Summary of Satellite Remote Sensing Concepts

Madison
29 Mar 2013

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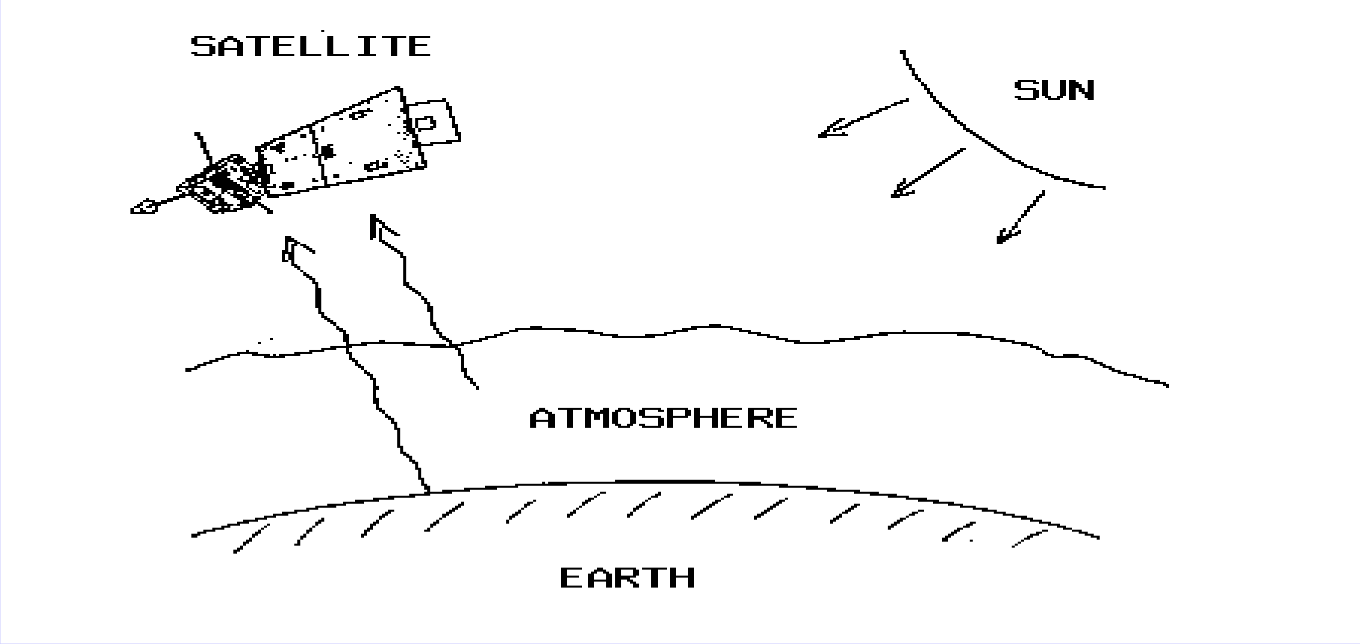
UW/CIMSS

Satellite remote sensing of the Earth-atmosphere

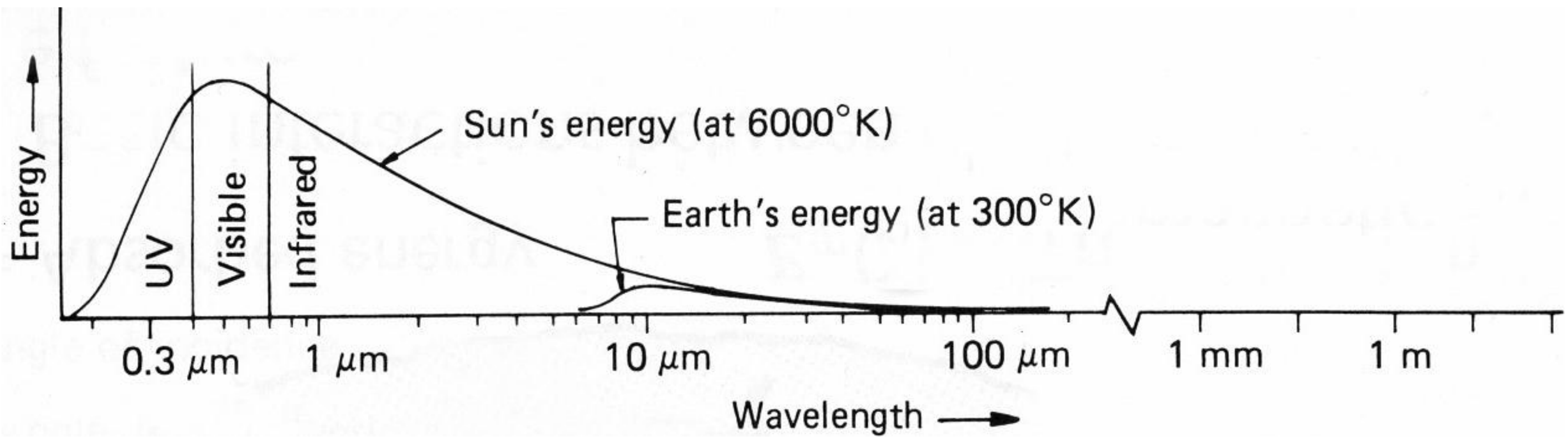


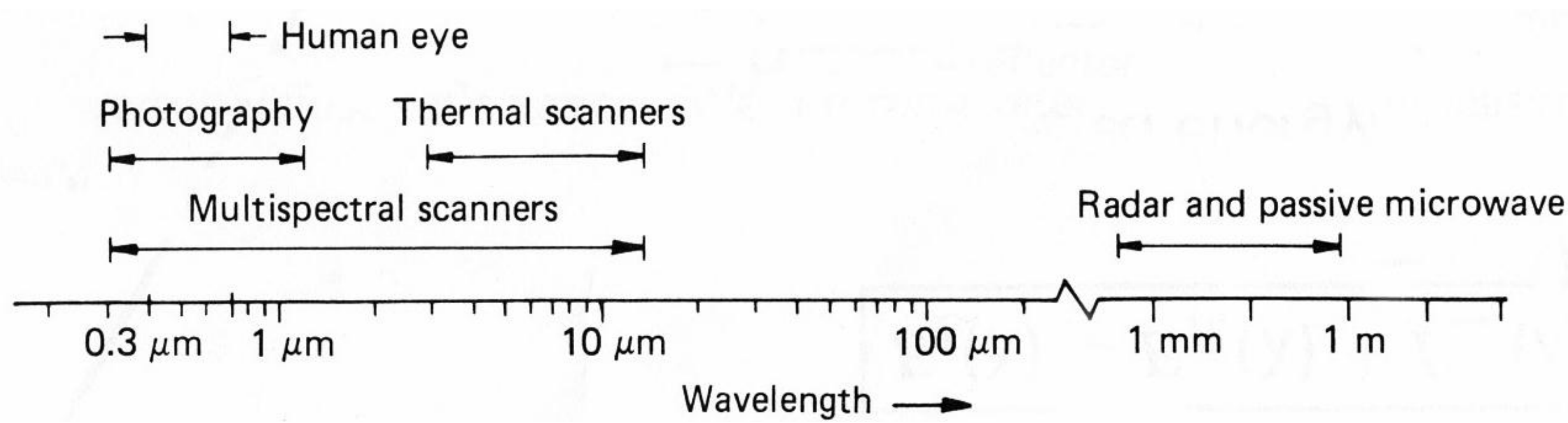
Observations depend on

telescope characteristics (resolving power, diffraction)
detector characteristics (signal to noise)
communications bandwidth (bit depth)
spectral intervals (window, absorption band)
time of day (daylight visible)
atmospheric state (T, Q, clouds)
earth surface (Ts, vegetation cover)

Radiation and the Planck Function

Spectral Characteristics of Energy Sources and Sensing Systems





Terminology of radiant energy

Energy from the Earth Atmosphere

over time is

Flux

which strikes the detector area

Irradiance

at a given wavelength interval

Monochromatic Irradiance

over a solid angle on the Earth

Radiance observed by satellite radiometer

is described by

The Planck function

can be inverted to

Brightness temperature

Definitions of Radiation

QUANTITY	SYMBOL	UNITS
Energy	dQ	Joules
Flux	dQ/dt	Joules/sec = Watts
Irradiance	dQ/dt/dA	Watts/meter^2
Monochromatic Irradiance	dQ/dt/dA/dλ	W/m^2/micron
	or	
	dQ/dt/dA/dν	W/m^2/cm^{-1}
Radiance	dQ/dt/dA/dλ/dΩ	W/m^2/micron/ster
	or	
	dQ/dt/dA/dν/dΩ	W/m^2/cm^{-1}/ster

Using wavenumbers

$$B(\nu,T) = c_1\nu^3 / [e^{c_2\nu/T} - 1]$$

$(mW/m^2/ster/cm^{-1})$

ν(max in cm-1) = 1.95T

$B(\nu_{max},T) \sim T^{**}3.$

$$E = \pi \int_o^\infty B(\nu,T)\, d\nu = \sigma T^4,$$

$$T = c_2\nu/[\ln(\frac{c_1\nu^3}{B_\nu} + 1)]$$

Using wavelengths

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} - 1] \}$$

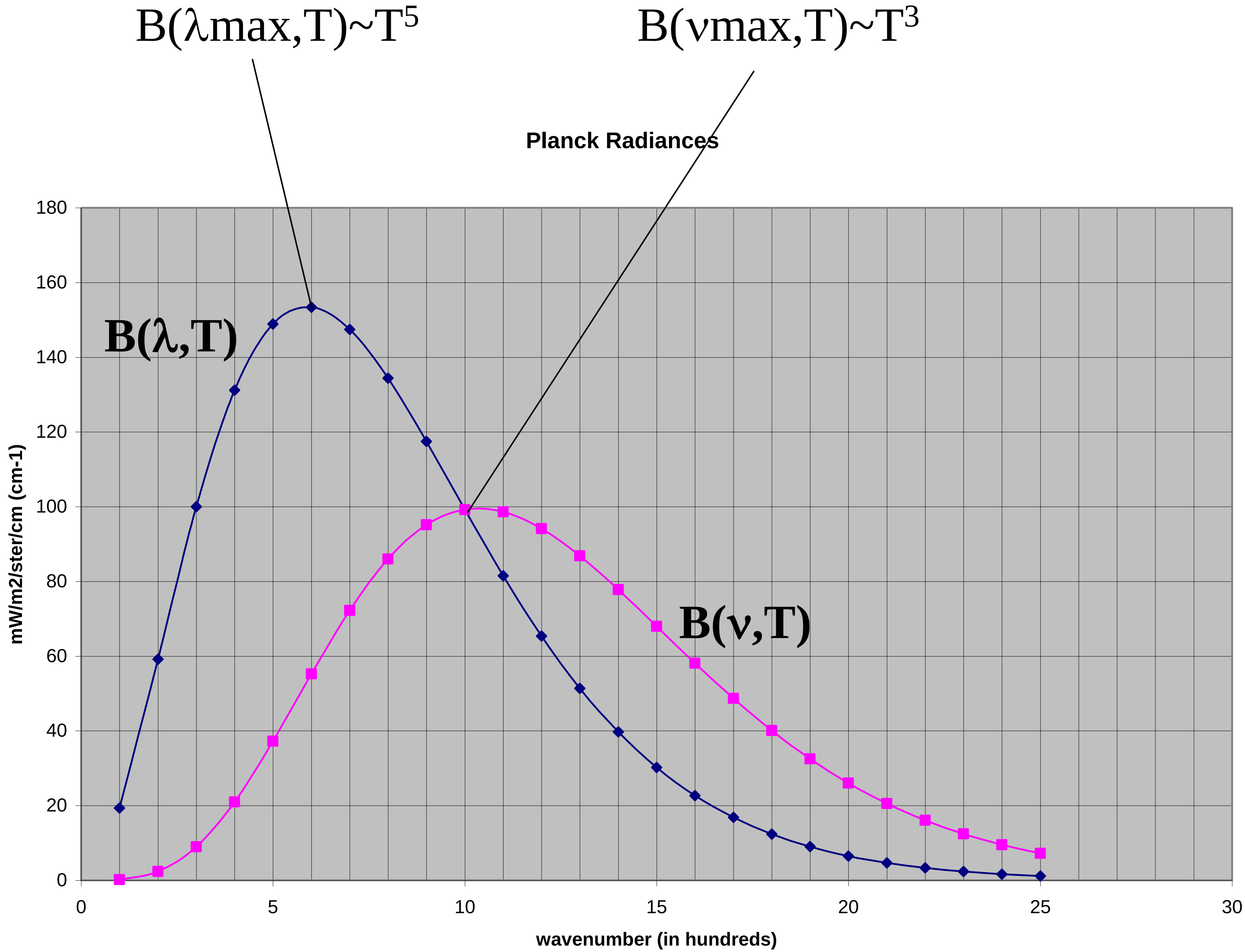
$(mW/m^2/ster/\mu m)$

λ(max in cm)T = 0.2897

$B(\lambda_{max},T) \sim T^{**}5.$

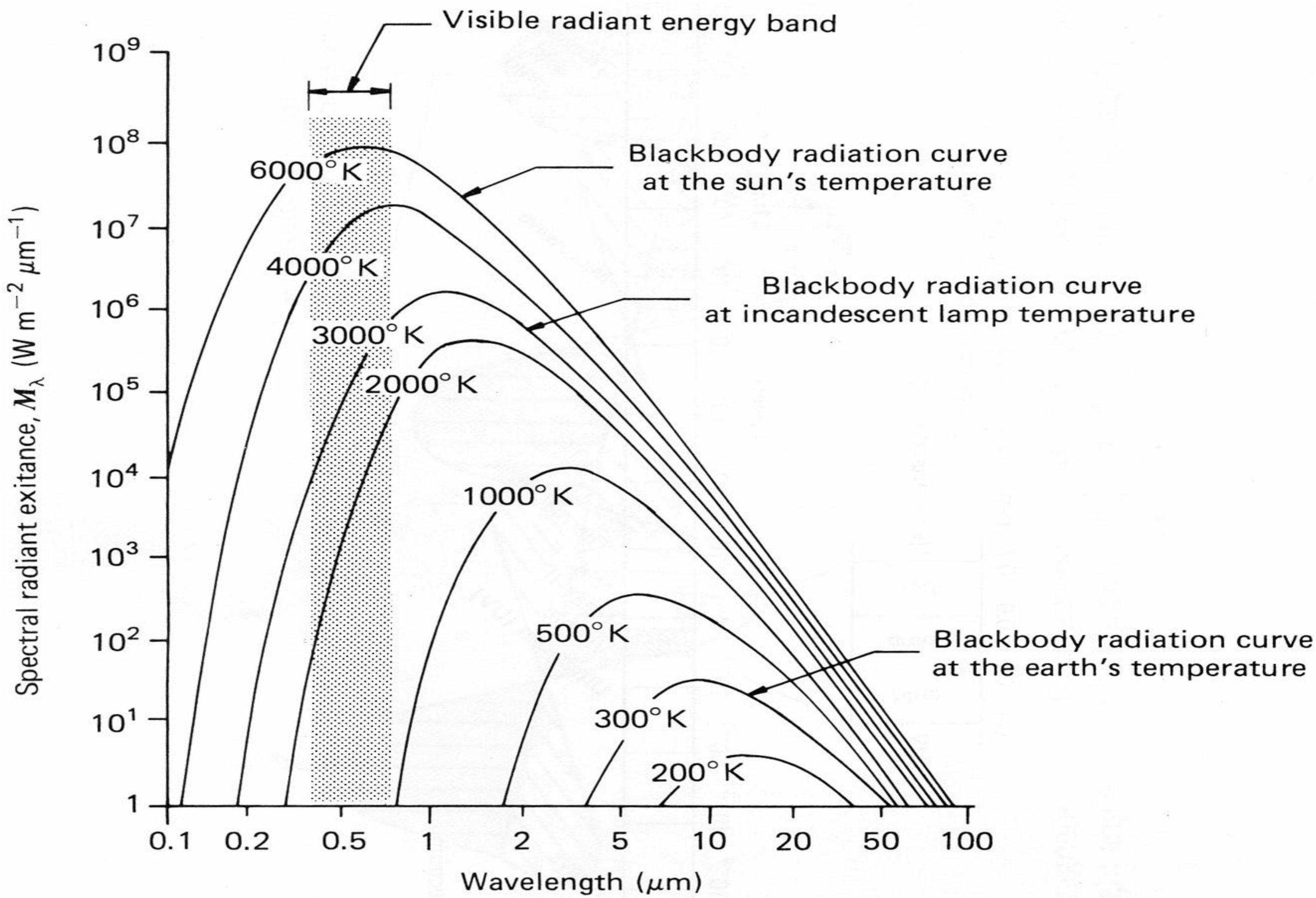
$$E = \pi \int_o^\infty B(\lambda,T)\, d\lambda = \sigma T^4,$$

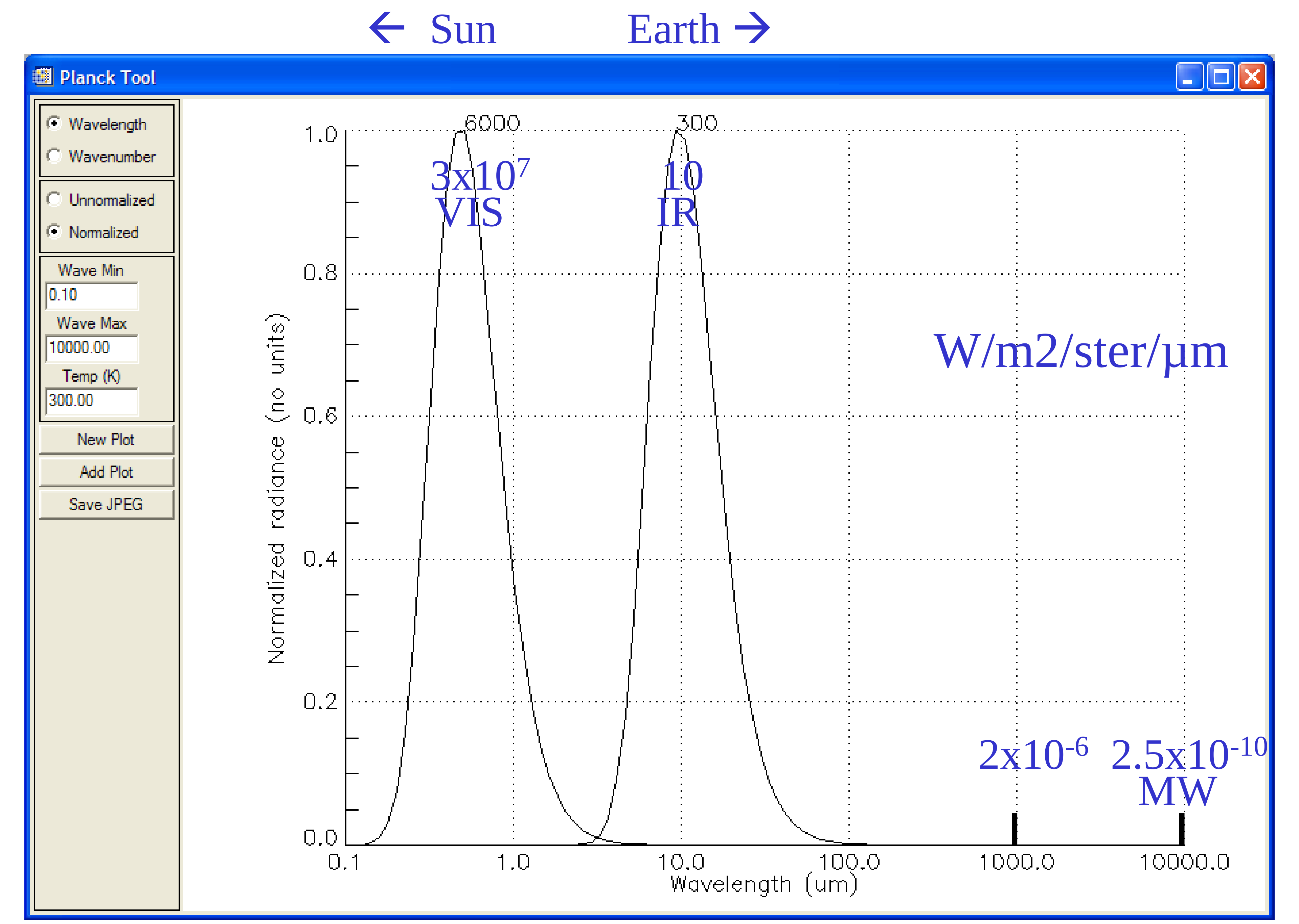
$$T = c_2/[\lambda \ln(\frac{c_1}{\lambda^5 B_\lambda} + 1)]$$



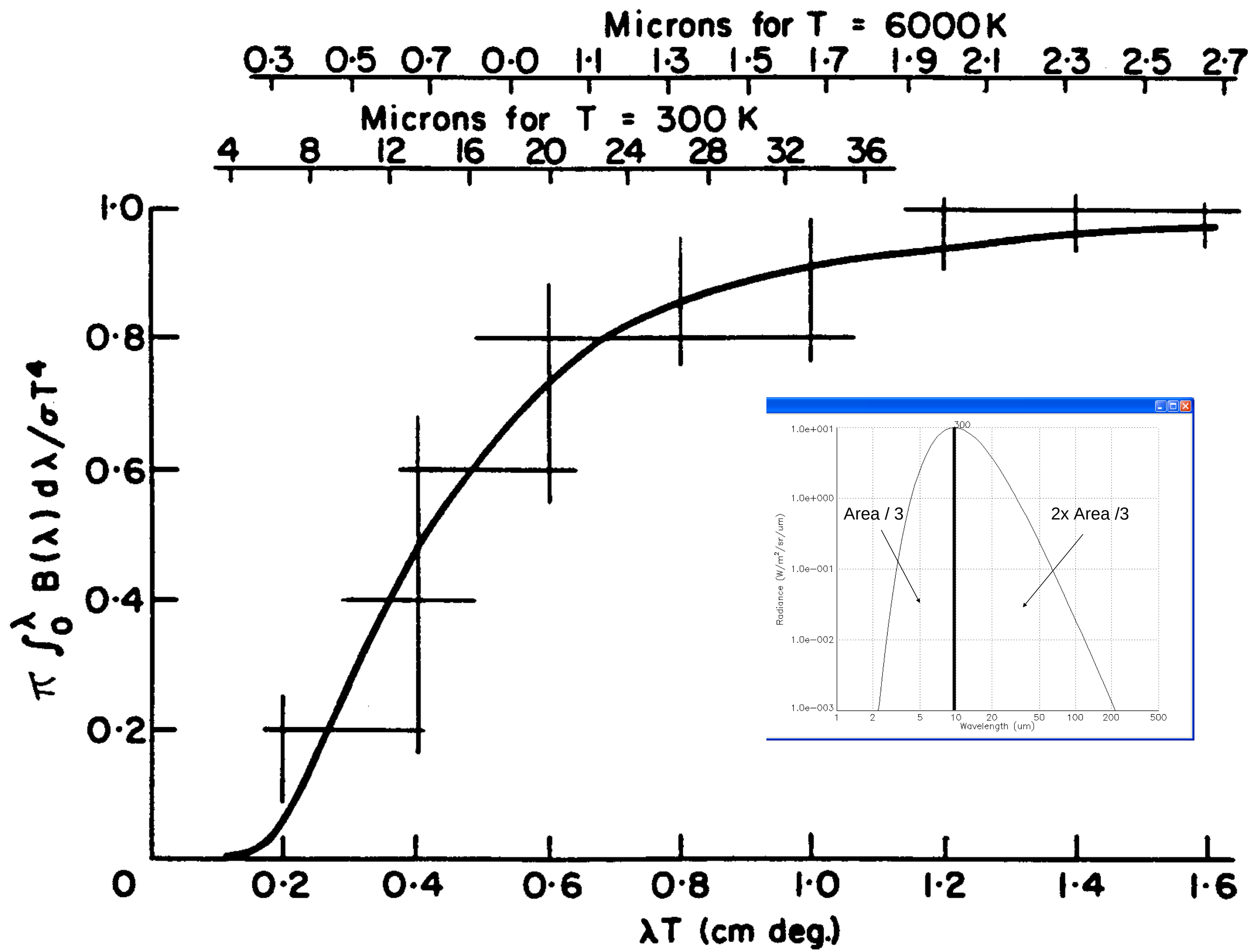
B(λ,T) versus B(ν,T)

Spectral Distribution of Energy Radiated from Blackbodies at Various Temperatures

