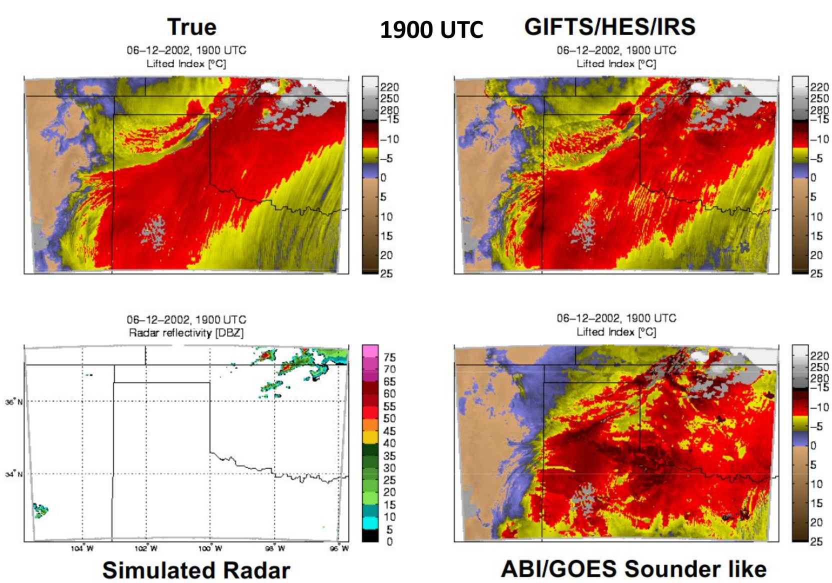
Extreme Instability Clearly Shown 5 Hours Later but Note False Alarms with Current Technology