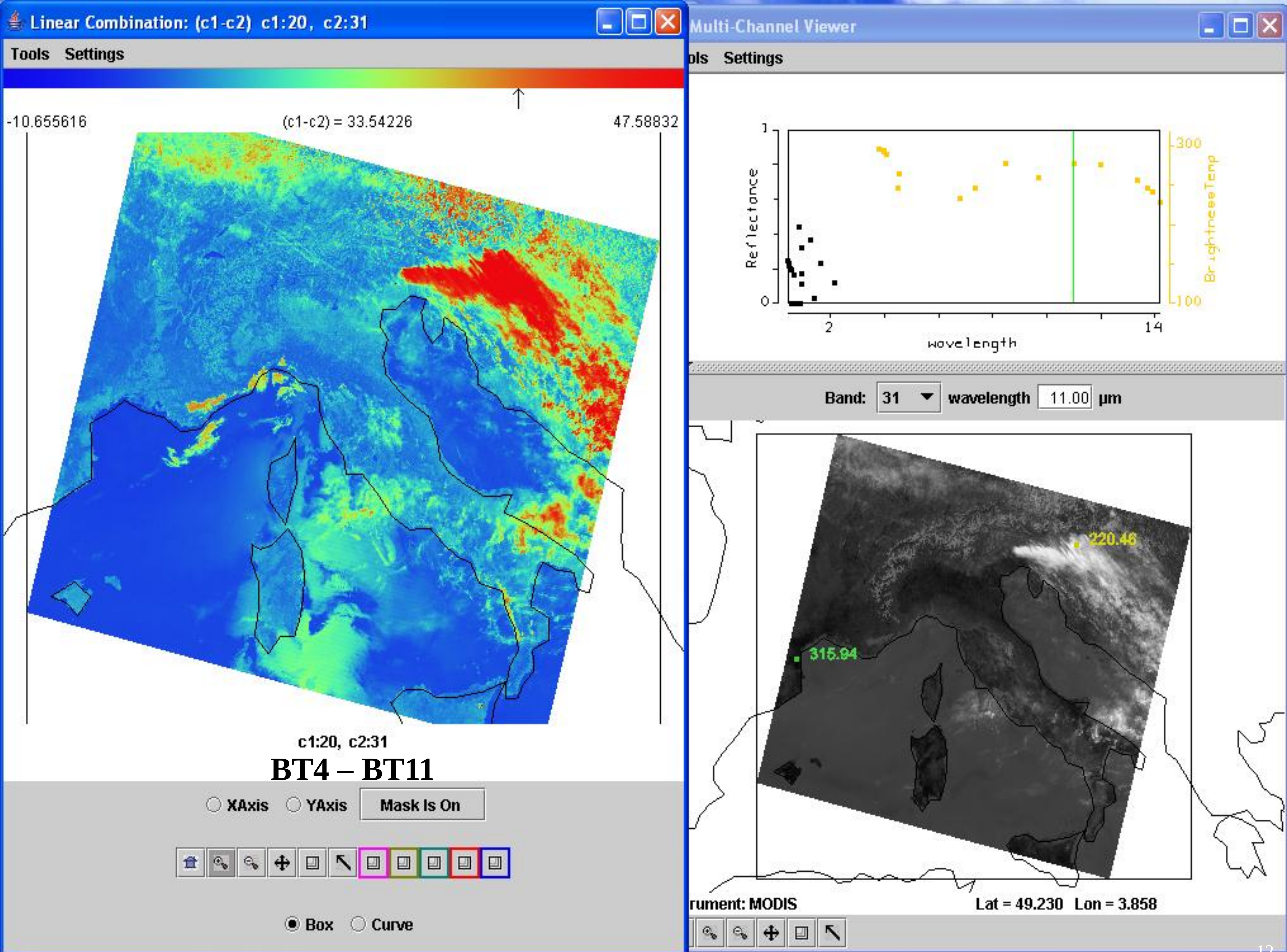




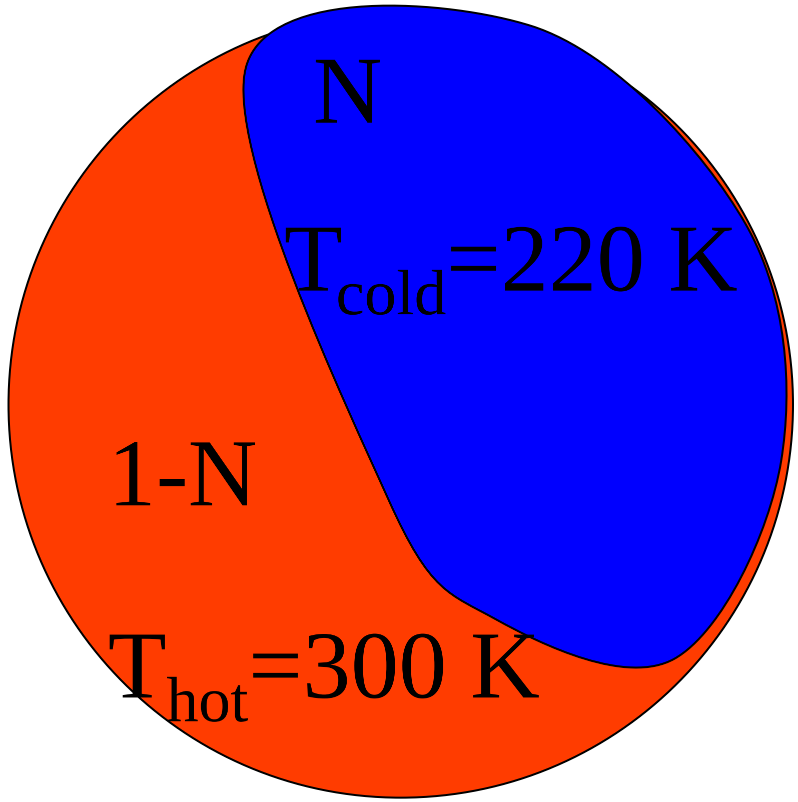
← Sun
Earth →
Planck Tool
Wavelength
Wavenumber
Unnormalized
Normalized
Wave Min
0.10
Wave Max
10000.00
Temp (K)
300.00
New Plot
Add Plot
Save JPEG
6000
300
3x10^7
VIS
10
IR
W/m2/ster/µm
2x10^-6
2.5x10^-10
MW
Normalized radiance (no units)
1.0
0.8
0.6
0.4
0.2
0.0
0.1
1.0
10.0
100.0
1000.0
10000.0
Wavelength (um)



Microns for T = 6000K
0·3 0·5 0·7 0·0 1·1 1·3 1·5 1·7 1·9 2·1 2·3 2·5 2·7
Microns for T = 300 K
4 8 12 16 20 24 28 32 36
1·0 0·8 0·6 0·4 0·2 0
$\pi \int_0^\lambda B(\lambda)\, d\lambda / \sigma T^4$
0·2 0·4 0·6 0·8 1·0 1·2 1·4 1·6
λT (cm deg.)
Area / 3
2x Area /3
300
1.0e+001
1.0e+000
1.0e−001
1.0e−002
1.0e−003
Radiance (W/m²/sr/um)
1 2 5 10 20 50 100 200 500
Wavelength (um)


Linear Combination: (c1-c2) c1:20, c2:31
Tools Settings
-10.655616
(c1-c2) = 33.54226
47.58832
c1:20, c2:31
BT4 – BT11
XAxis
YAxis
Mask Is On
Box
Curve
Multi-Channel Viewer
Settings
Reflectance
BrightnessTemp
wavelength
Band: 31
wavelength 11.00 µm
220.46
315.94
Lat = 49.230 Lon = 3.858

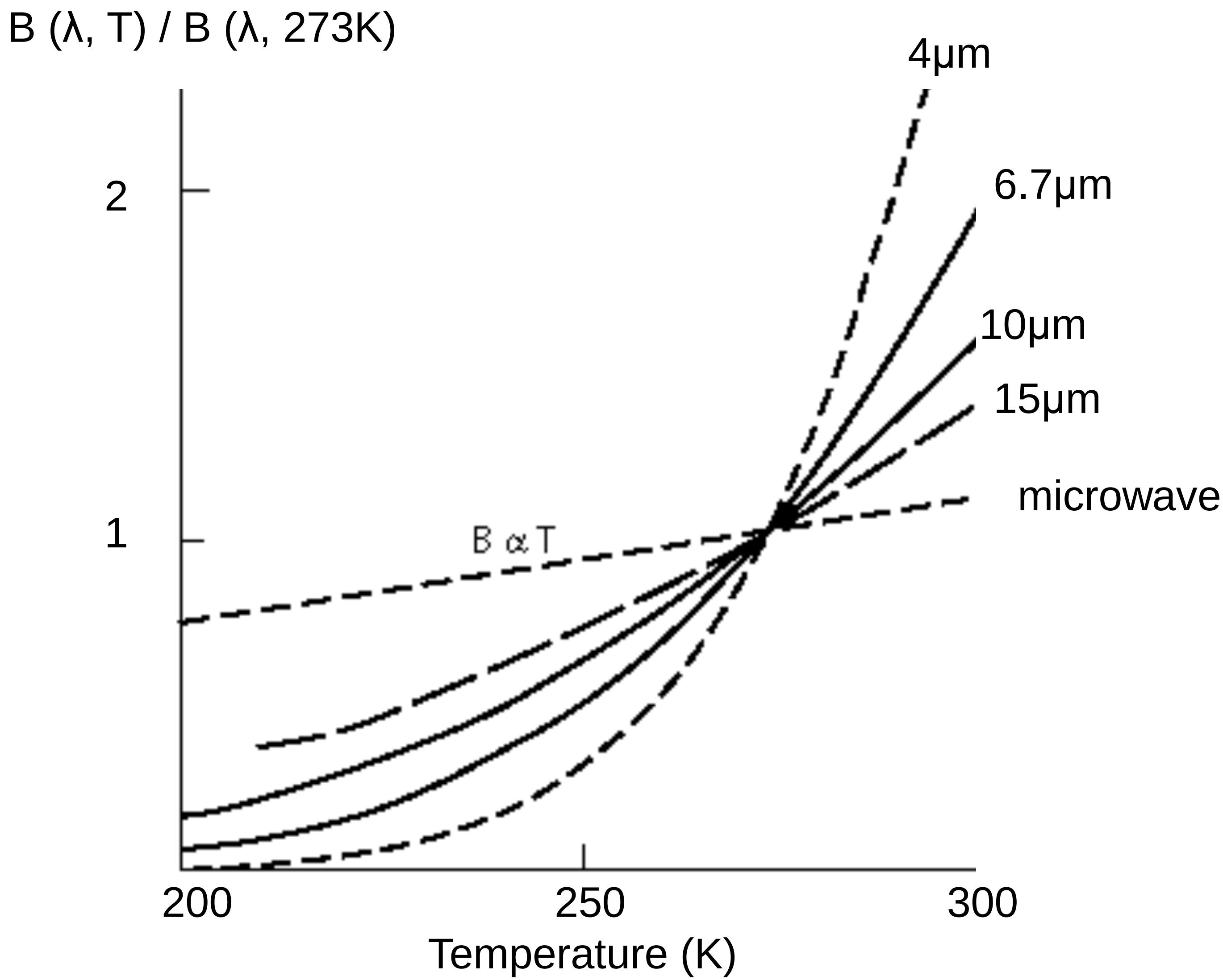
Non-Homogeneous FOV

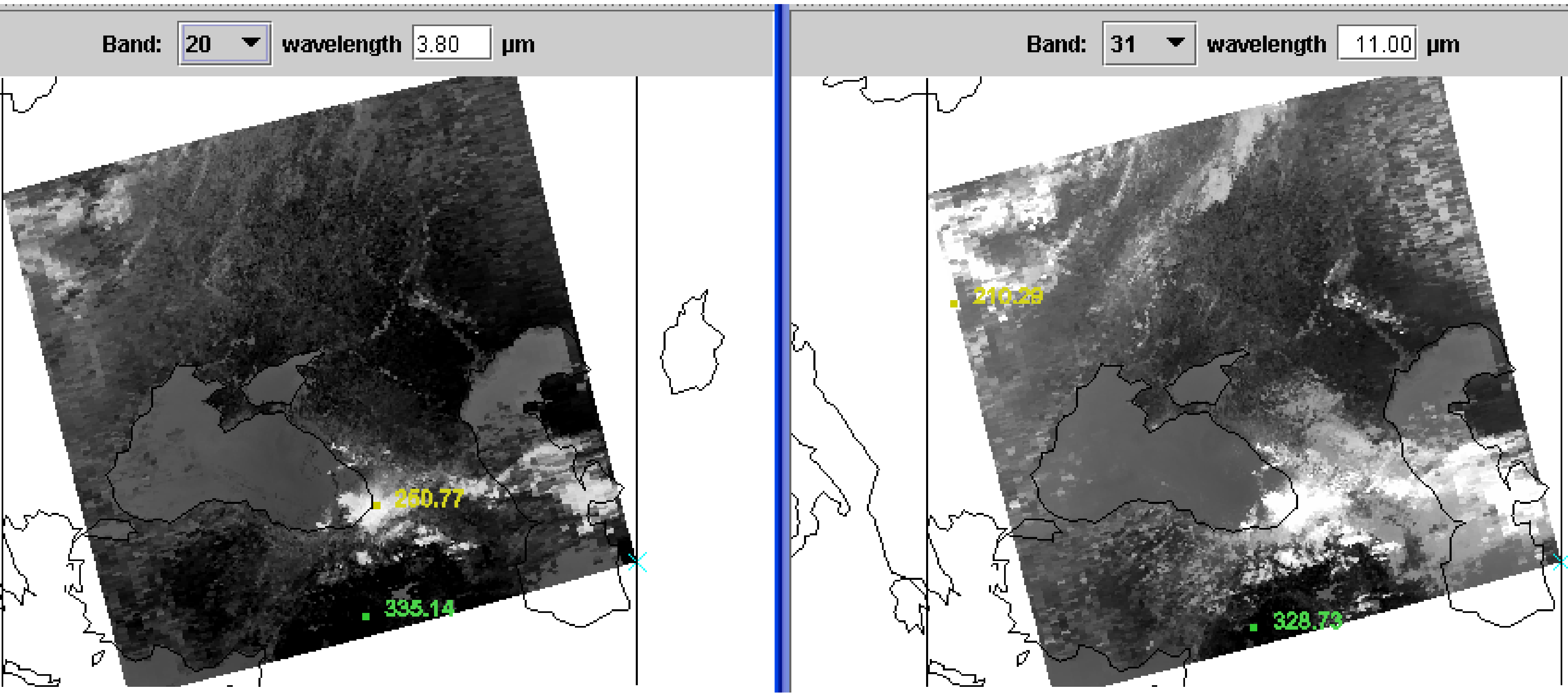


$$B=N*B(T_{cold})+(1-N)*B(T_{hot})$$

$$BT=N*T_{cold}+(1-N)*T_{hot}$$

Temperature Sensitivity of B(λ,T) for typical earth temperatures





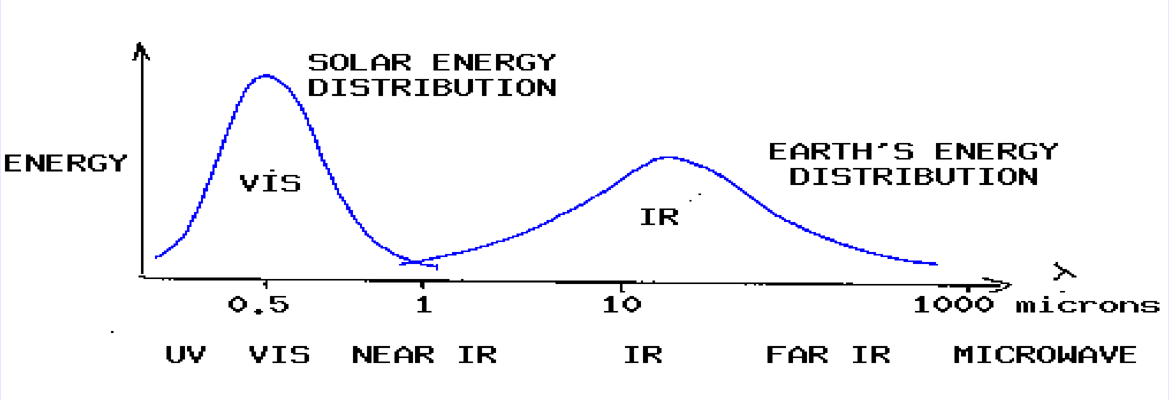
Cloud edges and broken clouds appear different in 11 and 4 um images.

T(11)**4=(1-N)*Tclr**4+N*Tcld**4~(1-N)*300**4+N*200**4
T(4)**12=(1-N)*Tclr**12+N*Tcld**12~(1-N)*300**12+N*200**12

Cold part of pixel has more influence for B(11) than B(4)

Solar and Earth Radiation

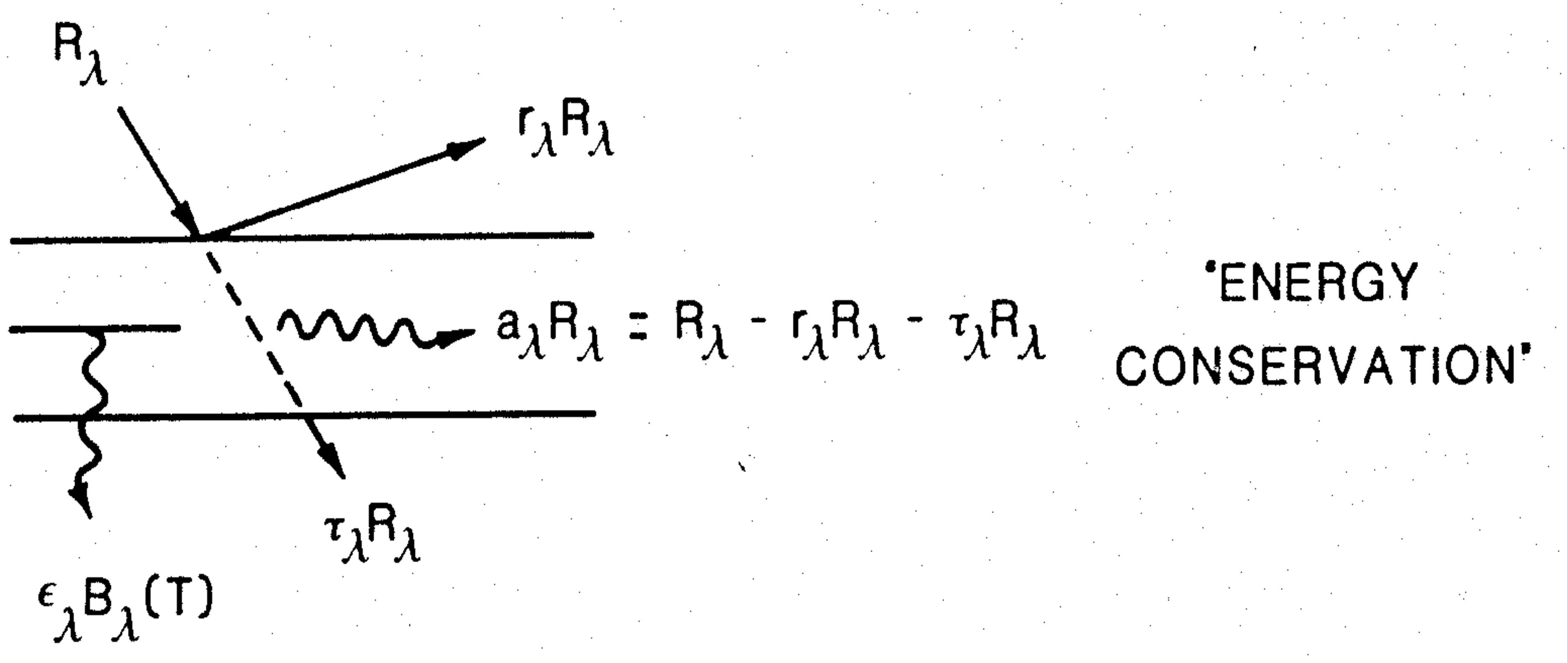
Solar (visible) and Earth emitted (infrared) energy

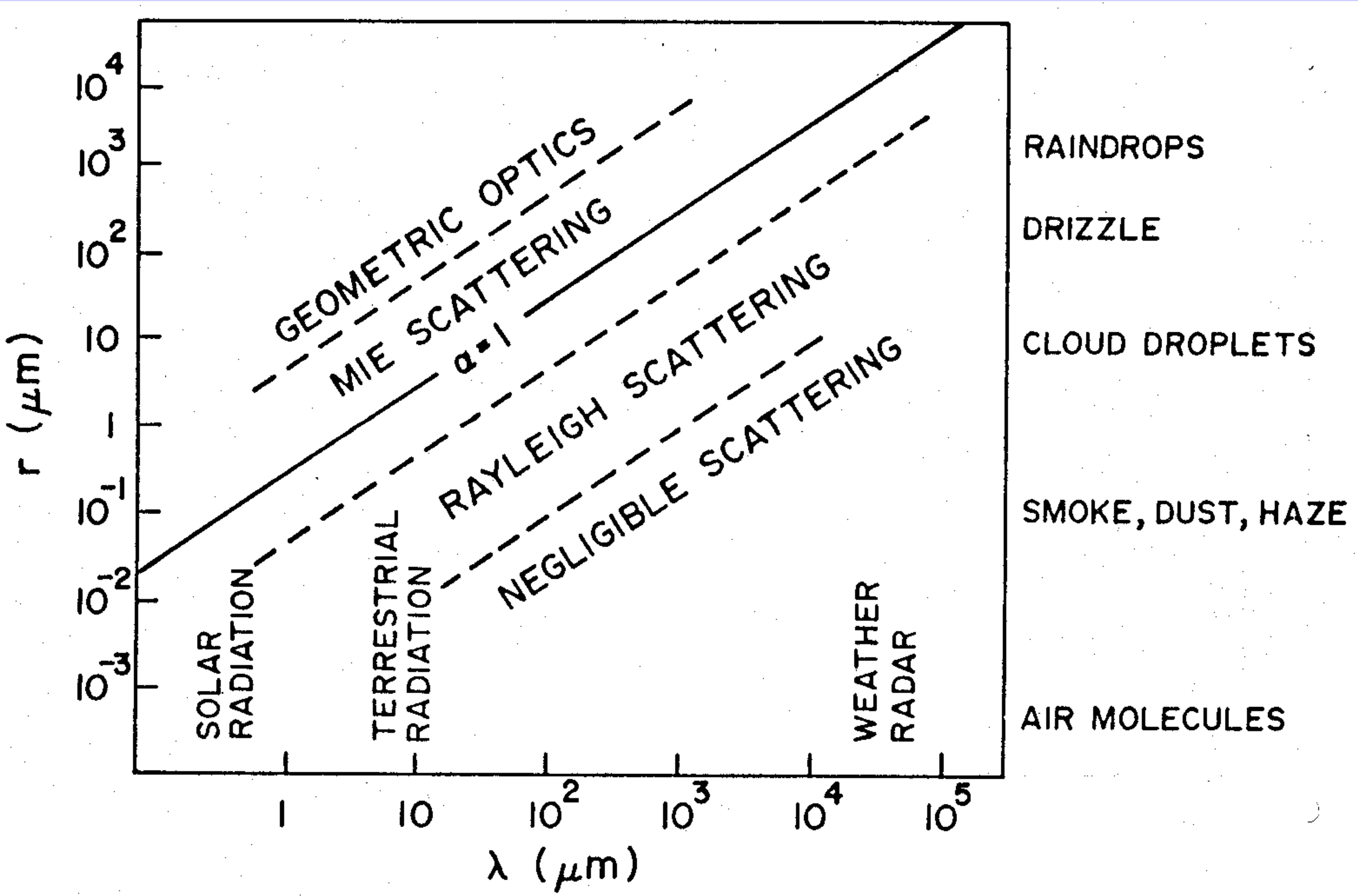


Incoming solar radiation (mostly visible) drives the earth-atmosphere (which emits infrared).

Over the annual cycle, the incoming solar energy that makes it to the earth surface (about 50 %) is balanced by the outgoing thermal infrared energy emitted through the atmosphere.

The atmosphere transmits, absorbs (by H2O, O2, O3, dust) reflects (by clouds), and scatters (by aerosols) incoming visible; the earth surface absorbs and reflects the transmitted visible. Atmospheric H2O, CO2, and O3 selectively transmit or absorb the outgoing infrared radiation. The outgoing microwave is primarily affected by H2O and O2.

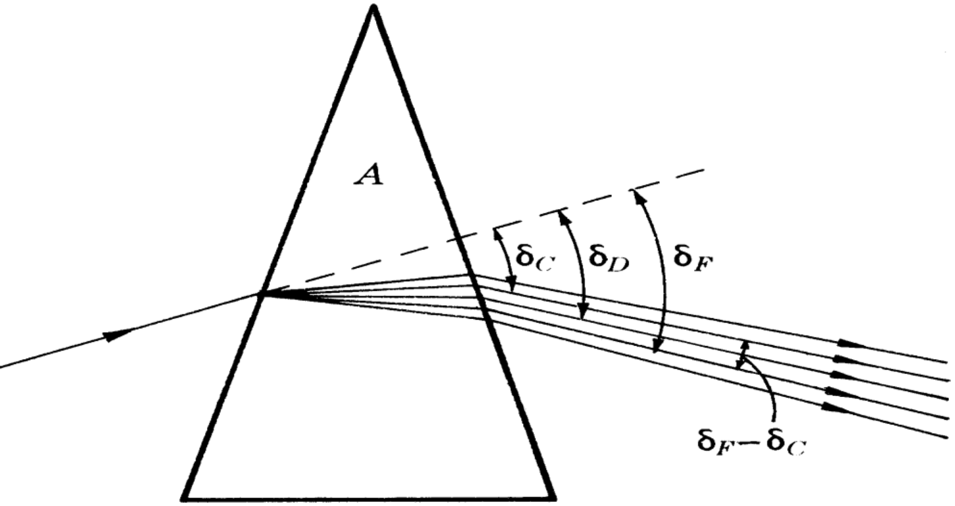

R_λ
$r_\lambda R_\lambda$
$a_\lambda R_\lambda = R_\lambda - r_\lambda R_\lambda - \tau_\lambda R_\lambda$
$\tau_\lambda R_\lambda$
$\epsilon_\lambda B_\lambda(T)$
"ENERGY CONSERVATION"



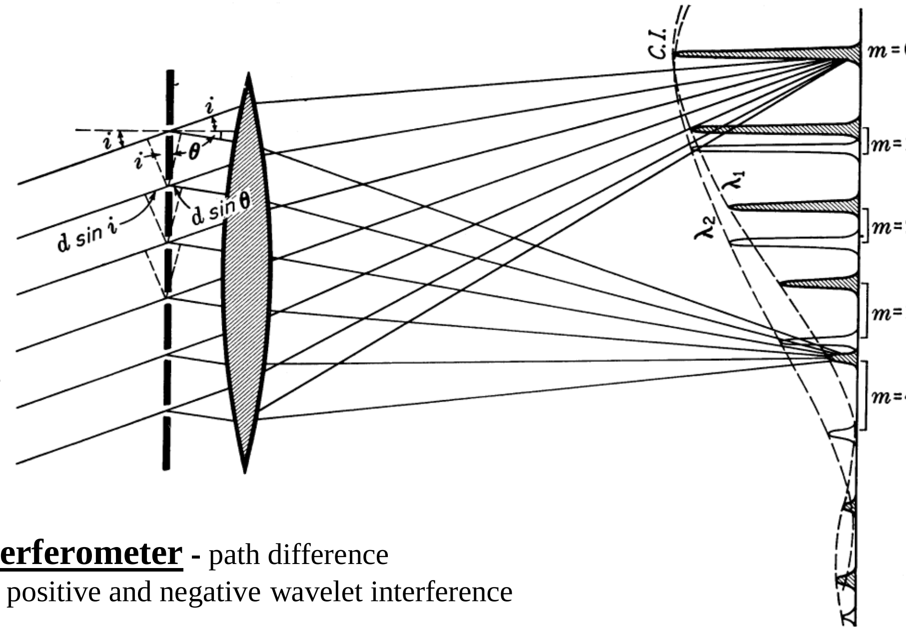
GEOMETRIC OPTICS
MIE SCATTERING
α=1
RAYLEIGH SCATTERING
NEGLIGIBLE SCATTERING
SOLAR RADIATION
TERRESTRIAL RADIATION
WEATHER RADAR
RAINDROPS
DRIZZLE
CLOUD DROPLETS
SMOKE, DUST, HAZE
AIR MOLECULES
r (μm)
λ (μm)

Spectral Separation
Visible, NIR, & IR

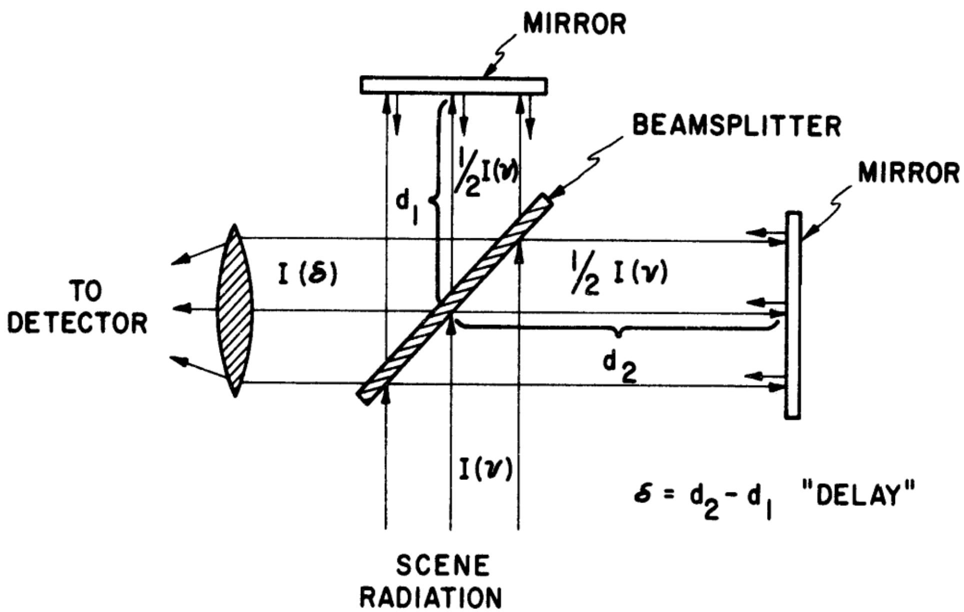
Spectral Separation with a Prism: longer wavelengths deflected less



Spectral Separation with a Grating: path difference from slits produces positive and negative wavelet interference on screen



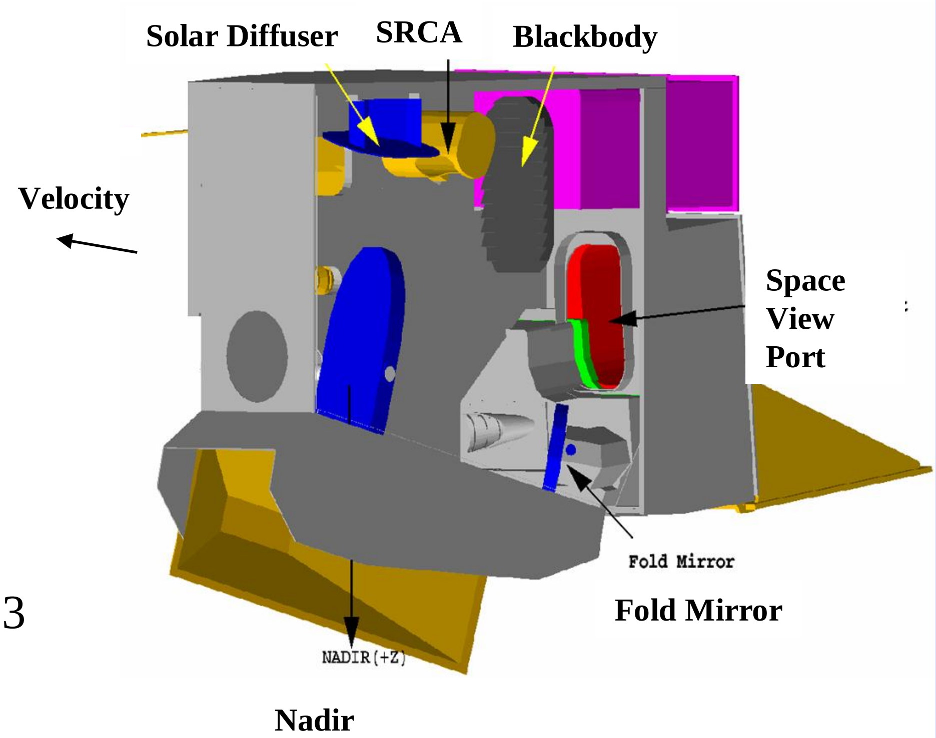
Spectral Separation with an Interferometer - path difference (or delay) from two mirrors produces positive and negative wavelet interference

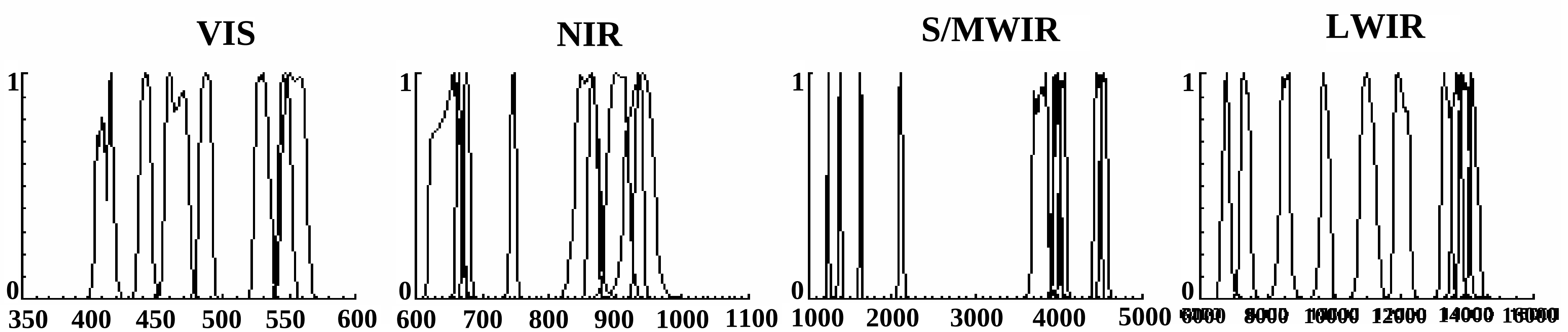


Visible & NIR

MODIS Instrument Overview

- 36 spectral bands (490 detectors) cover wavelength range from 0.4 to 14.5 μm
- Spatial resolution at nadir: 250m (2 bands), 500m (5 bands) and 1000m
- 4 FPAs: VIS, NIR, SMIR, LWIR
- On-Board Calibrators: SD/SDSM, SRCA, and BB (plus space view)
- 12 bit (0-4095) dynamic range
- 2-sided Paddle Wheel Scan Mirror scans 2330 km swath in 1.47 sec
- Day data rate = 10.6 Mbps; night data rate = 3.3 Mbps (100% duty cycle, 50% day and 50% night)





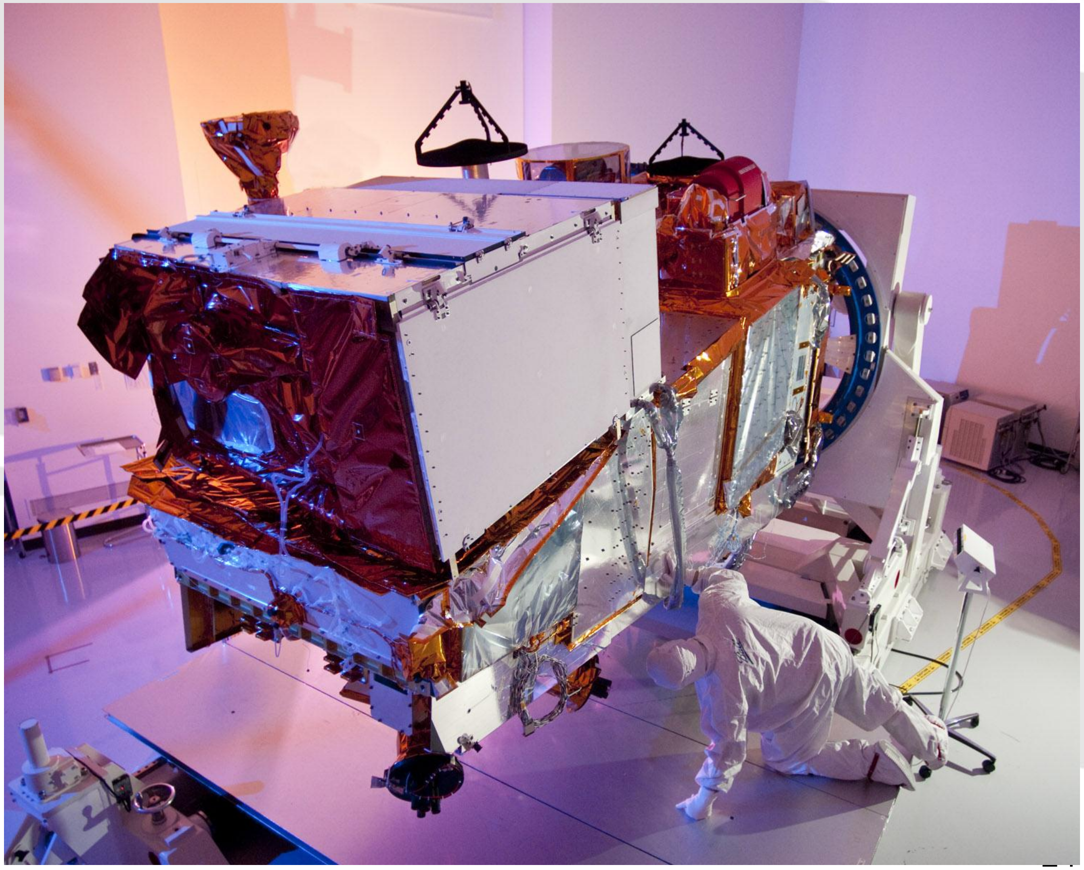
Visible Infrared Imaging Radiometer Suite
Raytheon SAS El Segundo, Ca

Description

- **Purpose:** Global observations of land, ocean, & atmosphere parameters at high temporal resolution (~ daily)
- **Predecessor Instruments:** AVHRR, OLS, MODIS, SeaWiFS
- **Approach:** Multi-spectral scanning radiometer (22 bands between 0.4 µm and 12 µm) 12-bit quantization
- **Swath width:** 3000 km

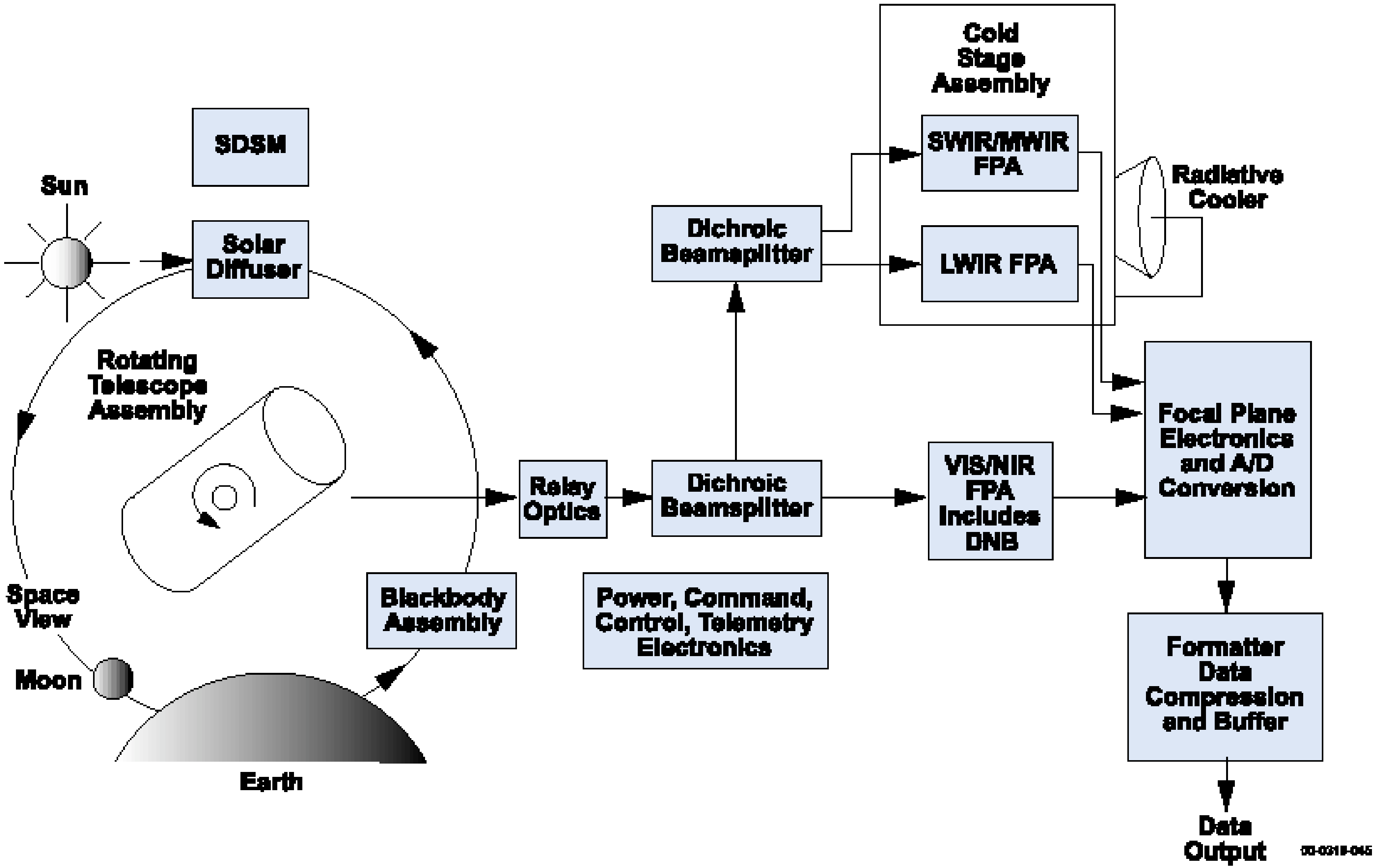
Spatial Resolution

- 16 bands at 750m
- 5 bands at 325m
- DNB

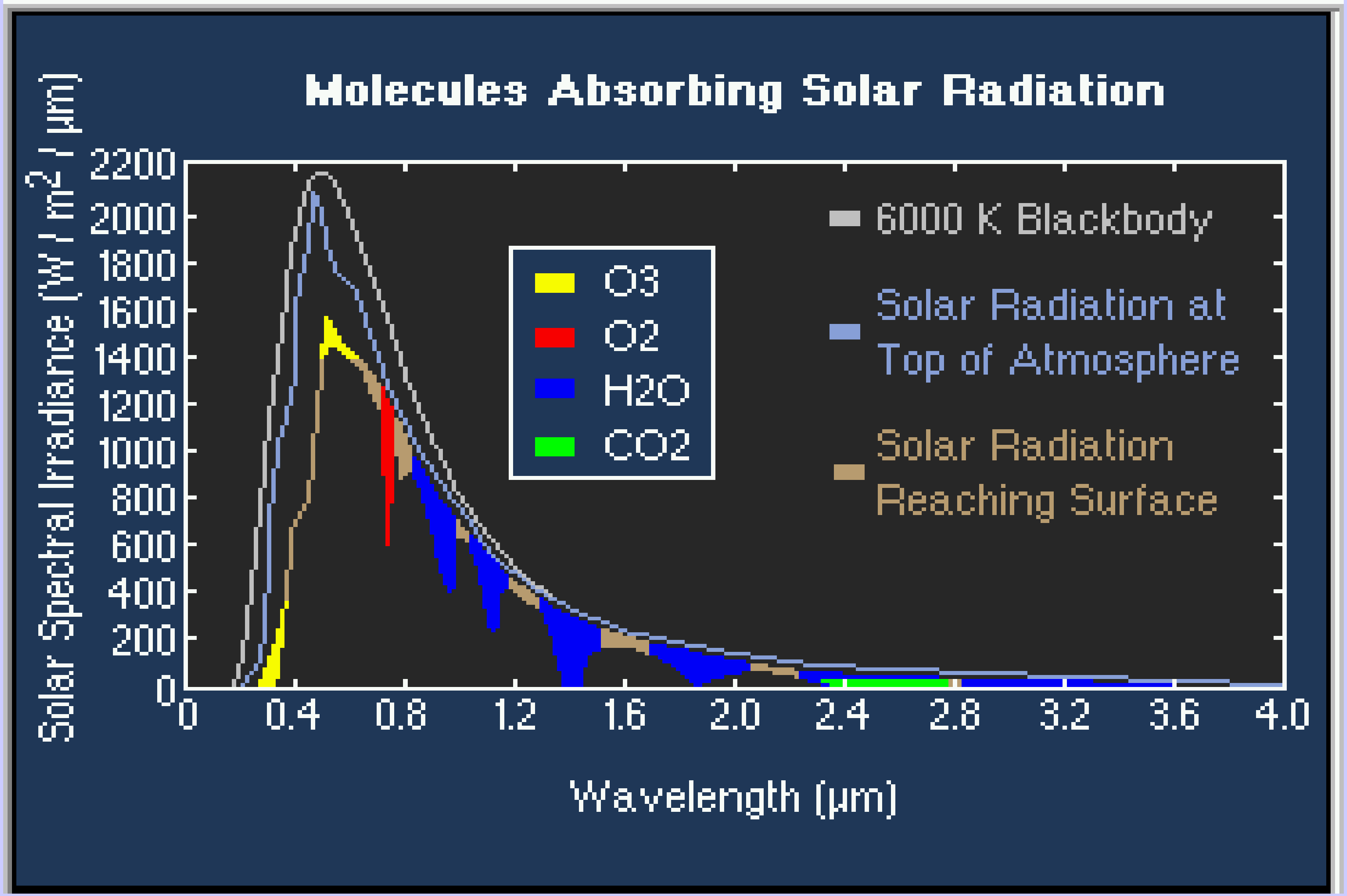


VIIRS on NPP

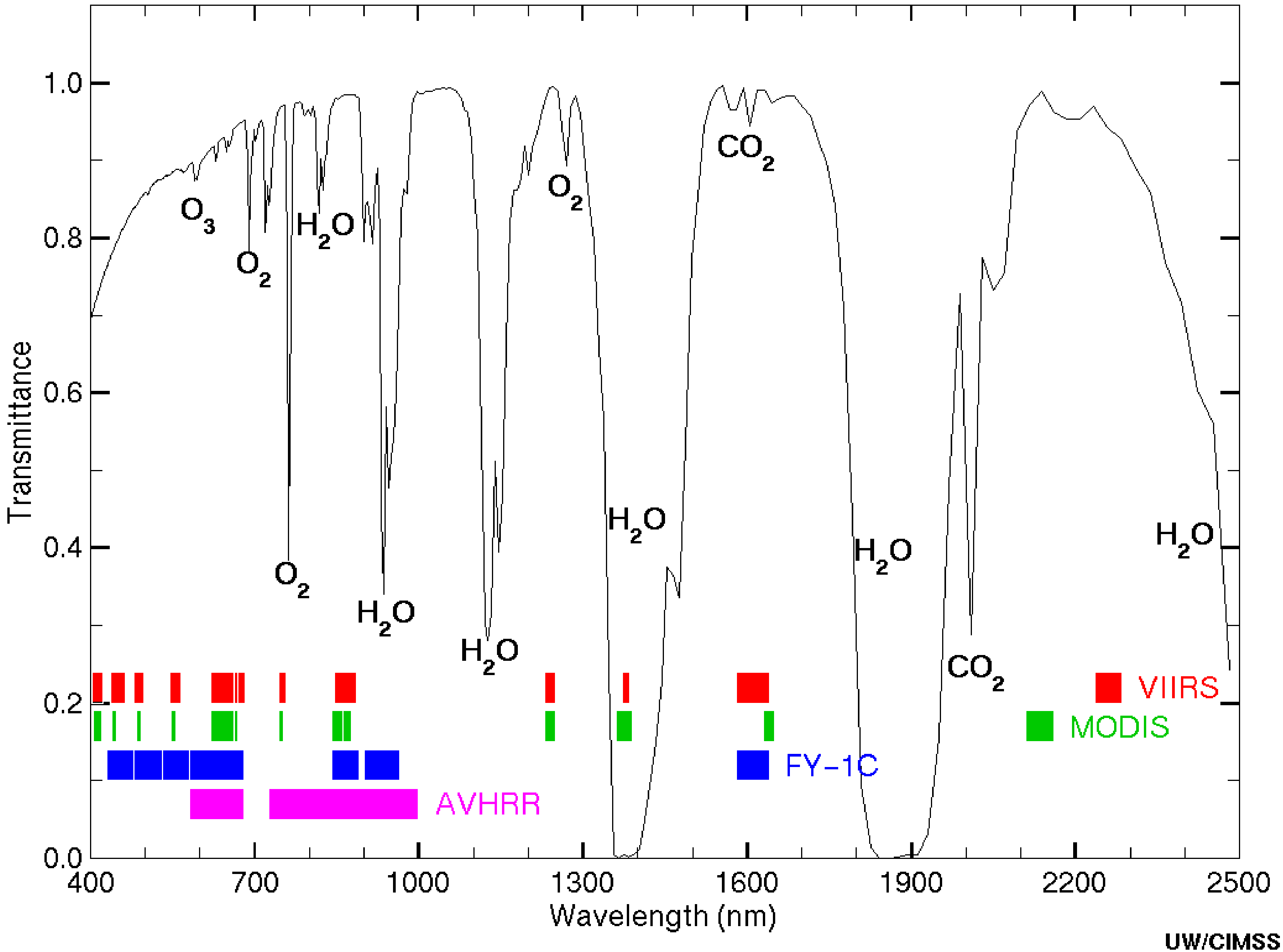
VIIRS Sensor From Photons In To Bits Out