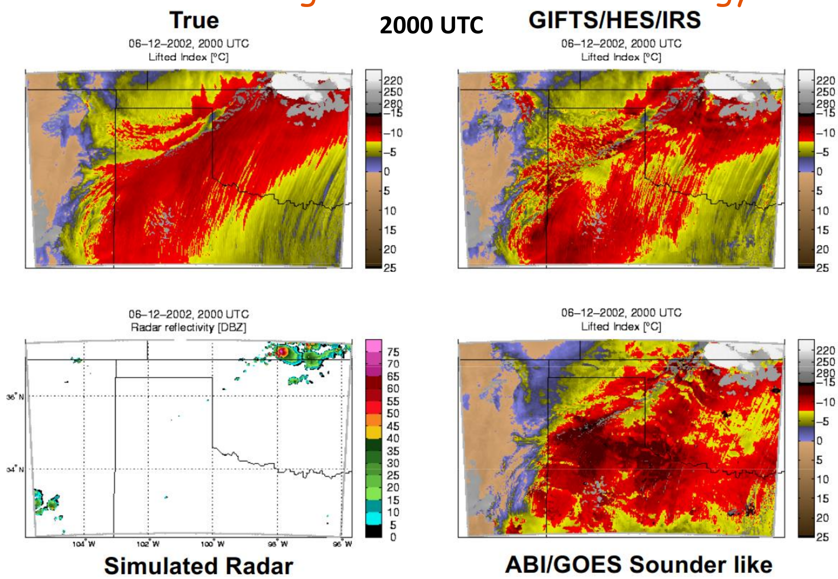
43

6 Hours Later



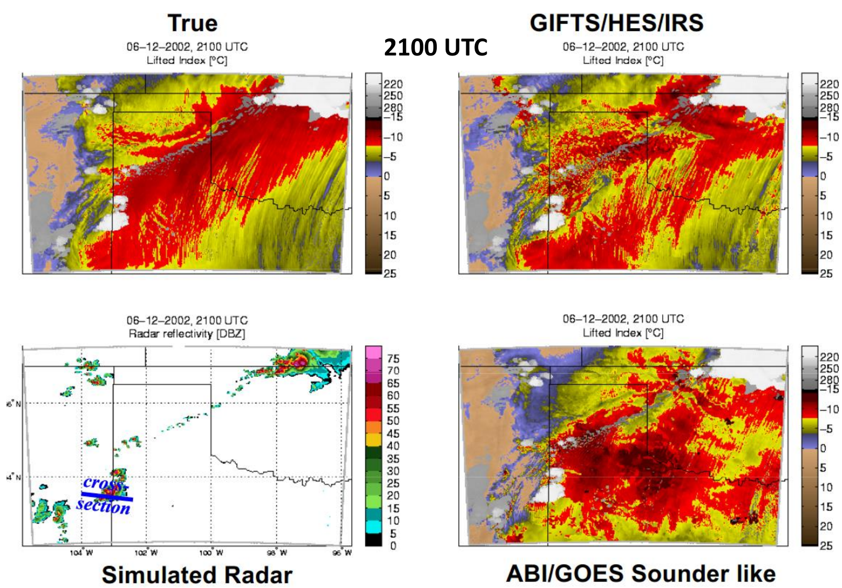
44

Hyperspectral Technology Improves Reliability of Storm Warnings Over Current Technology



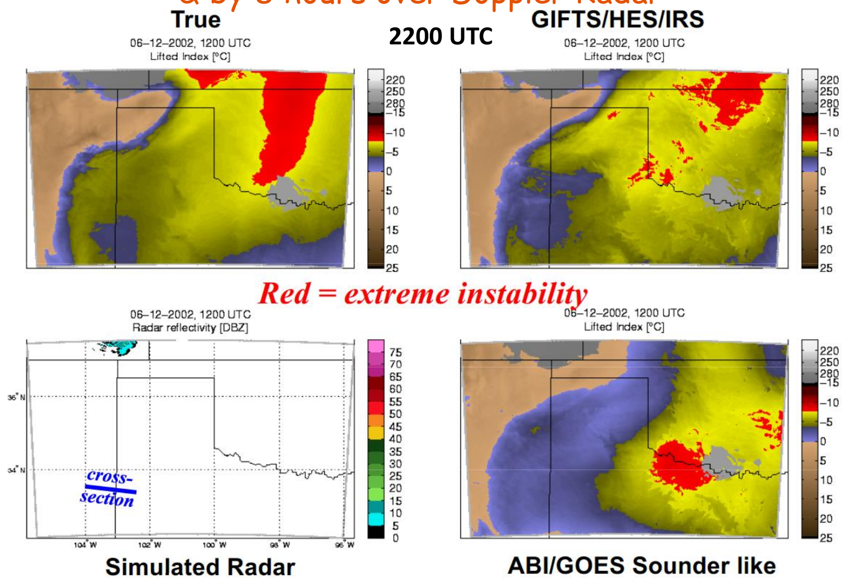
45

Rain Line Shows in Doppler Radar 8 hours Later



46

Hyperspectral Sensors Can Improve Severe Weather Prediction by 4 – 5 hours over Current Space Technology & by 8 hours over Doppler Radar



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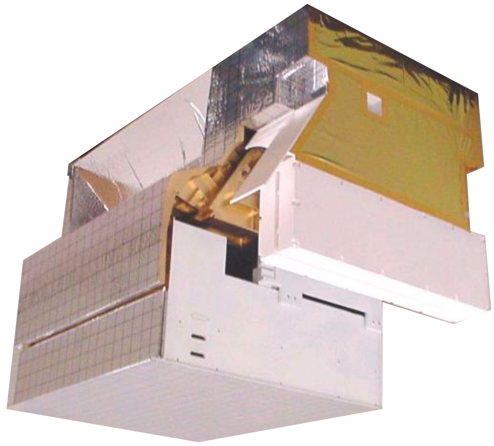
Precision Hysperspectral Satellite Cameras Are Being Developed to Better Trend Climate and Provide Better Weather Forecasting Capability

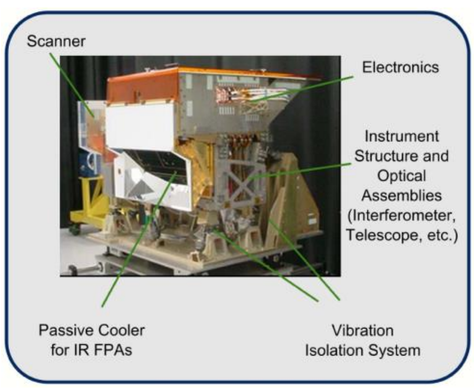
Fourier Transform Spectrometer Built By ITT Exelis in Fort Wayne, Indiana…………Now on-orbit to Improve NASA/NOAA Long Range Weather Forecasting



49

1305 Spectral Channels Covering the Infrared Spectrum with High Radiometric Sensitivity and Accuracy

Cross-track Infrared Sounder



- Large 8 cm Clear Aperture
- Three Spectral Bands
  - LWIR: 650-1095 cm^{-1}
  - MWIR: 1210-1750 cm^{-1}
  - SWIR: 2155-2550 cm^{-1}
- 1305 Total Spectral Channels
- 0.625 cm^{-1} spectral resolution
- 3x3 FOVs at 14 km Diameter
- Photovoltaic Detectors in All 3 Bands
- 4-Stage Passive Detector Cooler
- Plane-Mirror Interferometer With DA
- Internal Laser Wavelength Calibration
- Deep-Cavity Internal Calibration Target
- Passive Vibration Isolation System Allows Robust Operation in 50 mG Environment

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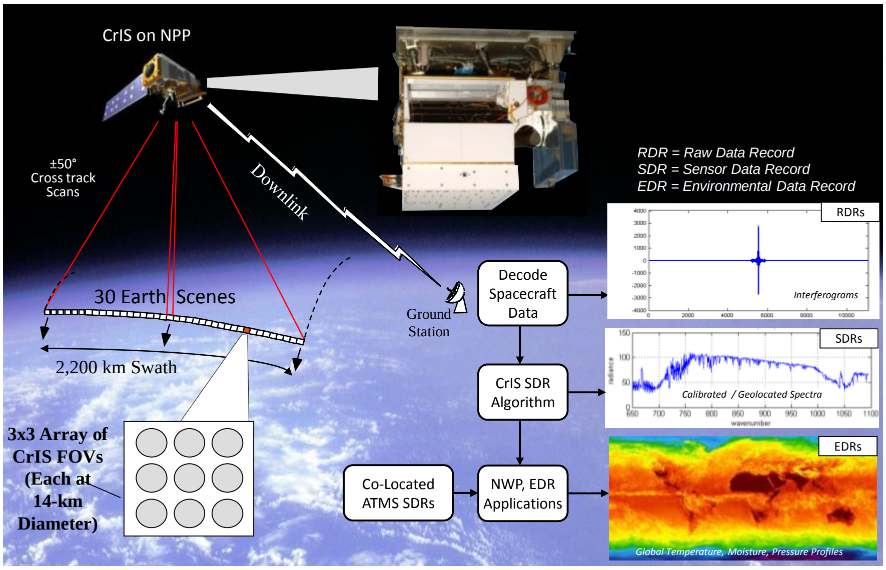
3 x 3 Hyperspectral Detector Array Step Scanned Across Earth Surface Ground Algorithms then Calibrate Observations & Convert to Science



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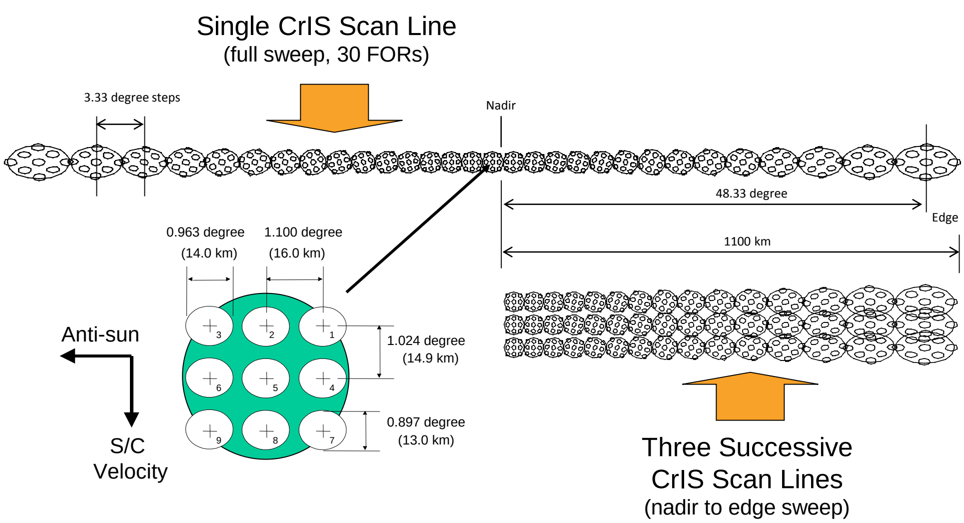
3x3 Pixel Hyperspectral Array Used to Scan Earth Surface