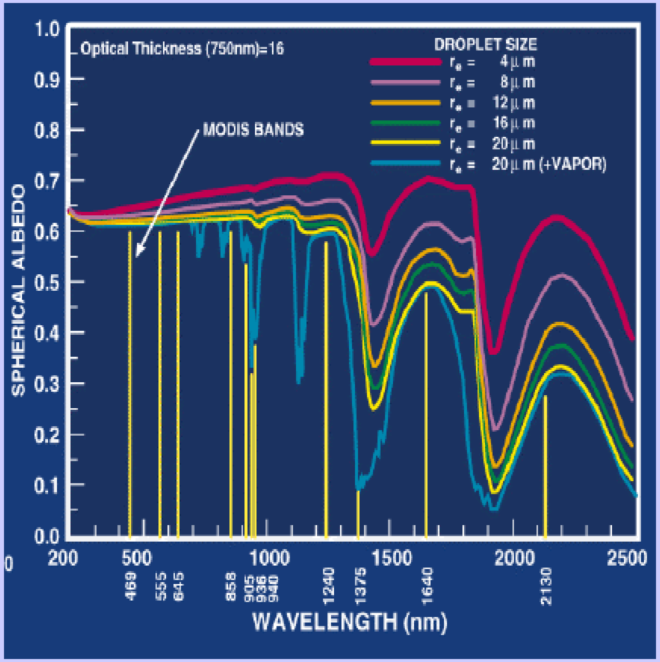


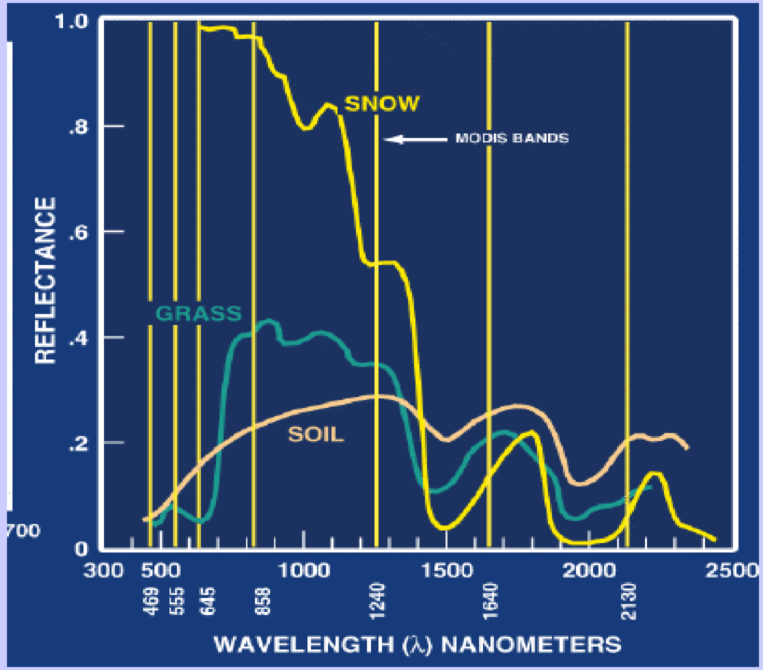
Solar Spectrum

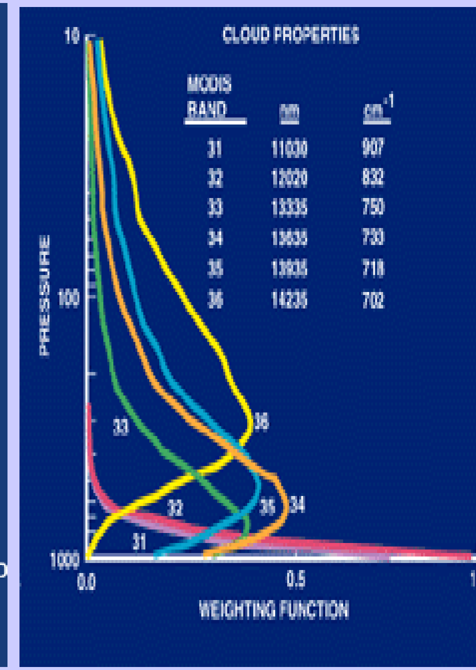


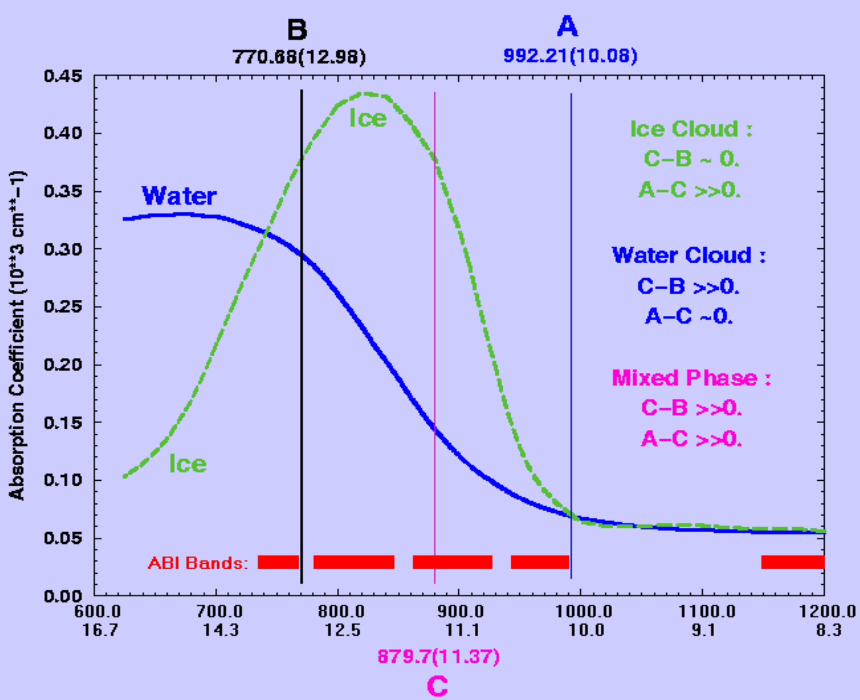
VIIRS, MODIS, FY-1C, AVHRR

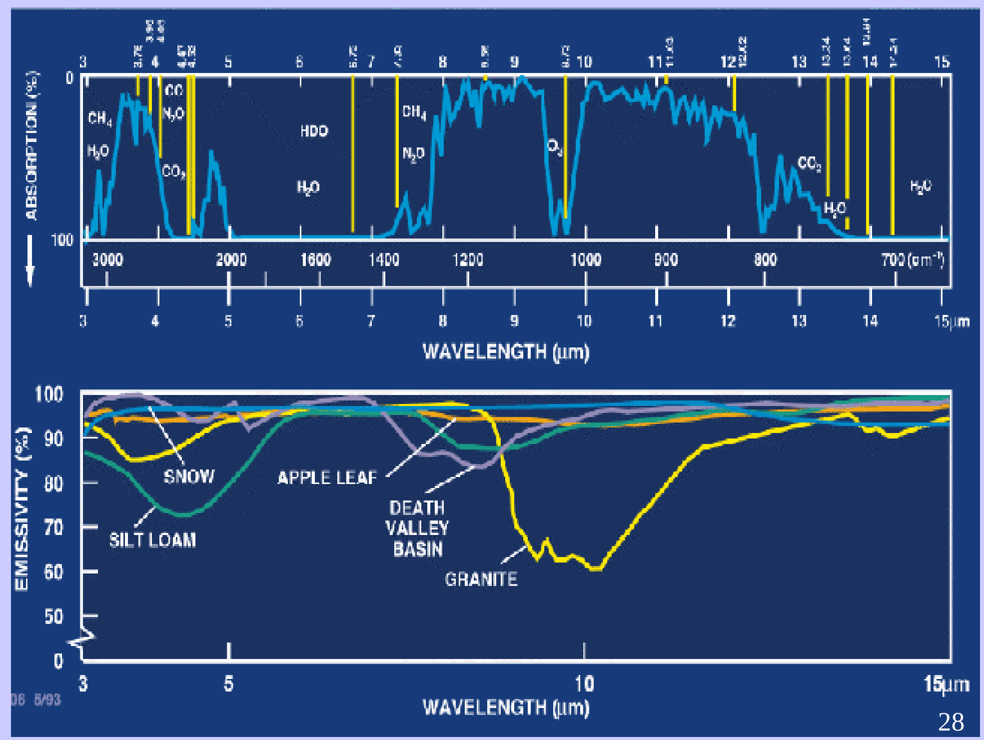


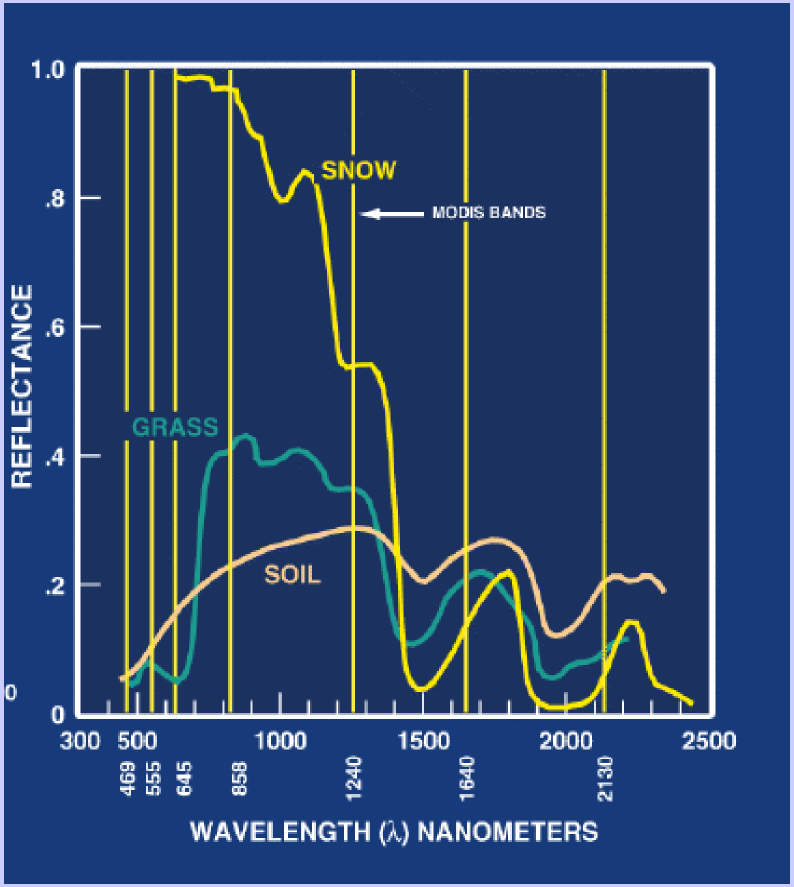

Optical Thickness (750nm)=16
DROPLET SIZE
r_e = 4 µm
r_e = 8 µm
r_e = 12 µm
r_e = 16 µm
r_e = 20 µm
r_e = 20 µm (+VAPOR)
MODIS BANDS
SPHERICAL ALBEDO
WAVELENGTH (nm)
469 555 645 858 905 936 940 1240 1375 1640 2130


SNOW
MODIS BANDS
GRASS
SOIL
REFLECTANCE
WAVELENGTH (λ) NANOMETERS
469 555 645 858 1240 1640 2130


CLOUD PROPERTIES
MODIS BAND
nm
cm^{-1}
31 11030 907
32 12020 832
33 13335 750
34 13635 733
35 13935 718
36 14235 702
PRESSURE
WEIGHTING FUNCTION


B
770.66(12.98)
A
992.21(10.08)
Ice
Water
Ice Cloud :
C–B ~ 0.
A–C >>0.
Water Cloud :
C–B >>0.
A–C ~0.
Mixed Phase :
C–B >>0.
A–C >>0.
ABI Bands:
Absorption Coefficient (10**3 cm**–1)
879.7(11.37)
C

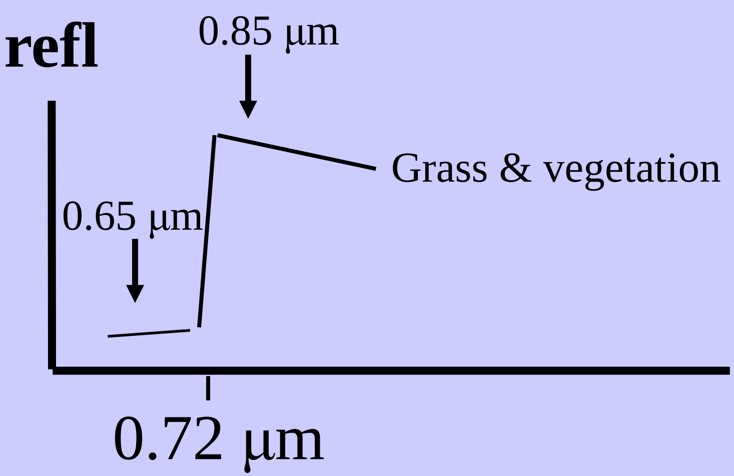

ABSORPTION (%)
CH_4
H_2O
CO
N_2O
CO_2
HDO
O_3
WAVELENGTH (µm)
EMISSIVITY (%)
SNOW
APPLE LEAF
SILT LOAM
DEATH VALLEY BASIN
GRANITE
WAVELENGTH (µm)



Investigating with Multi-spectral Combinations

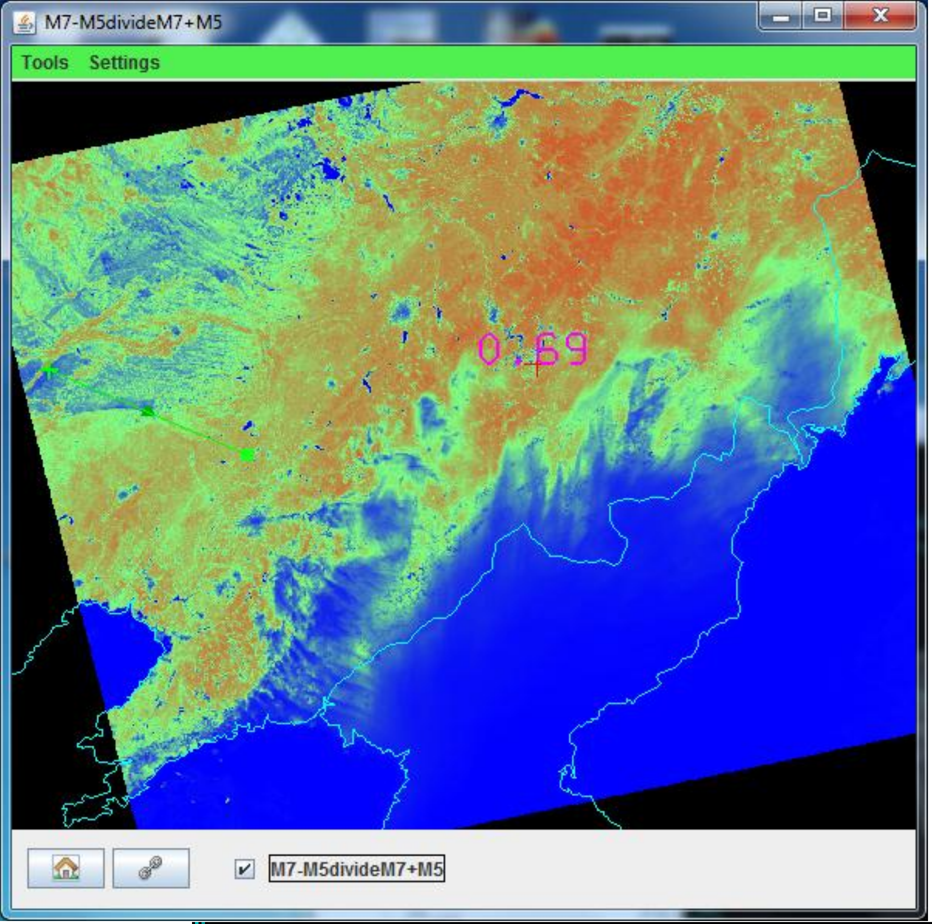
Given the spectral response of a surface or atmospheric feature

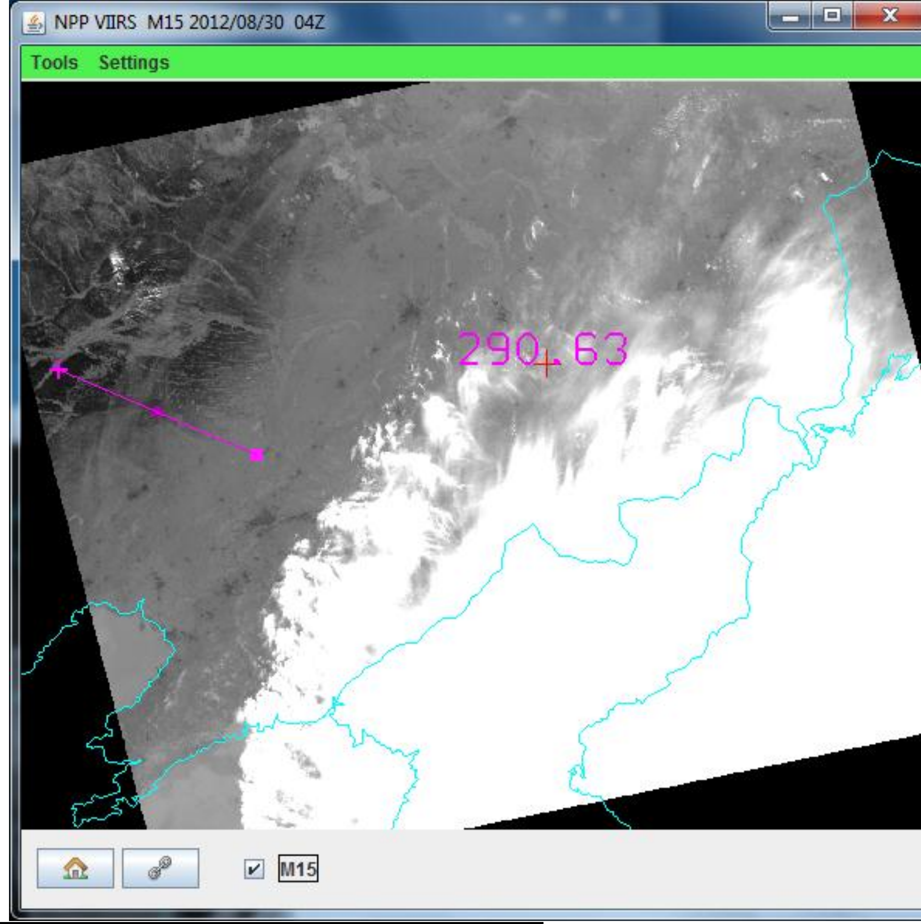
Select a part of the spectrum where the reflectance or absorption changes with wavelength

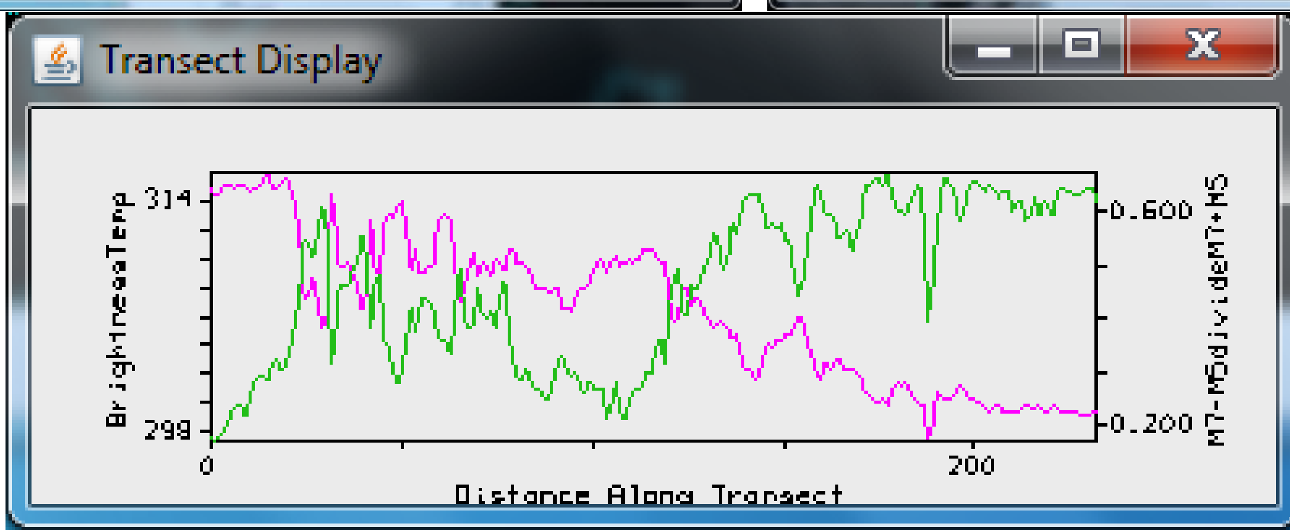


e.g. reflection from grass

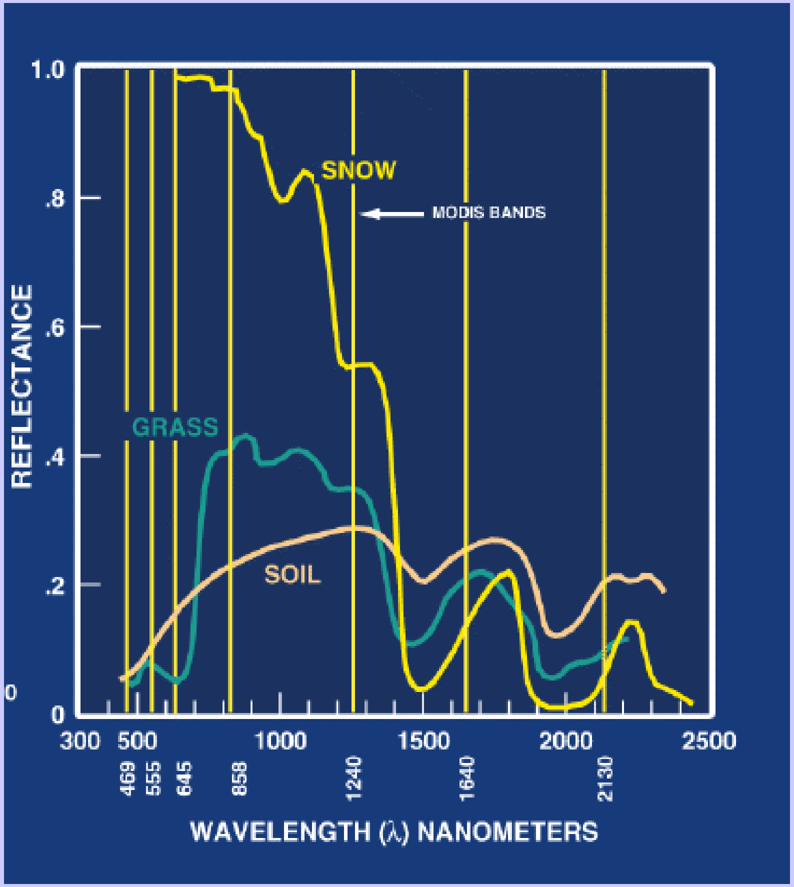
If 0.65 µm and 0.85 µm channels see the same reflectance than surface viewed is not grass;
if 0.85 µm sees considerably higher reflectance than 0.65 µm then surface might be grass







John, Becky, Lisha, Denis

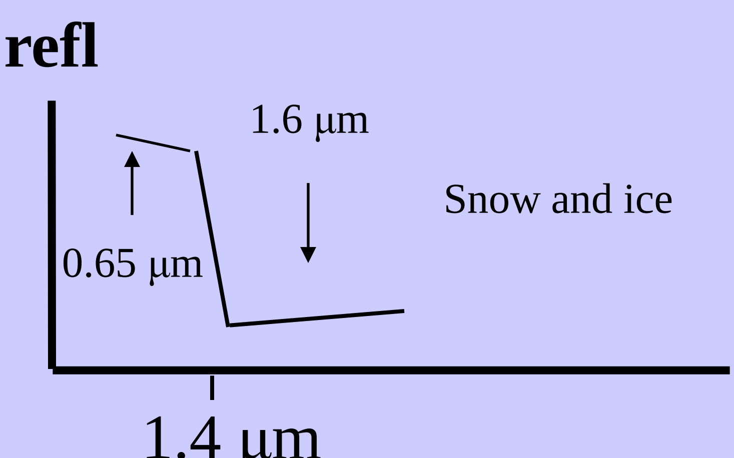


Investigating with Multi-spectral Combinations

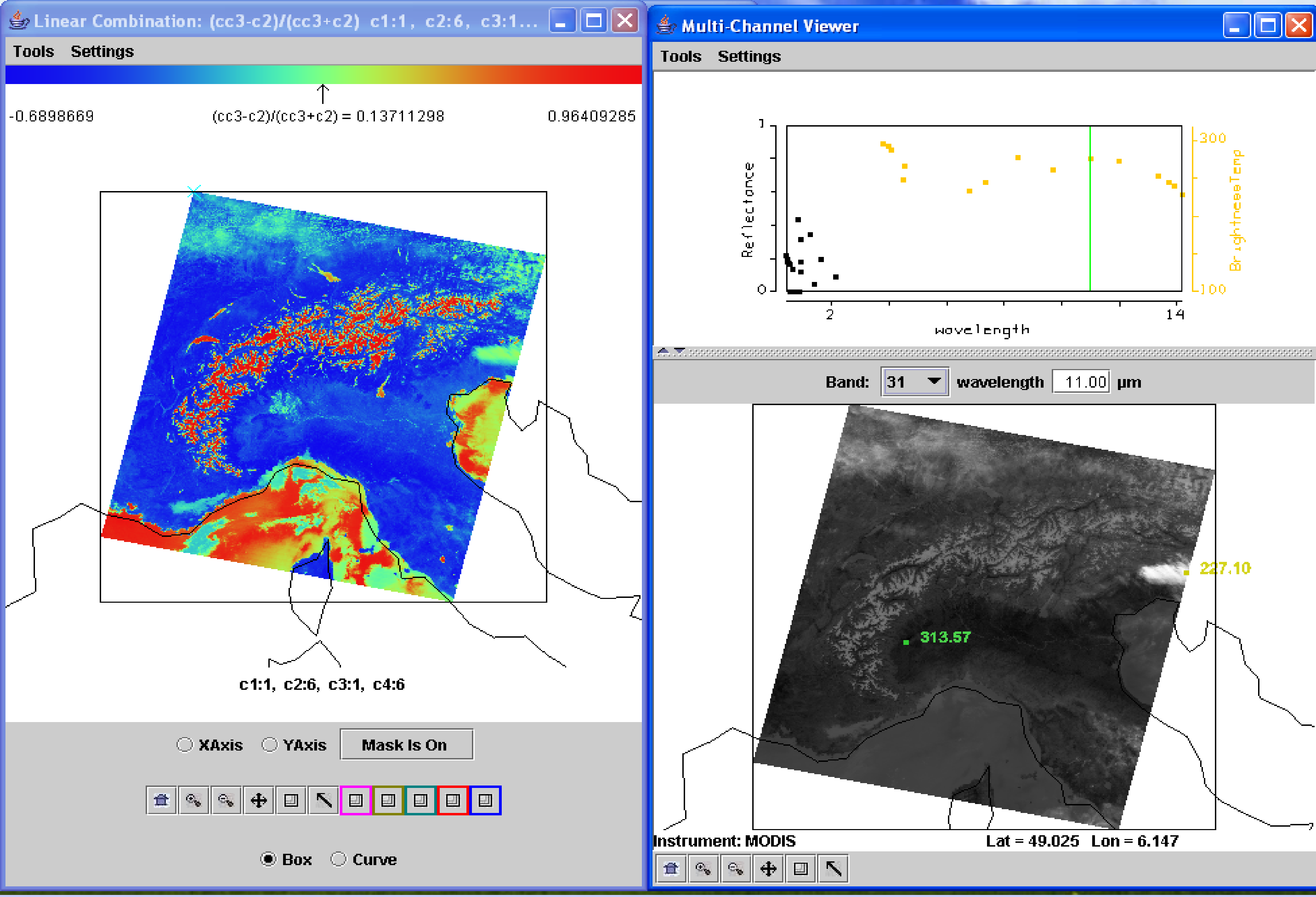
Given the spectral response of a surface or atmospheric feature

Select a part of the spectrum where the reflectance or absorption changes with wavelength

e.g. reflection from snow/ice

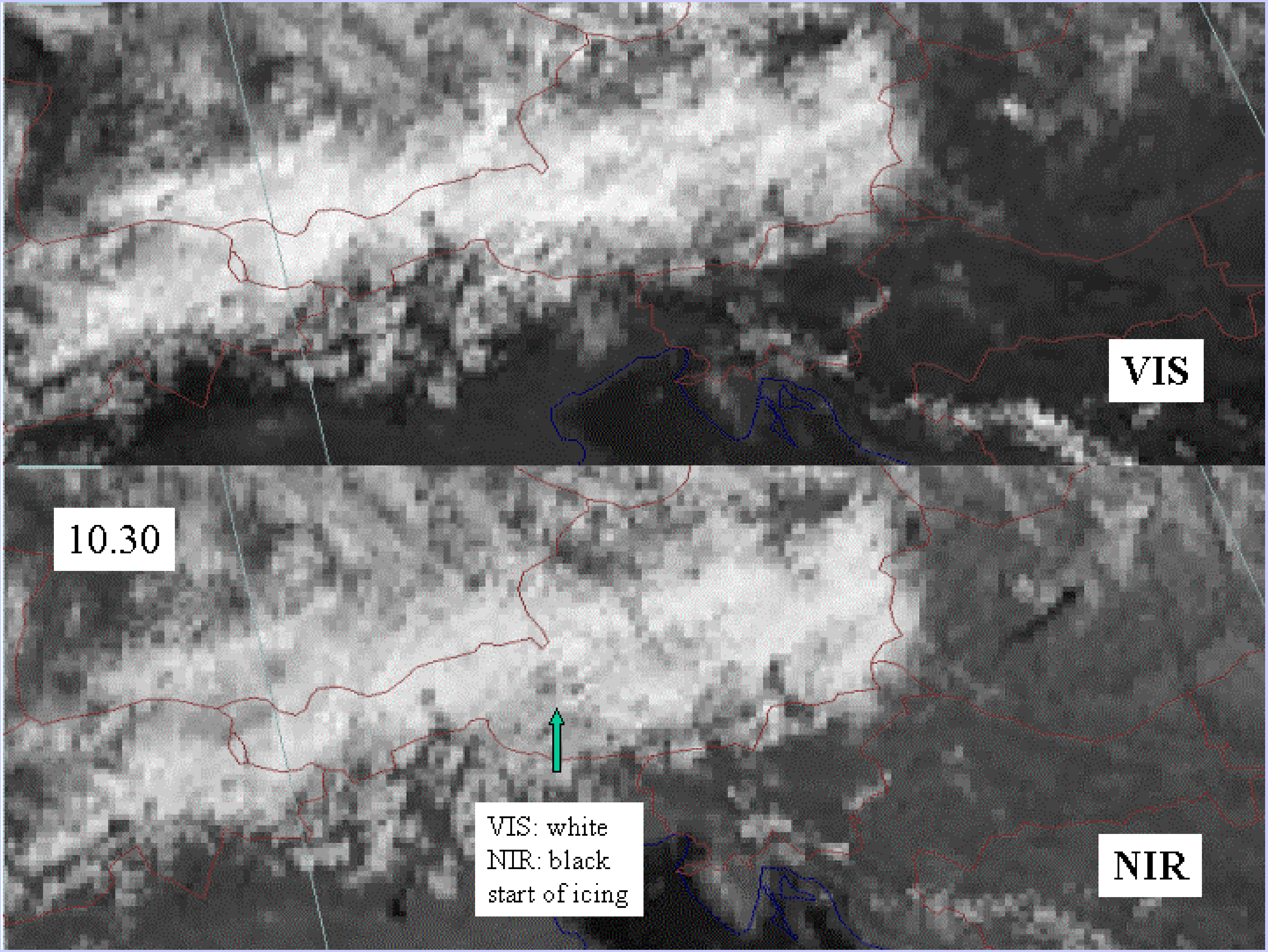


If 0.65 μm and 1.6 μm channels see the same reflectance than surface viewed is not snow;
if 1.6 μm sees considerably lower reflectance than 0.65 μm then surface might be snow



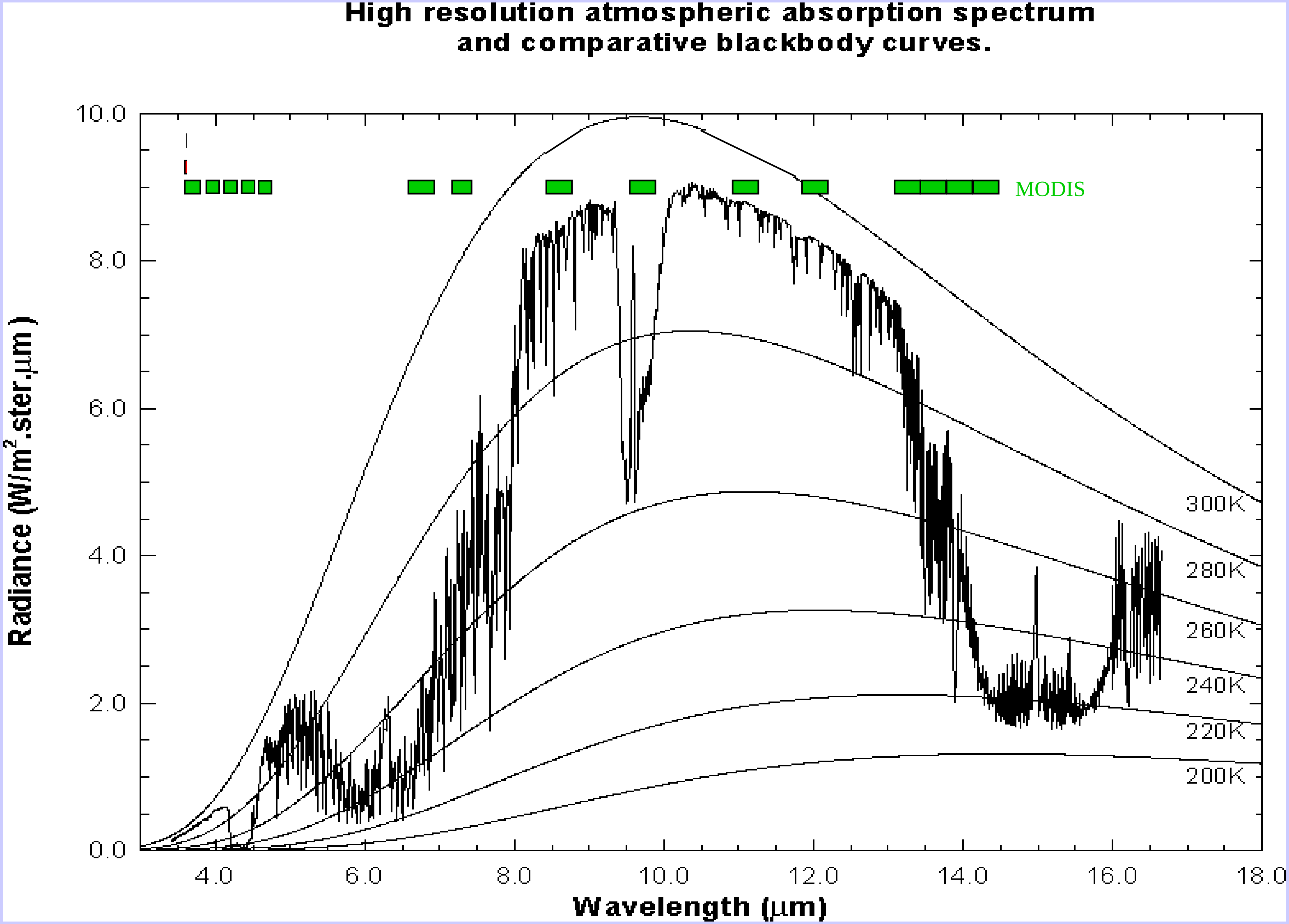
NDSI = [r0.6-r1.6]/[r0.6+r1.6] is near one in snow in Alps

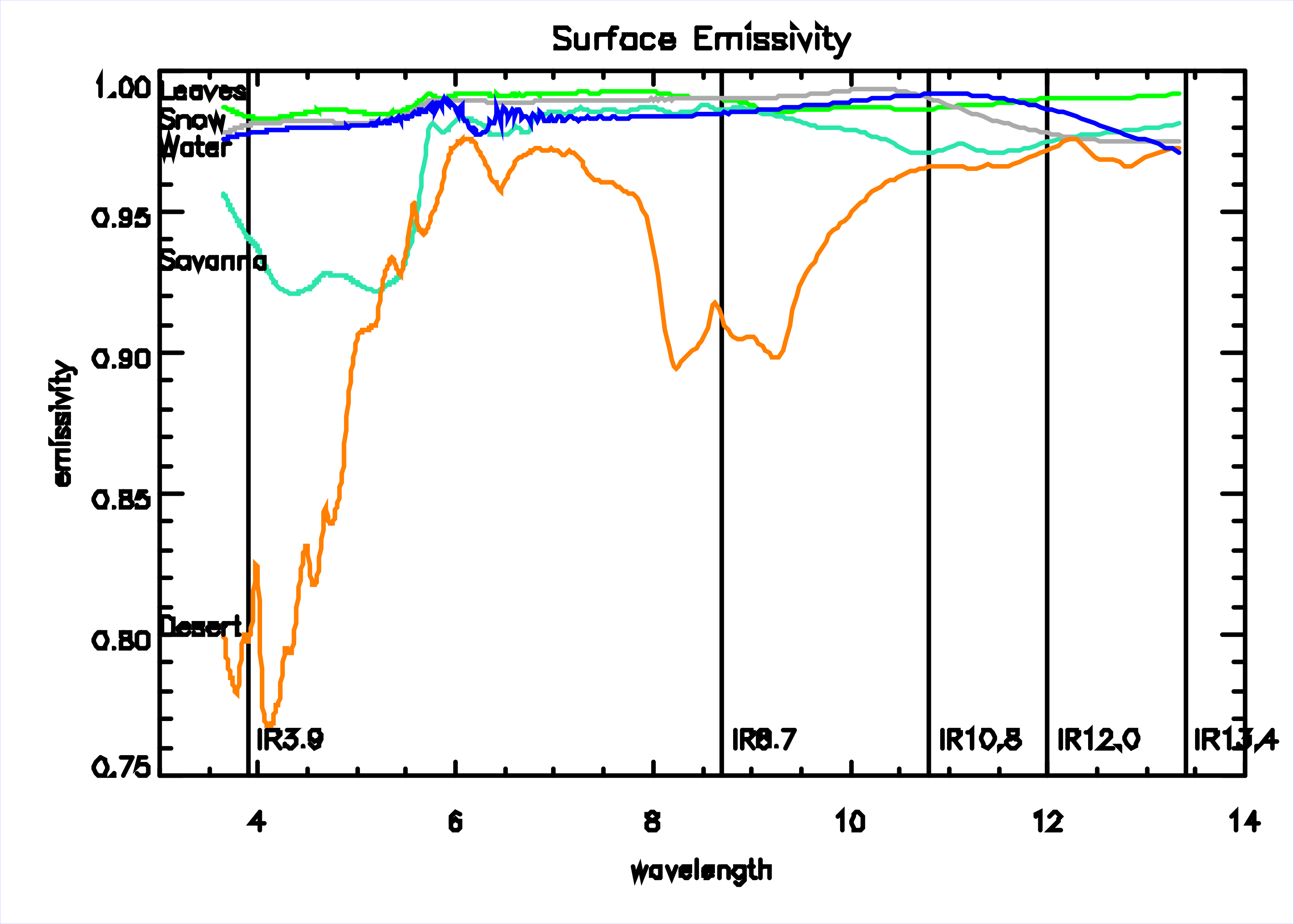
Meteosat-8 sees icing in clouds (Lutz et al)



IR

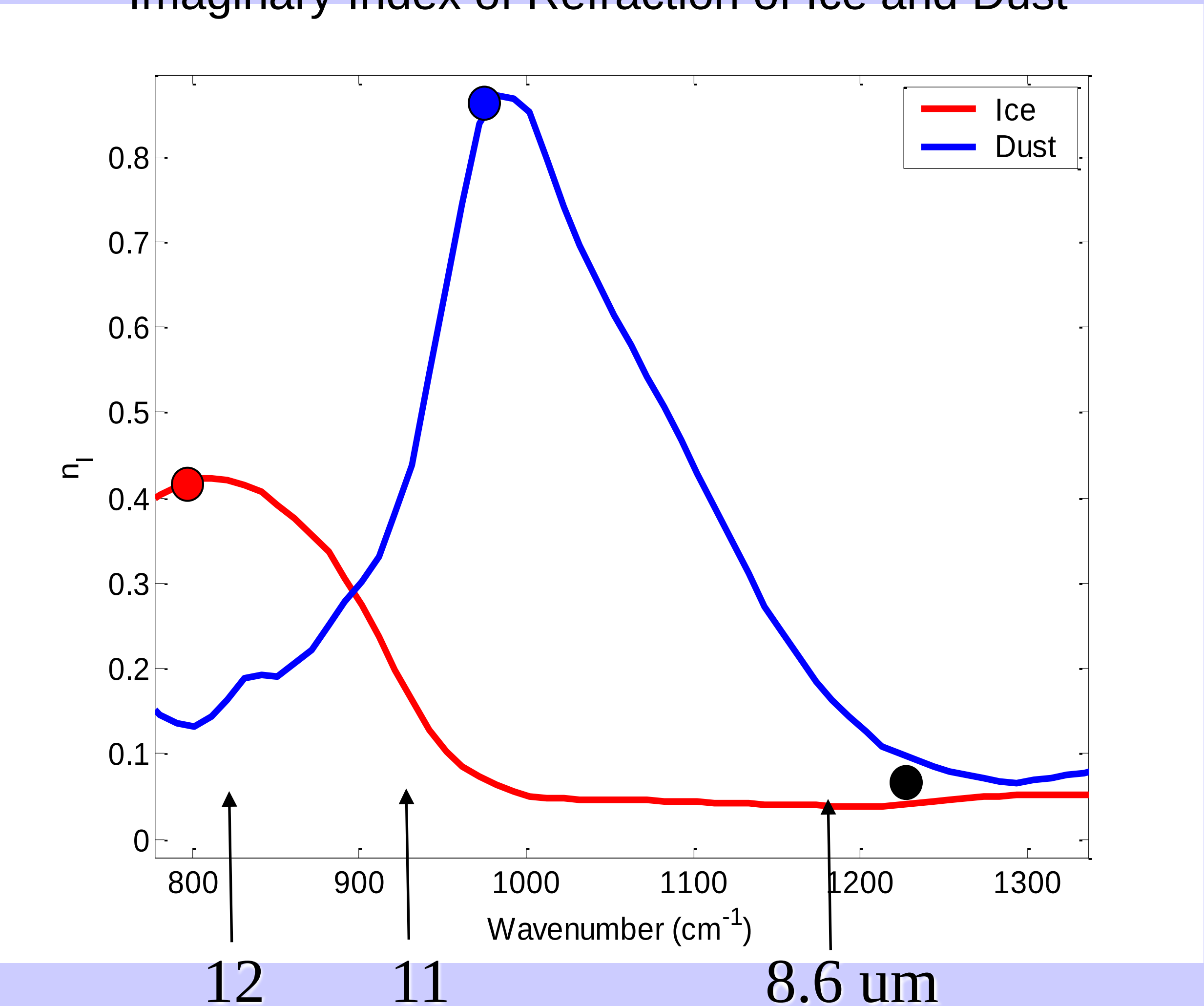
MODIS IR Spectral Bands




Surface Emissivity
Leaves
Snow
Water
Savanna
Desert
emissivity
1.00
0.95
0.90
0.85
0.80
0.75
IR3.9
IR8.7
IR10.8
IR12.0
IR13.4
4
6
8
10
12
14
wavelength

Dust and Cirrus Signals

Imaginary Index of Refraction of Ice and Dust



- Both ice and silicate absorption small in 1200 cm^{-1} window
- In the 800-1000 cm^{-1} atmospheric window:

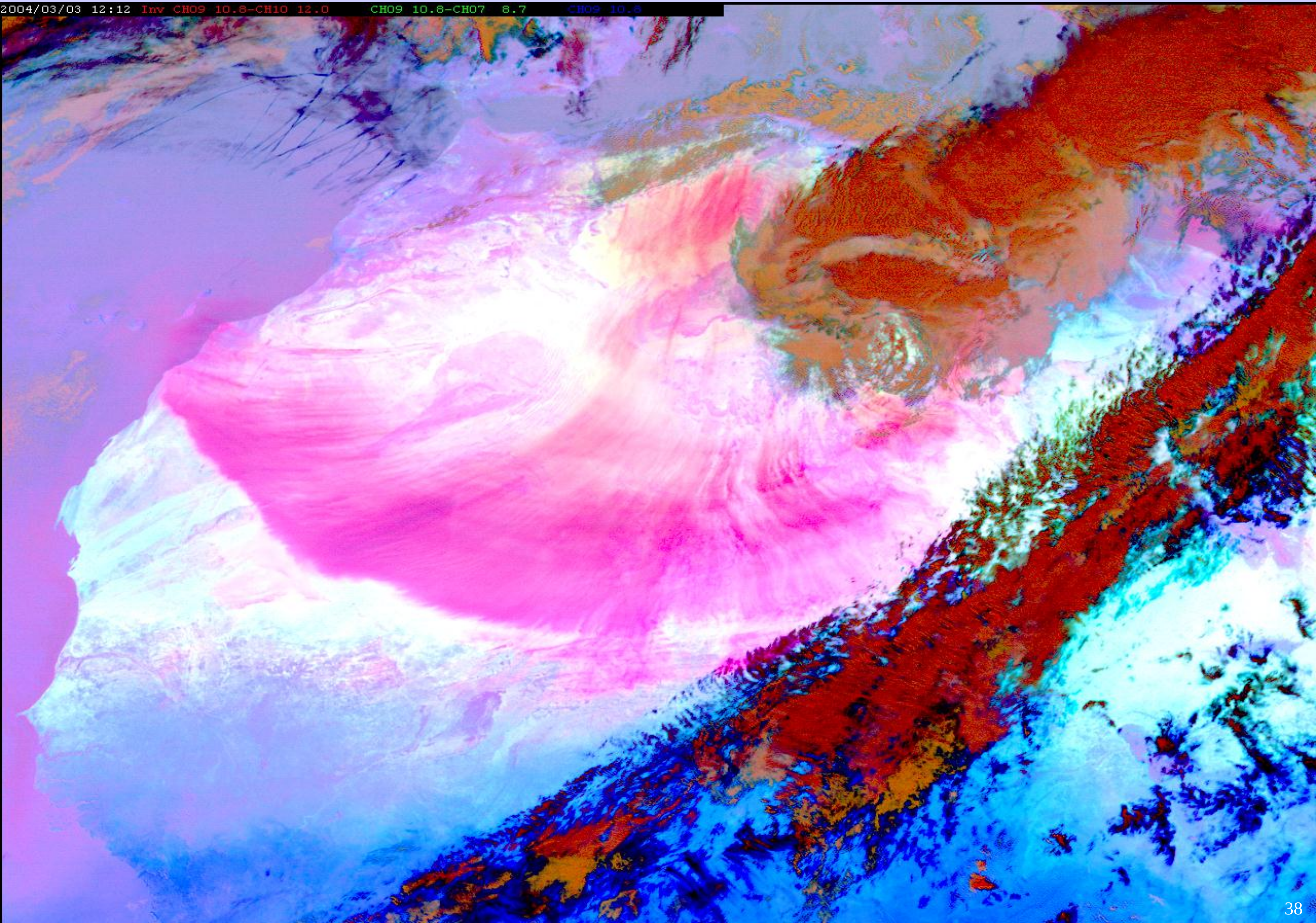
  Silicate index *increases*

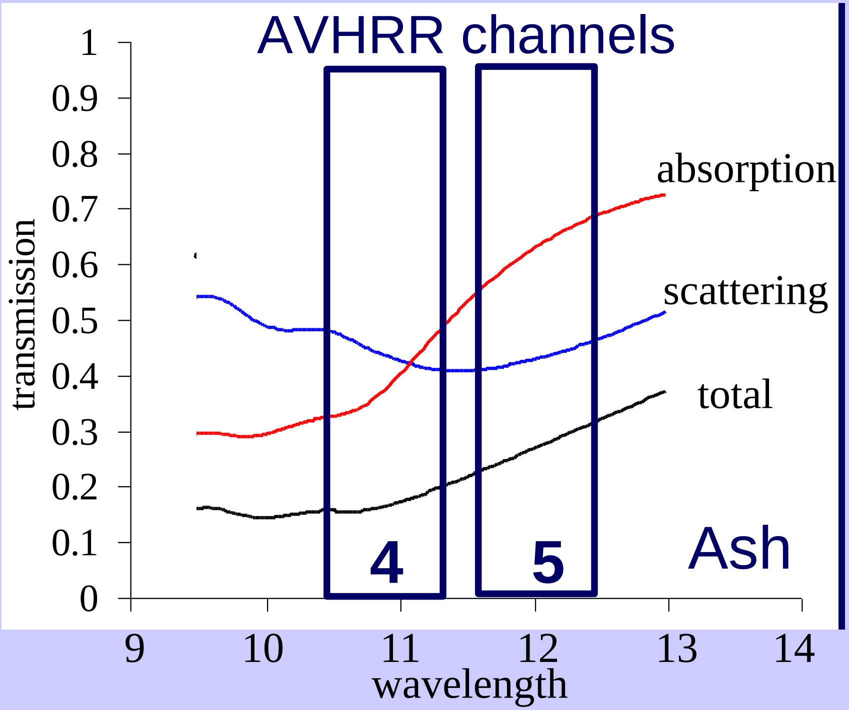
  Ice index *decreases*

  with wavenumber

Volz, F.E. : Infrared optical constant of ammonium sulphate, Sahara Dust, volcanic pumice and flash, Appl Optics **12** 564-658 (1973)