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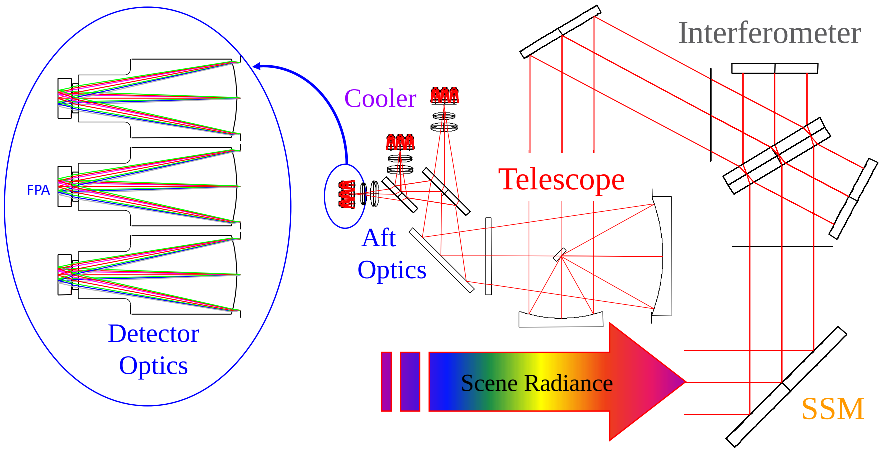
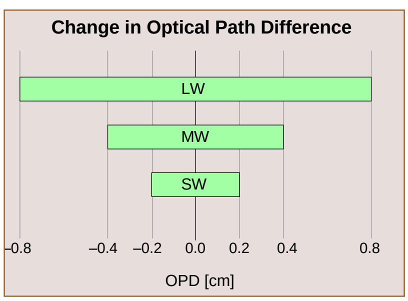
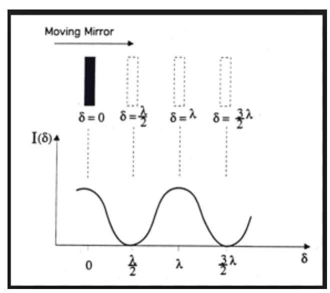
Partially Unfolded CrIS Optical System Shows Flow of Signal Radiance to Detectors

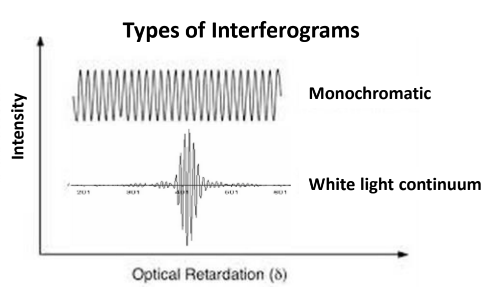


Optics are Uncooled From Telescope Forward

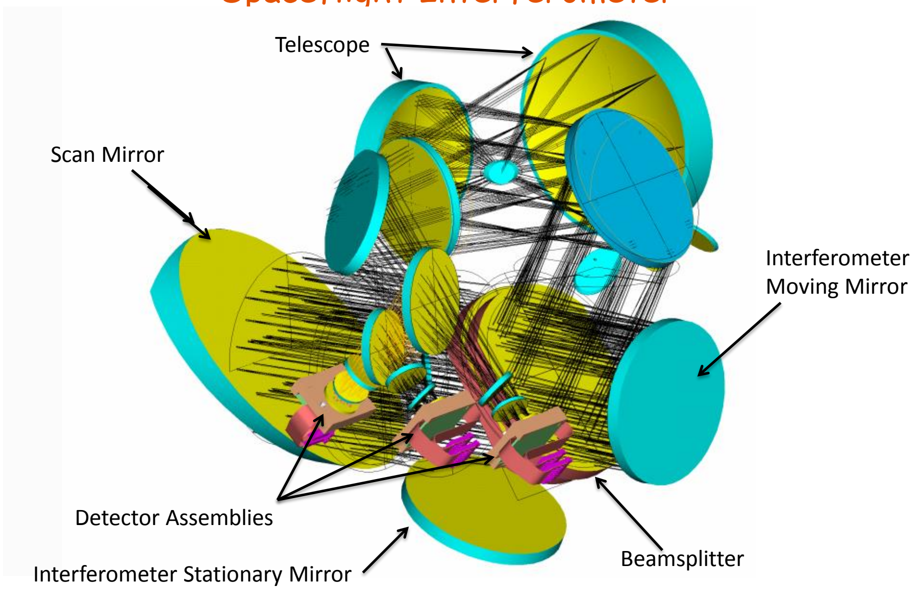
Interferograms Are Generated Using a Moving Mirror