SEVIRI sees dust storm over Africa

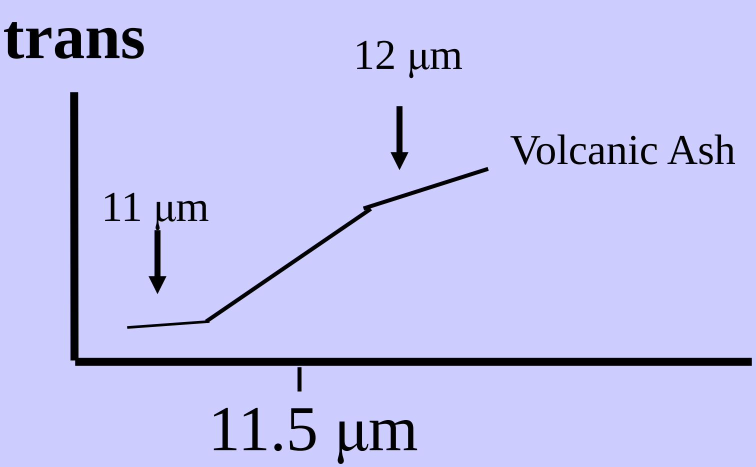




Investigating with Multi-spectral Combinations

Given the spectral response of a surface or atmospheric feature

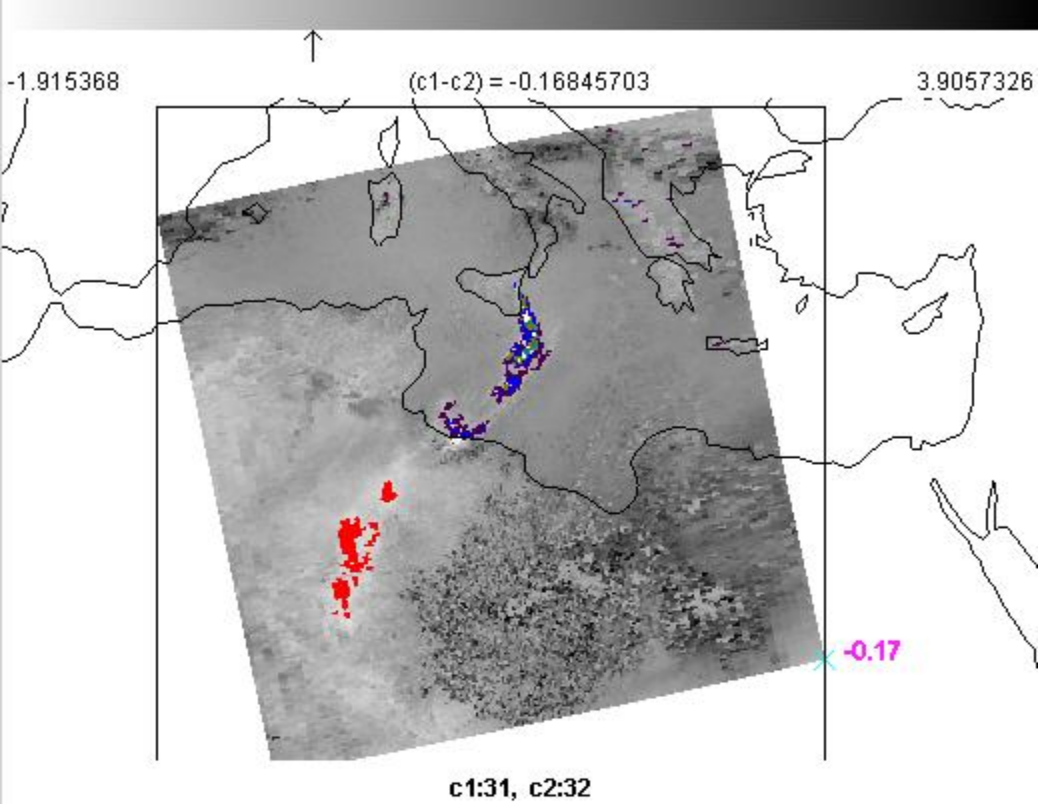
Select a part of the spectrum where the reflectance or absorption changes with wavelength

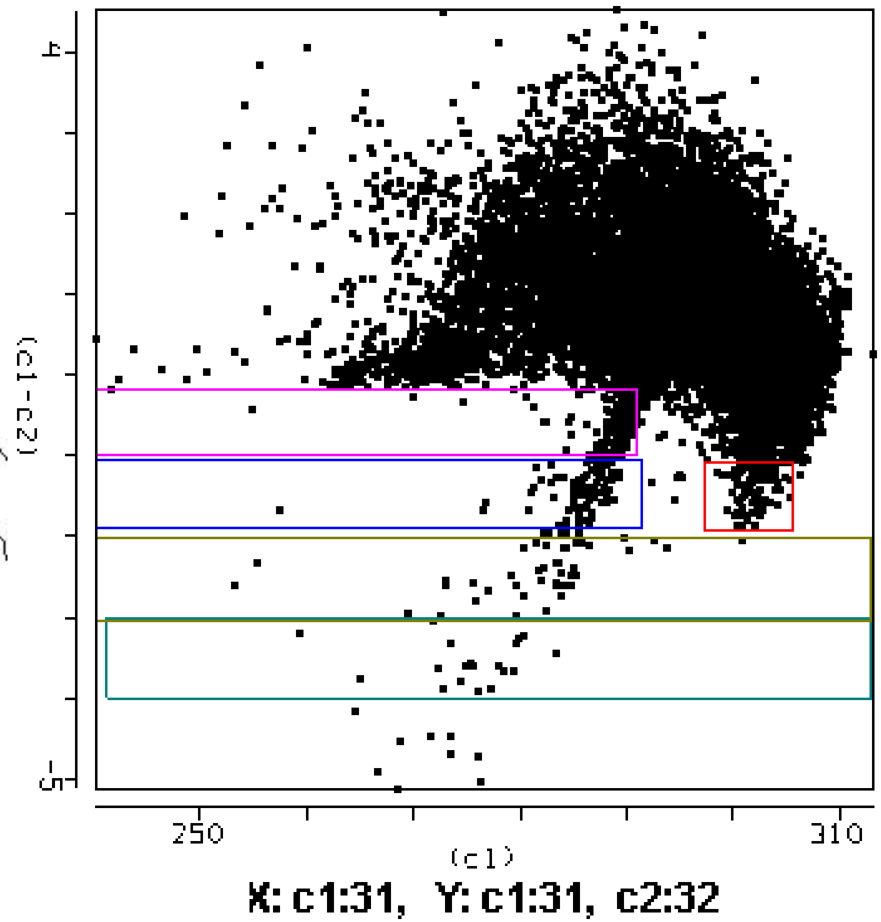


e.g. transmission through ash

If 11 μm sees the same or higher BT than 12 μm the atmosphere viewed does not contain volcanic ash;
if 12 μm sees considerably higher BT than 11 μm then the atmosphere probably contains volcanic ash

Frank Honey, CSIRO 1980s

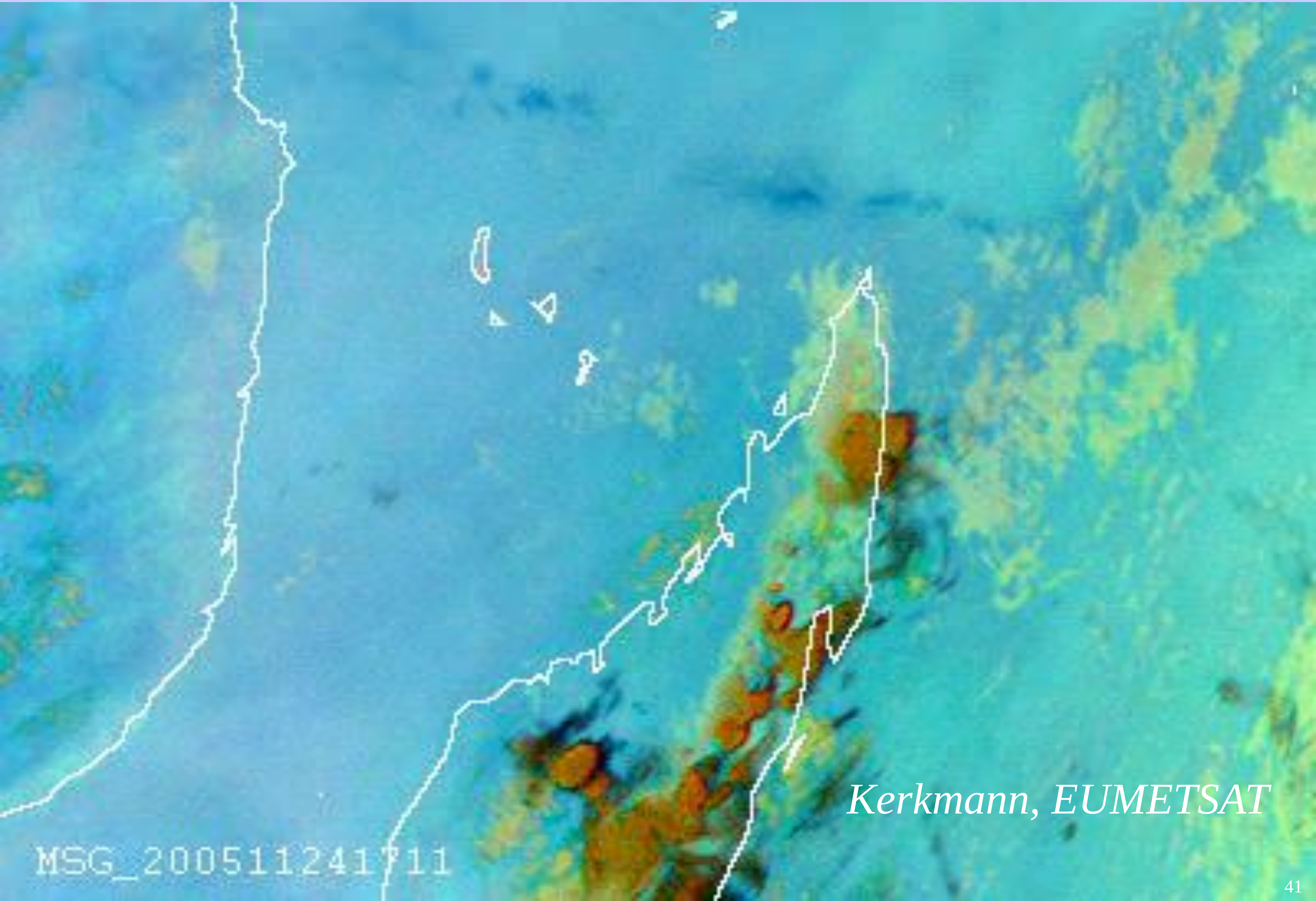




Volcanic Ash is characterised by low brightness temperatures (i.e. High in the atmosphere) and negative differences in band 31-32.

The emissivity of desert at 12 µm is higher than at 11 µm, and hence BT(12 µm) > BT(11 µm) thus negative values. The red pixels are very arid regions of the desert and are not ash clouds.

SEVIRI sees volcanic ash & SO2 and downwind inhibition of convection



Radiative Transfer Equation

When reflection from the earth surface is also considered, the RTE for infrared radiation can be written

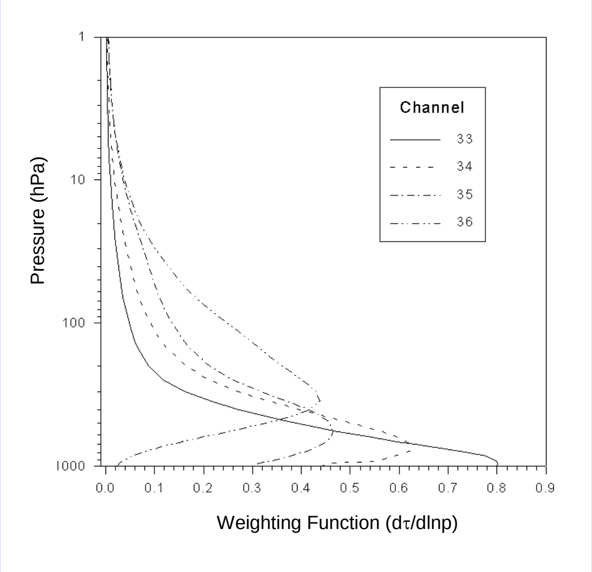
$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_s)\, \tau_\lambda(p_s) + \int_{p_s}^{o} B_\lambda(T(p))\, F_\lambda(p)\, [d\tau_\lambda(p)/ dp]\, dp$$

where

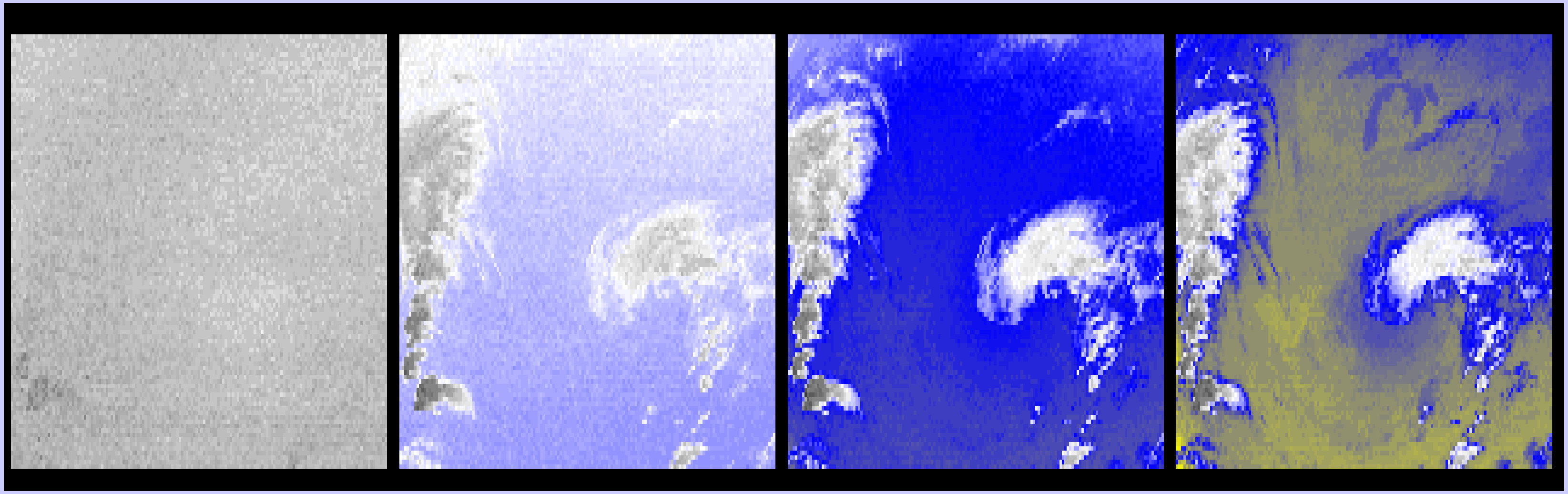
$$F_\lambda(p) = \{ 1 + (1 - \varepsilon_\lambda) [\tau_\lambda(p_s) / \tau_\lambda(p)]^2 \}$$

The first term is the spectral radiance emitted by the surface and attenuated by the atmosphere, often called the boundary term and the second term is the spectral radiance emitted to space by the atmosphere directly or by reflection from the earth surface.

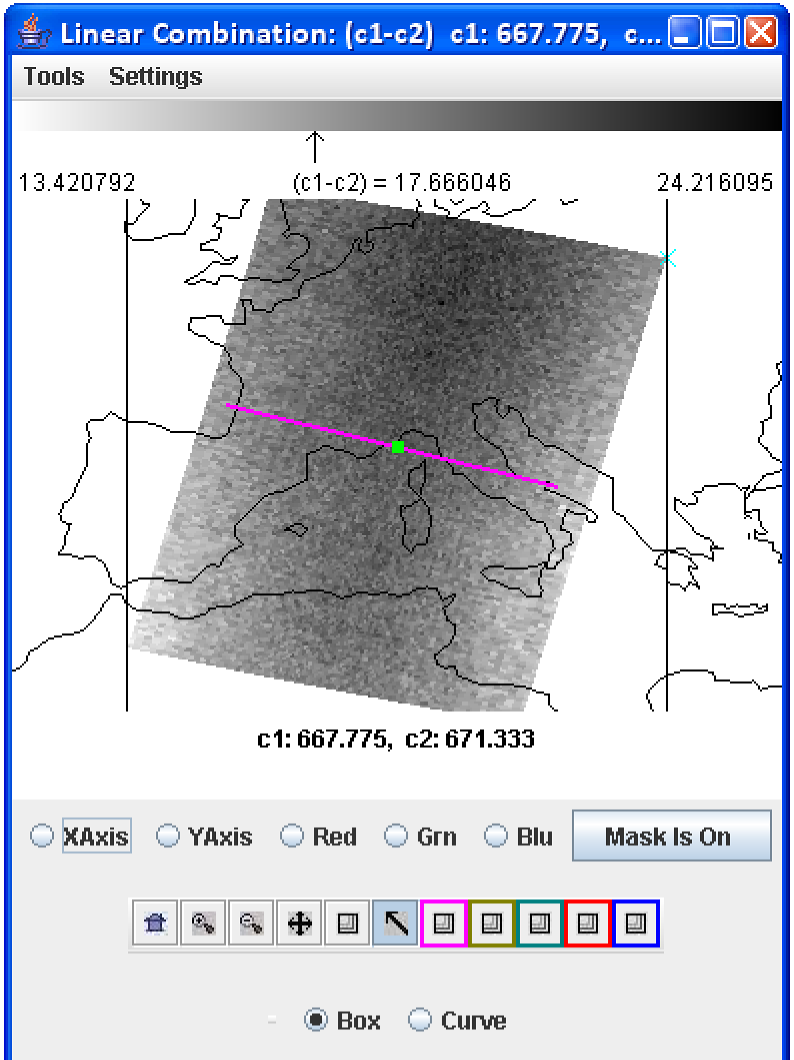
The atmospheric contribution is the weighted sum of the Planck radiance contribution from each layer, where the weighting function is [$d\tau_\lambda(p) / dp$]. This weighting function is an indication of where in the atmosphere the majority of the radiation for a given spectral band comes from.



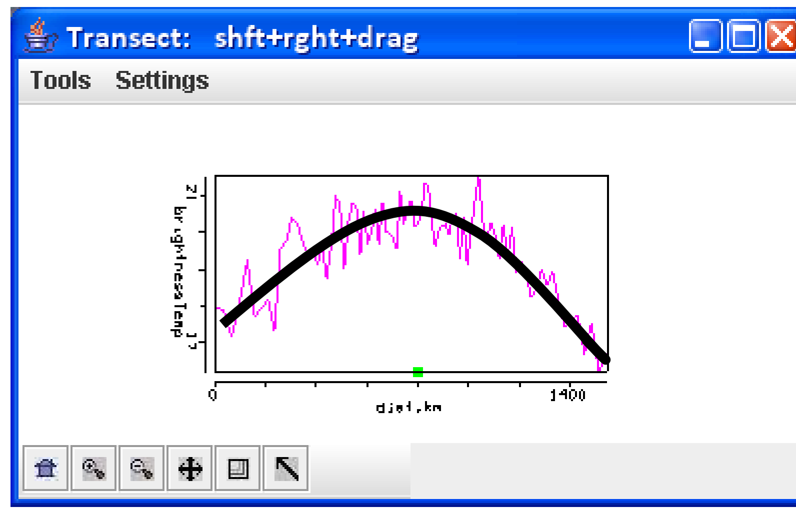
CO2 channels see different layers in the atmosphere



14.2 um 13.9 um 13.6 um 13.3 um

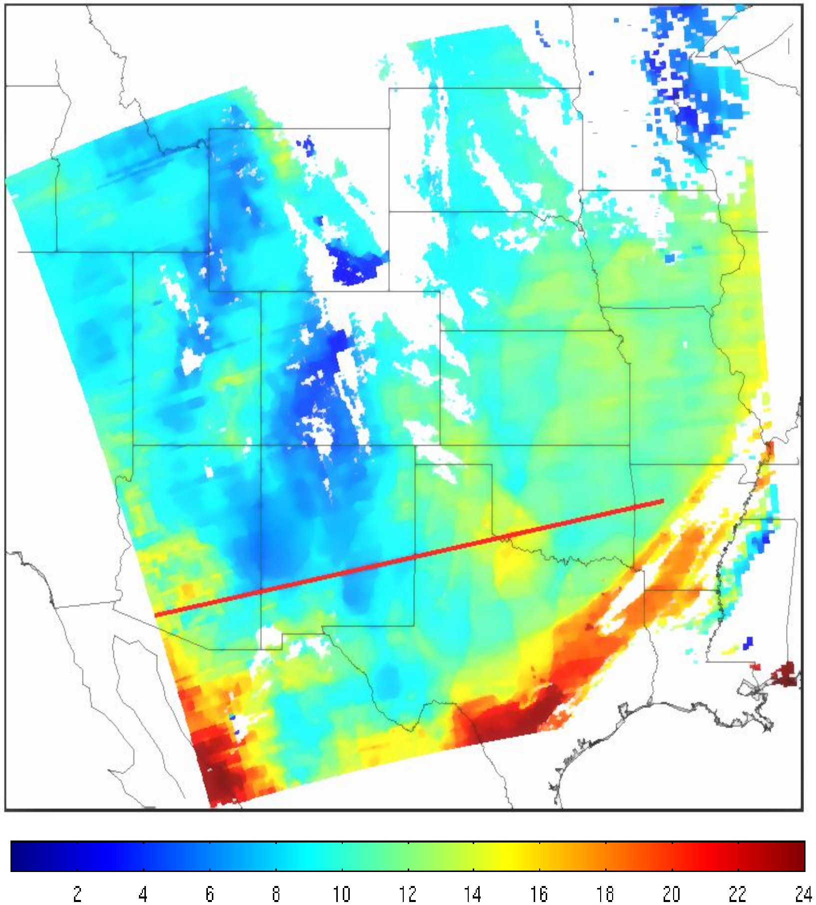


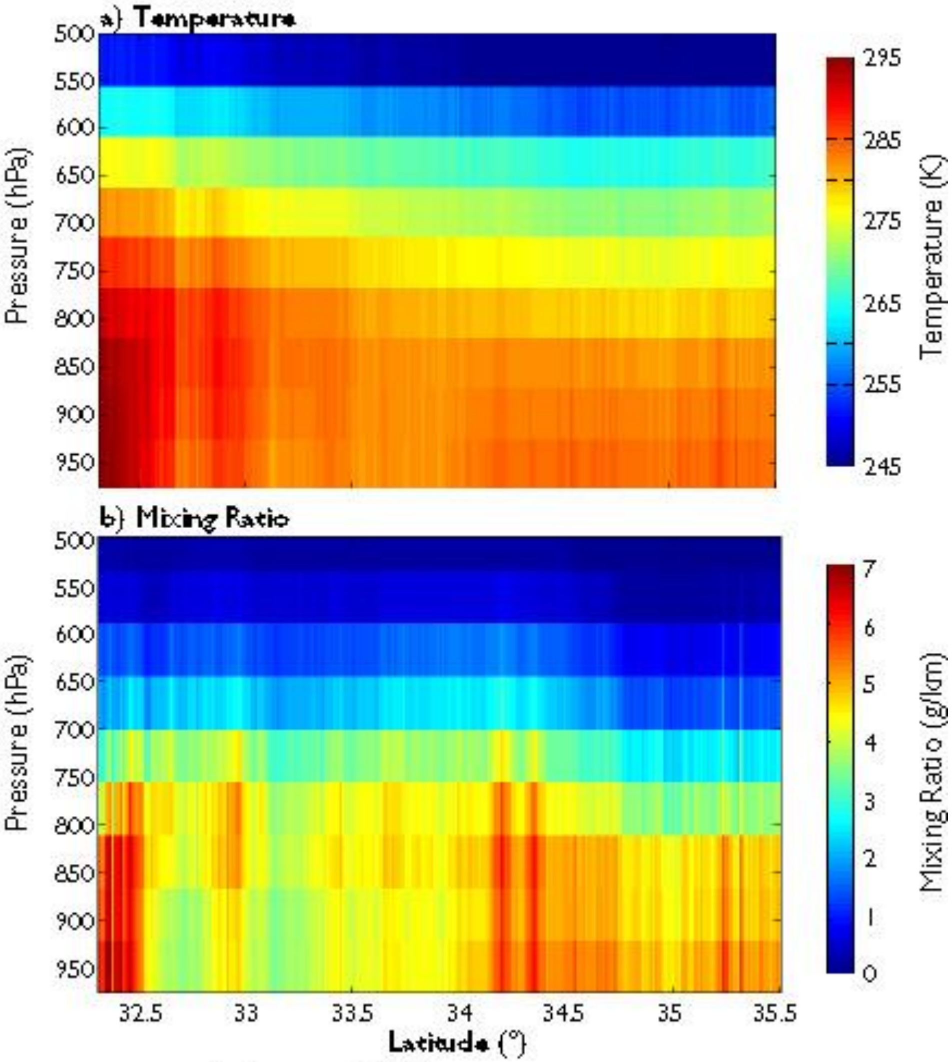
Perpedicular at nadir



Limb darkening

MODIS TPW

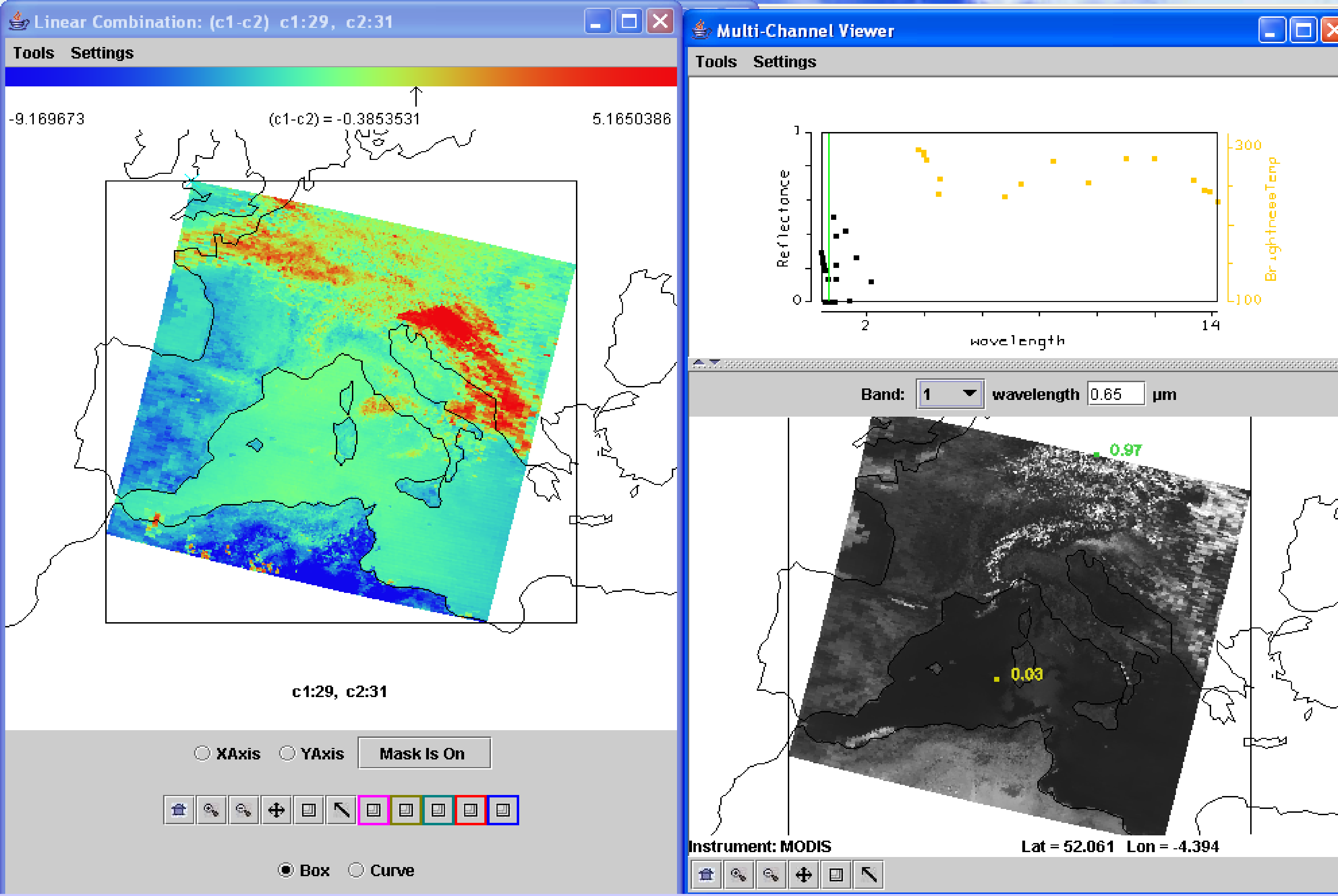




Clear sky layers of temperature and moisture on 2 June 2001

Cloud Mask Tests

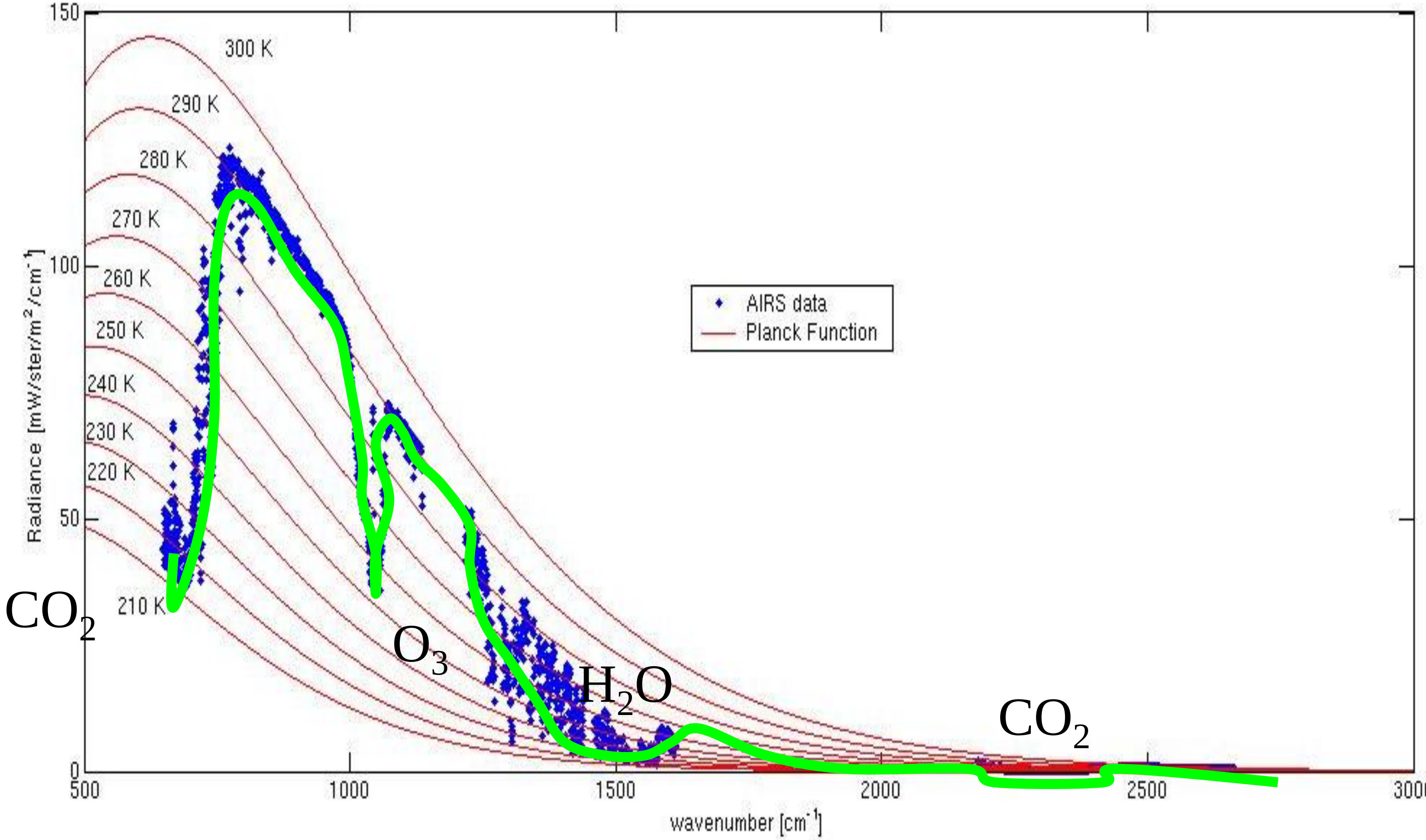
• BT11	clouds over ocean
• BT13.9	high clouds
• BT6.7	high clouds
• BT3.9-BT11	broken or scattered clouds
• BT11-BT12	high clouds in tropics
• BT8.6-BT11	ice clouds
• BT6.7-BT11 or BT13.9-BT11	clouds in polar regions
• BT11+aPW(BT11-BT12)	clouds over ocean
• r0.65	clouds over land
• r0.85	clouds over ocean
• r1.38	thin cirrus
• r1.6	clouds over snow, ice cloud
• r0.85/r0.65 or NDVI	clouds over vegetation
• σ(BT11)	clouds over ocean



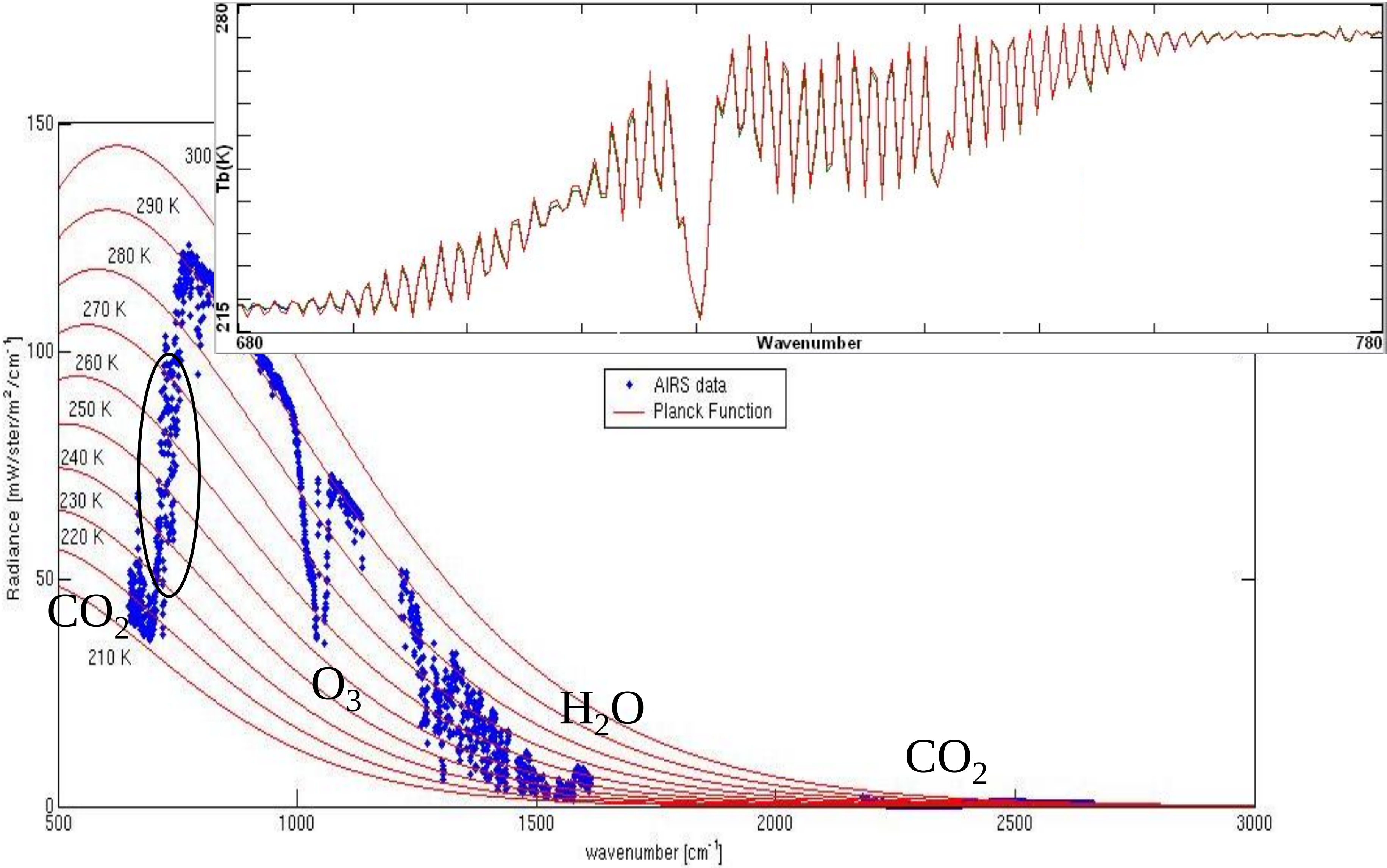
Ice clouds are revealed with BT8.6-BT11>0 & water clouds and fog show in r0.65

High Spectral Resolution IR

Vibrational Lines



Rotational Lines



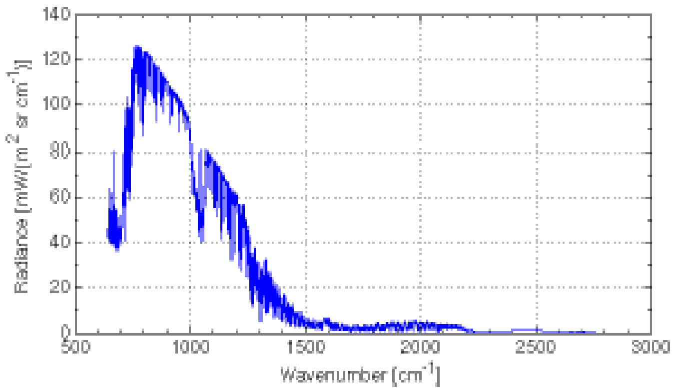
Infrared Radiance and Brightness Temperature Spectrum

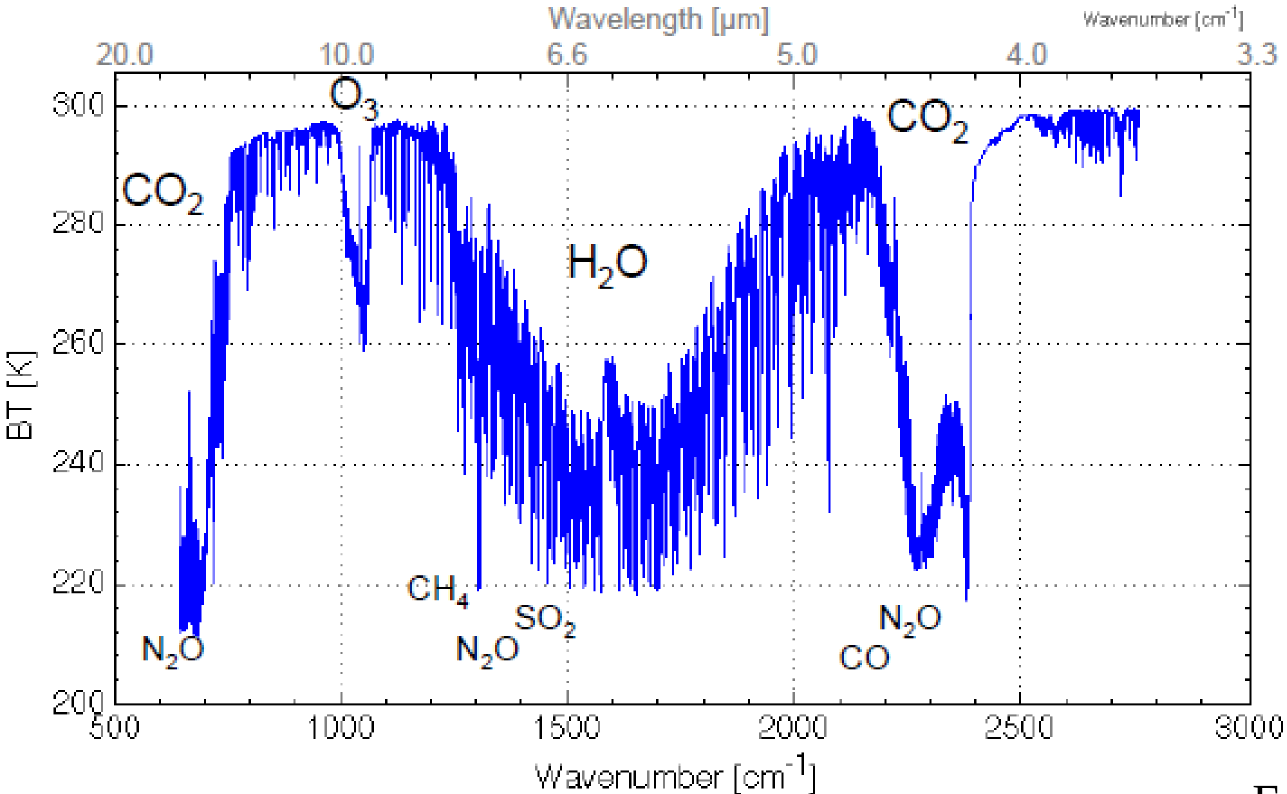
Planck Function

$$B_\nu(T) = 2hc^2\nu^3 \Big/ \exp\left(\frac{hc\nu}{kT}\right) - 1$$

Upwelling IR radiation

$$R_\nu = \int_{z_0}^{\infty} B_\nu(T(z)) \frac{d\tau_\nu(z)}{dz} dz$$

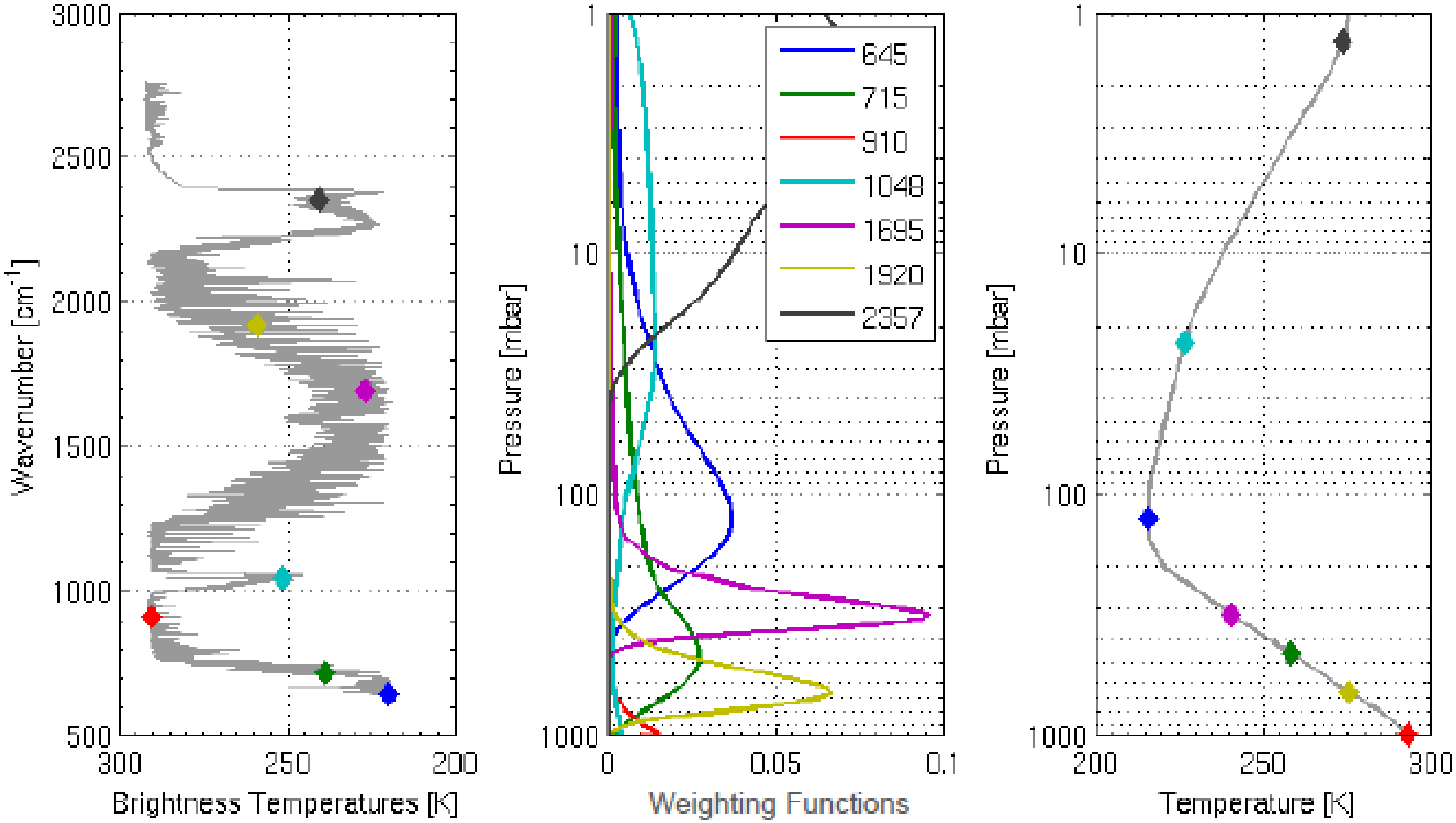




From E. Weisz

Atmospheric Temperature Profile Retrieval

$$R_\nu = \int_{ps}^{0} B_\nu(T(p)) W_\nu(p)\, dp \qquad W_\nu(p) = \frac{\partial \tau_\nu(p)}{\partial \ln p}$$

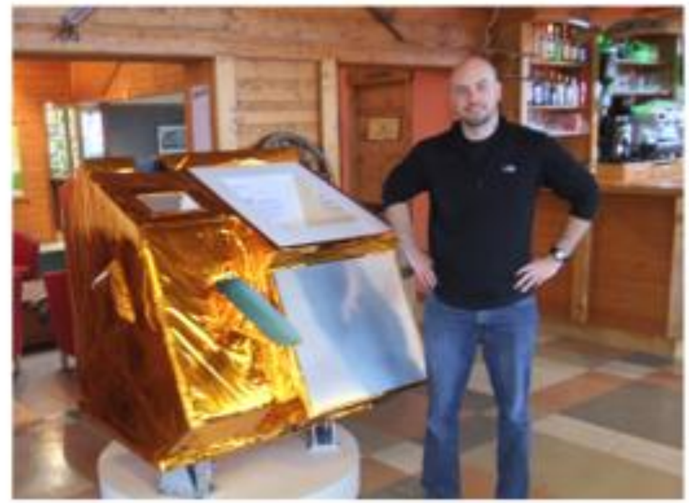


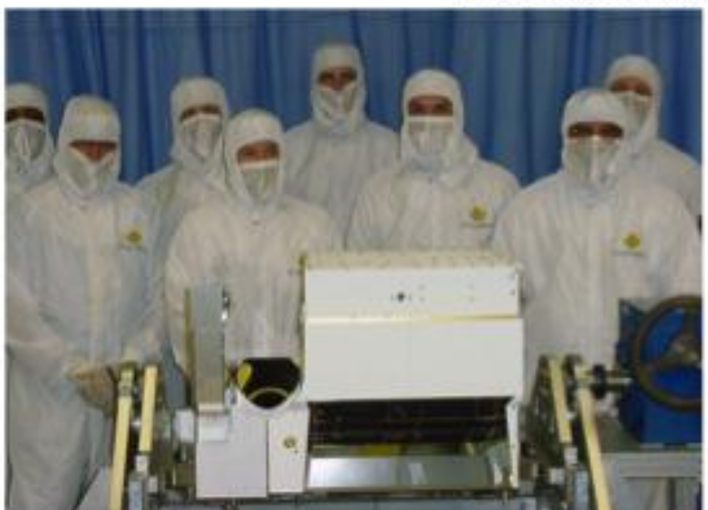
High-spectral measurements → Profiles at high-vertical resolution

From E. Weisz

AIRS
Atmospheric InfraRed Sounder
Grating spectrometer
166 kg, 256 W
13.5 km FOV at nadir, contiguous
Launched on Aqua in 2002