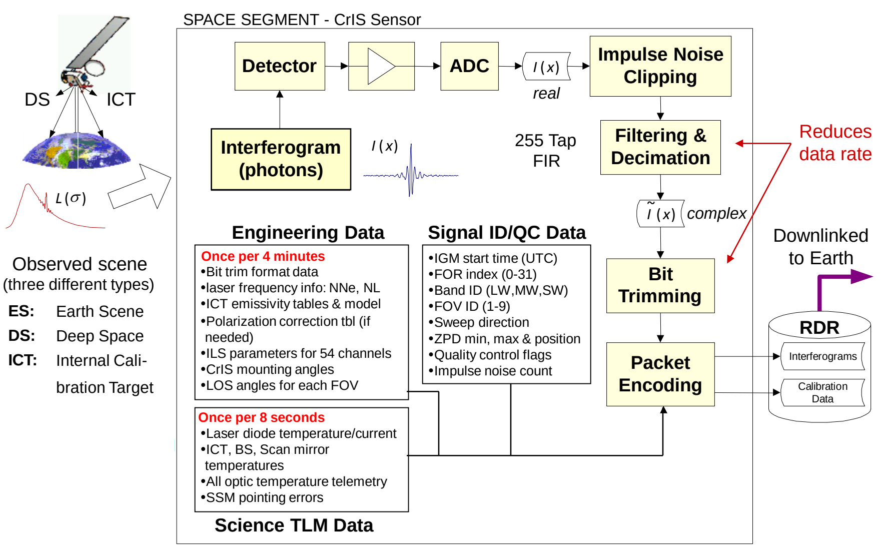




Example of Compact Optics Packaging for Spaceflight Interferometer

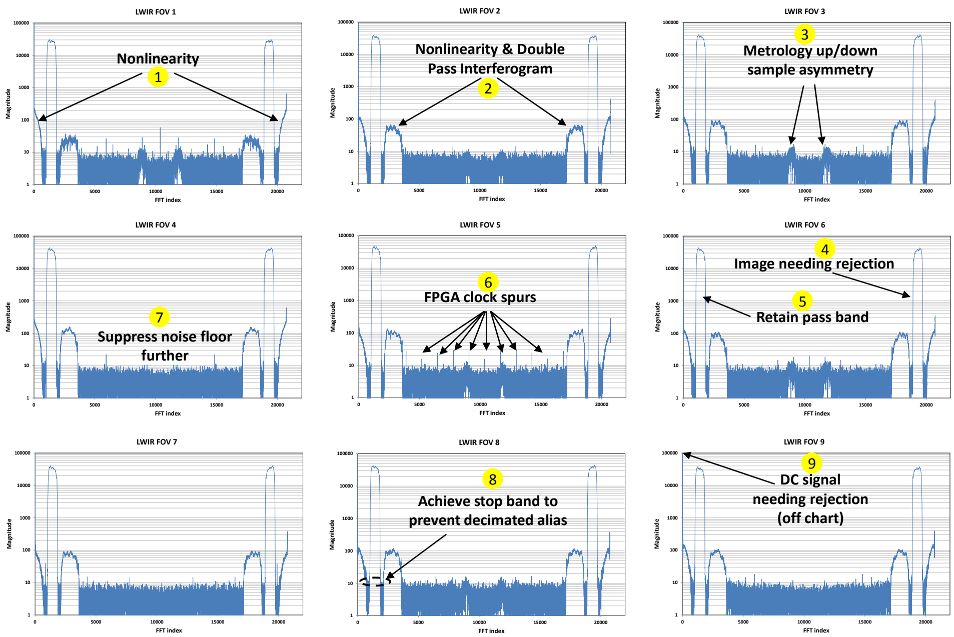


Satellite Collects Interferogram Data for Transmission to Ground

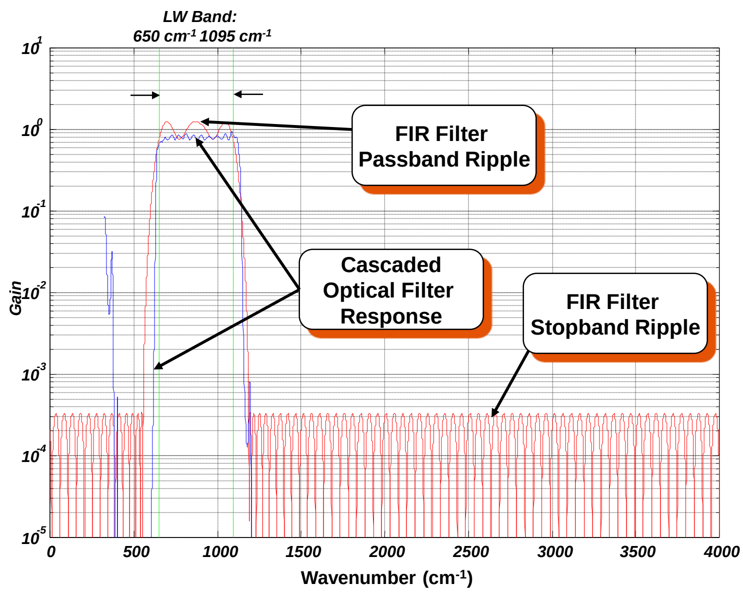


Only Processing of Science Data Shown

Typical Spectrum with 20,736 DFT Bins



255 Tap Digital Filter & Optical Filter Eliminates Out of Band Artifacts Prior to Data Compression



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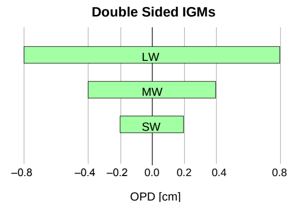
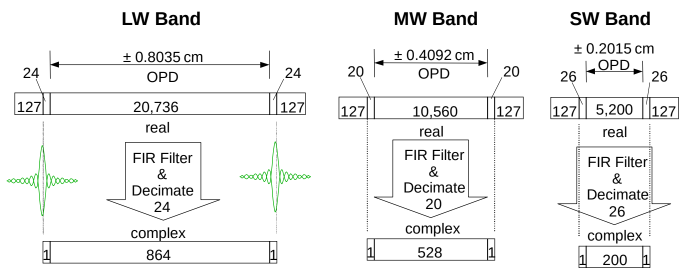
Filtering and Decimation Reduces Downlink Data Rates

CrIS Interferogram Measurements





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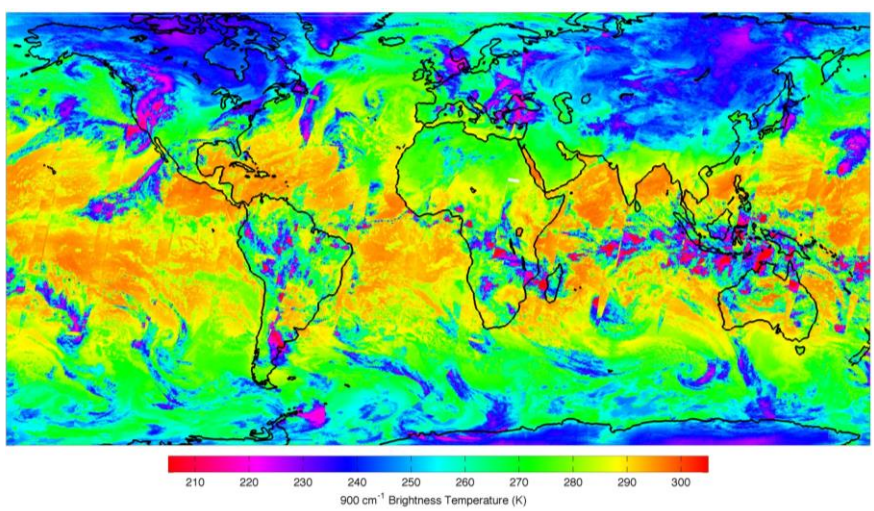
Typical Brightness Temperature Map of Earth from Hyperspectral Weather Satellite



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