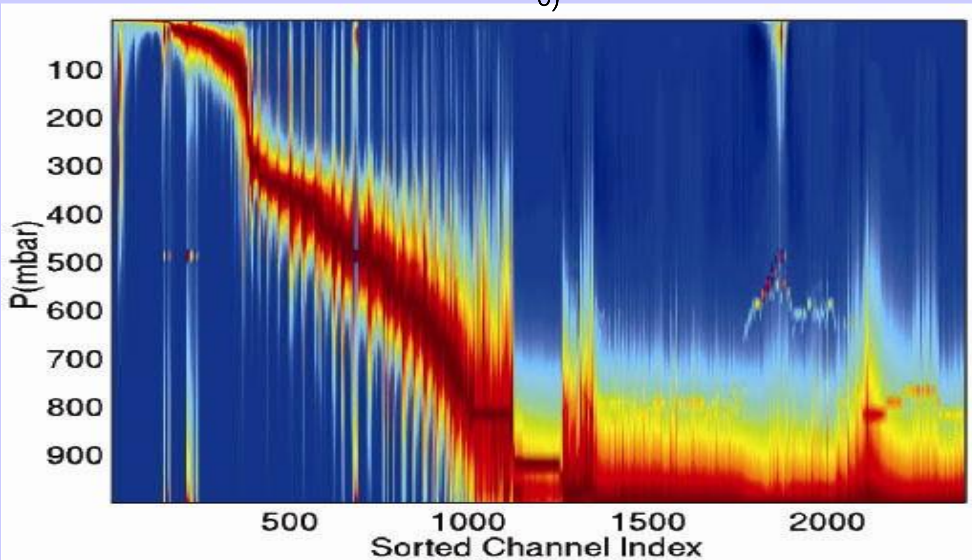
IASI
Infrared Atmospheric Sounding Interferometer
Michelson interferometer
236 kg, 210 W
2x2 12 km FOVs at nadir, non-contiguous
Launched on Metop-A in 2006



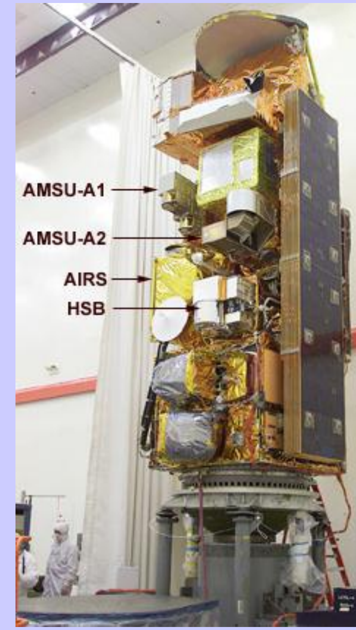


CrIS
Cross-track Infrared Sounder
Michelson interferometer
146 kg, 110 W
3x3 14 km FOVs at nadir, contiguous
To be launched on NPP

temperature weighting functions sorted by pressure of their peak (blue = 0)



AIRS On Aqua

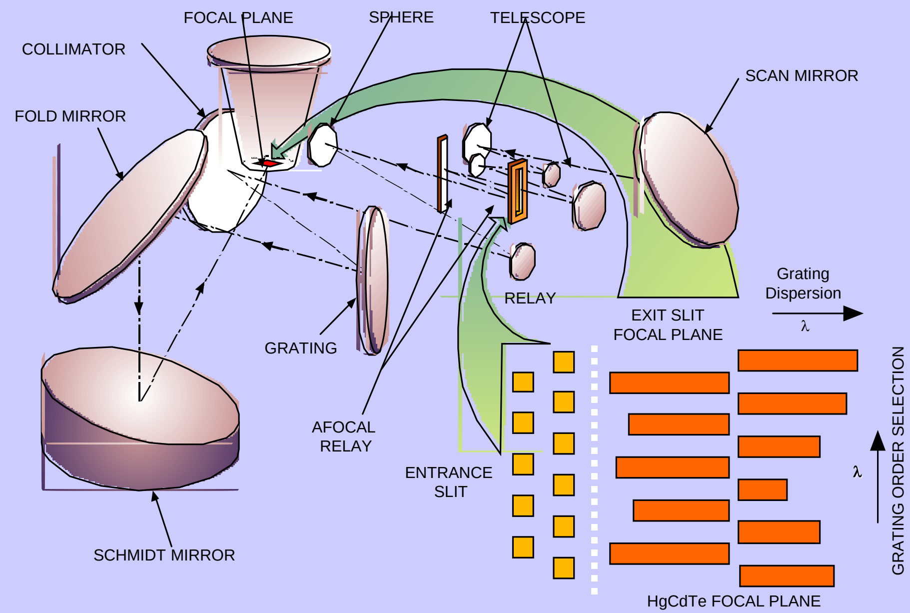


Instrument

- Hyperspectral radiometer with **resolution of 0.5 – 2 cm^{-1}**
- Extremely well calibrated pre-launch
- **Spectral range: 650 – 2700 cm^{-1}**
- Associated microwave instruments (AMSU, HSB)

Design

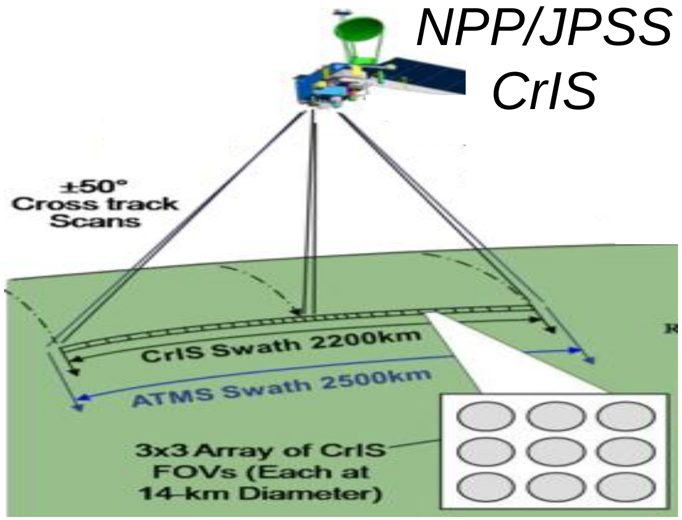
- Grating Spectrometer passively cooled to 160K, stabilized to 30 mK
- **PV and PC HdCdTe focal plane cooled to 60K** with redundant active pulse tube cryogenic coolers
- **Focal plane has ~5000 detectors,** 2378 channels. PV detectors (all below 13 microns) are doubly redundant. Two channels per resolution element (n/Dn = 1200)
- 310 K Blackbody and space view provides radiometric calibration
- Paralyene coating on calibration mirror and upwelling radiation provides spectral calibration
- **NEDT (per resolution element) ranges from 0.05K to 0.5K**



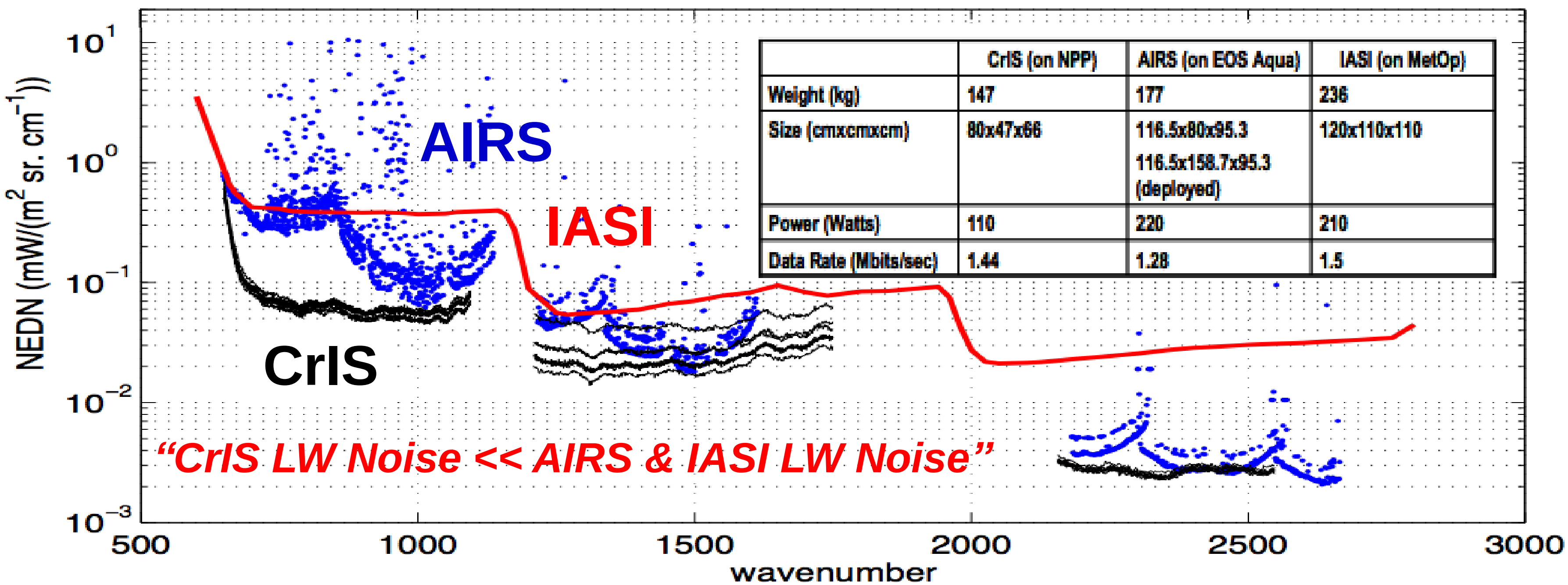
Spectral filters at each entrance slit and over each FPA array isolate color band (grating order) of interest

Cross-Track Infrared Sounder (CrIS)

NPOESS Preparatory Satellite – Launch: October 2011

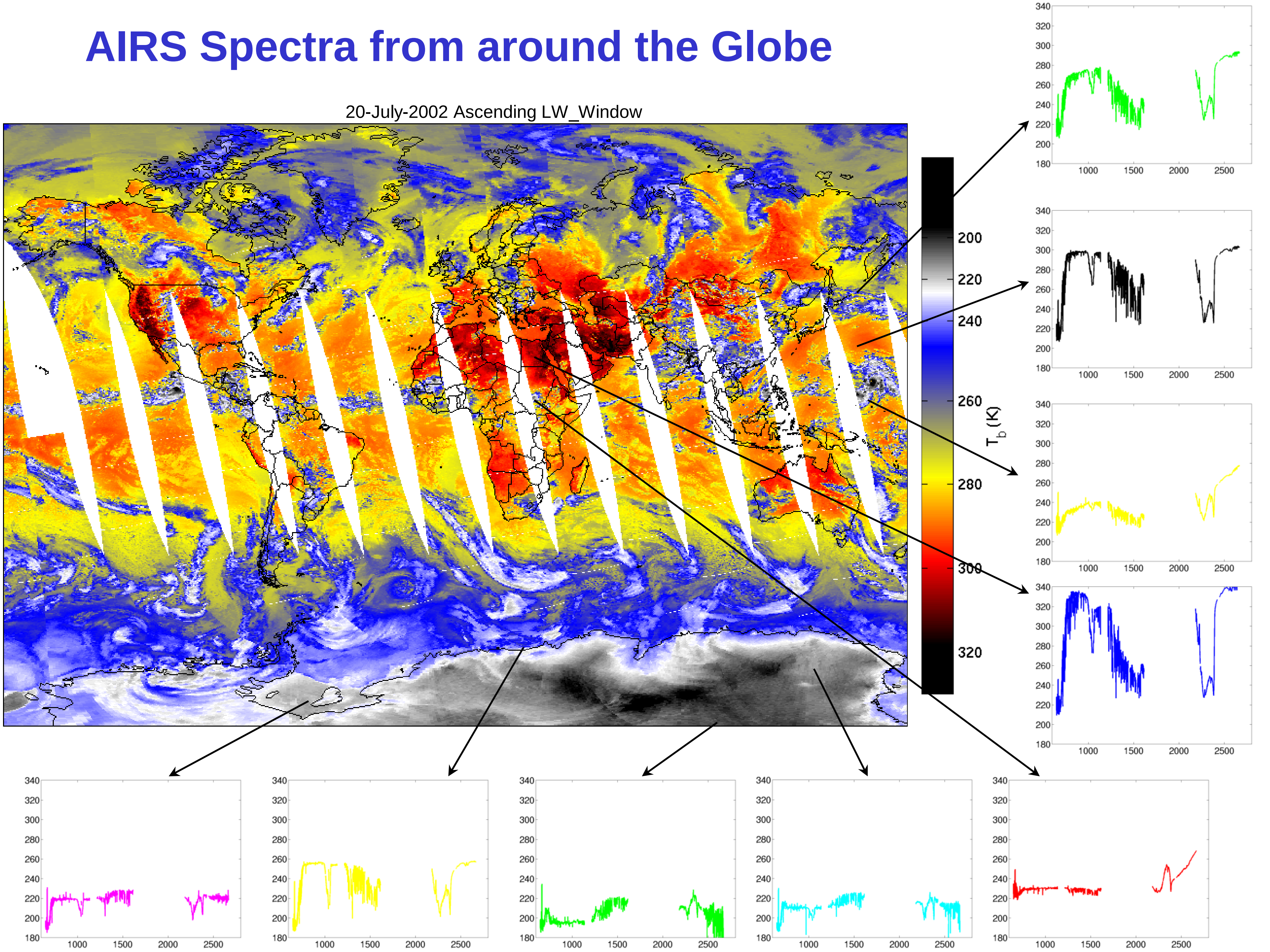


- Michelson Interferometer: 0.625,1.25, 2.5cm^{-1} (resolving power of 1000)
- Spectral range: 660-2600 cm^{-1}
- 3 x 3 HdCdTe focal plane passively cooled (4-stages) to 85K
- Focal plane 27 detectors, 1305 spectral channels
- 310 K Blackbody and space view provides radiometric calibration
- NEDT ranges from 0.05 K to 0. 5 K

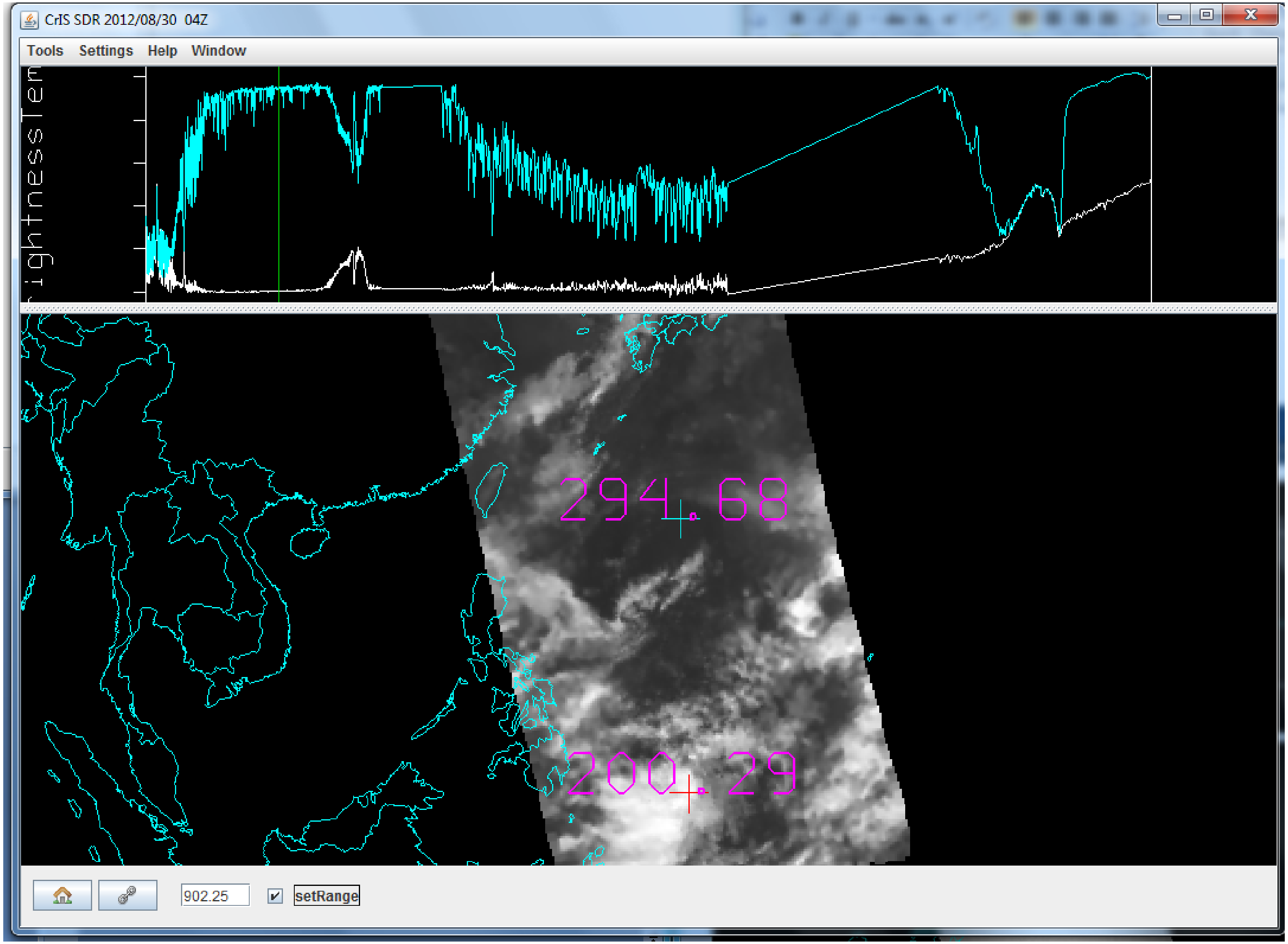


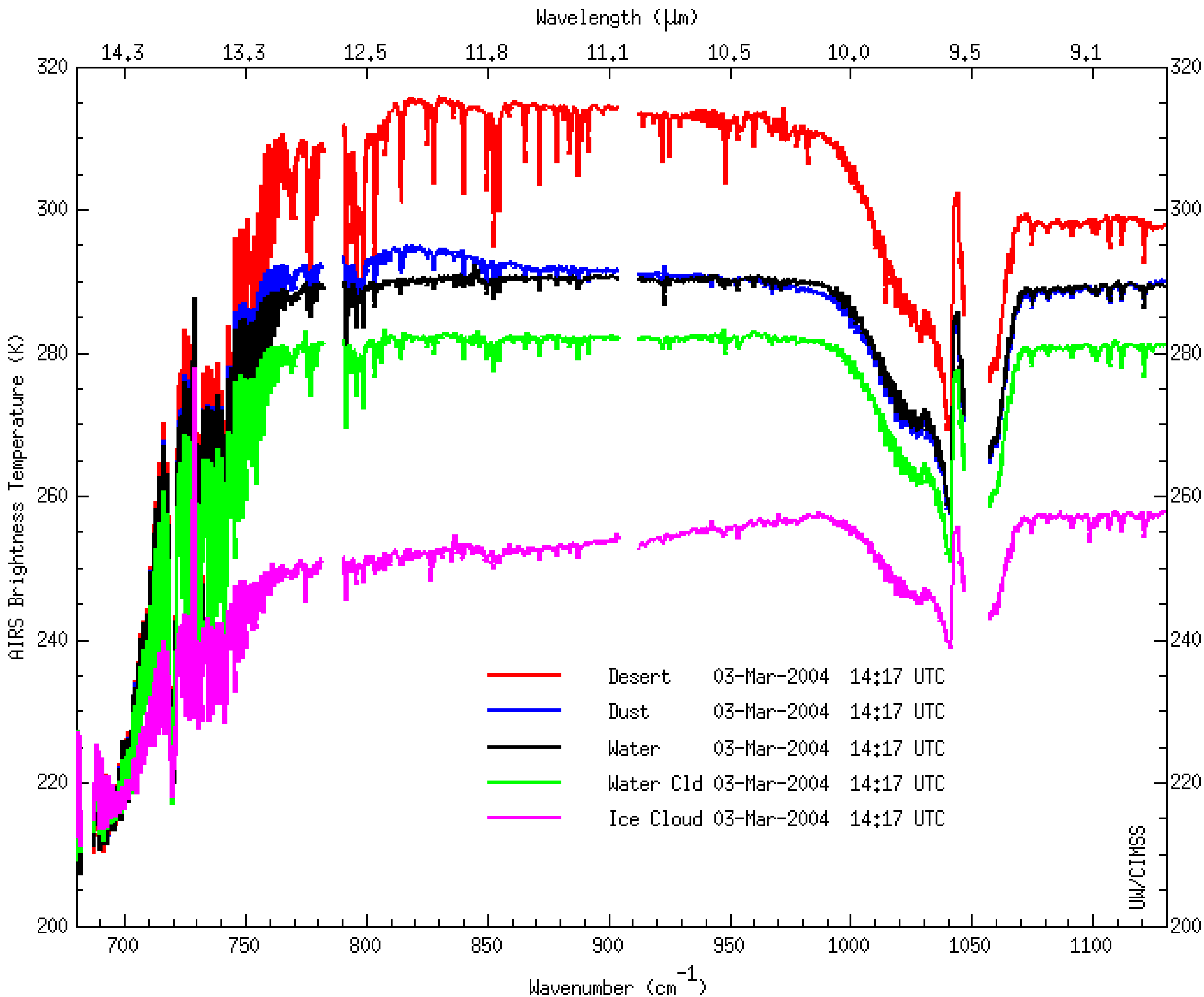
	CrIS (on NPP)	AIRS (on EOS Aqua)	IASI (on MetOp)
Weight (kg)	147	177	236
Size (cmxcmxcm)	80x47x66	116.5x80x95.3 116.5x158.7x95.3 (deployed)	120x110x110
Power (Watts)	110	220	210
Data Rate (Mbits/sec)	1.44	1.28	1.5

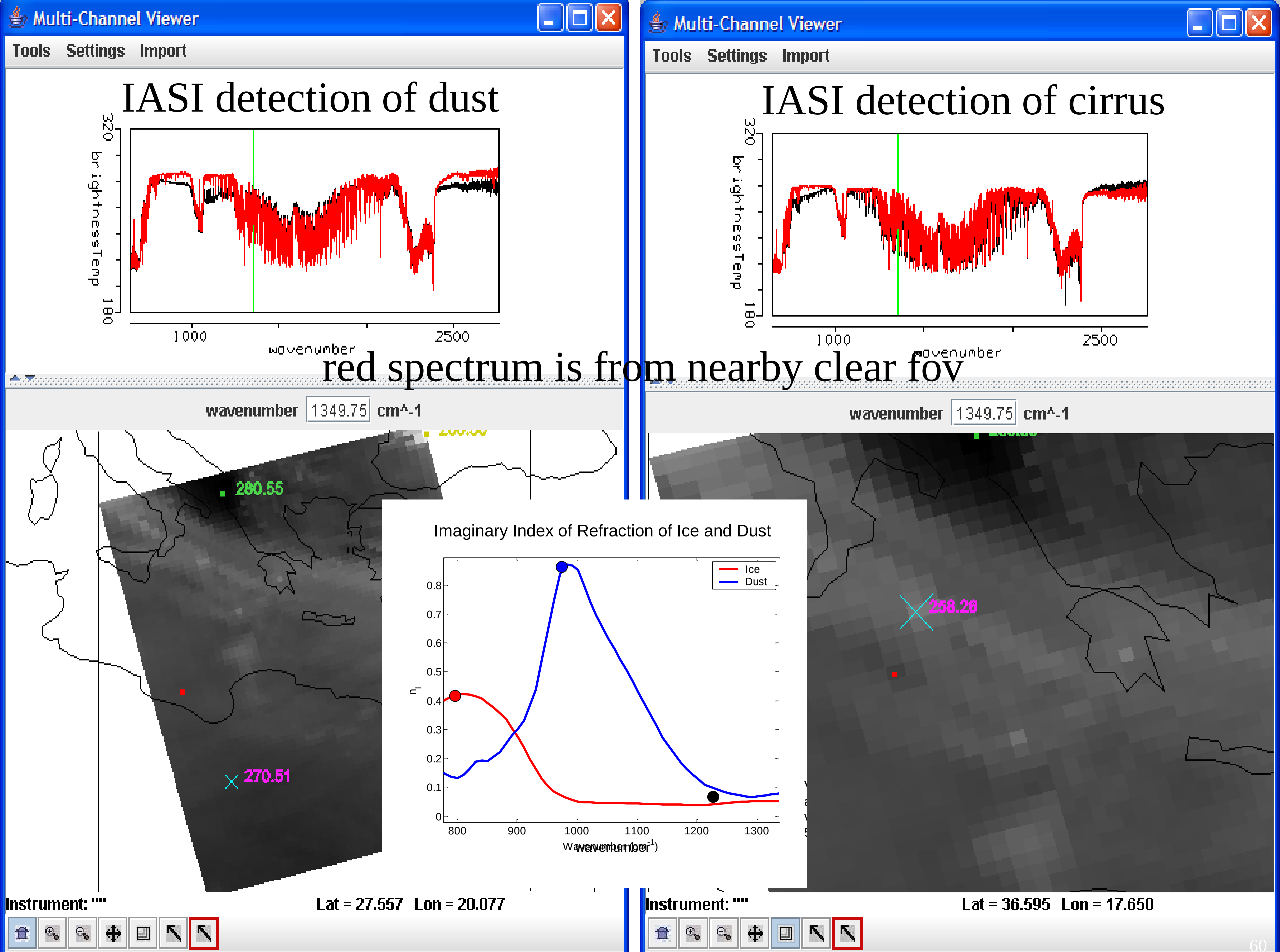
AIRS Spectra from around the Globe



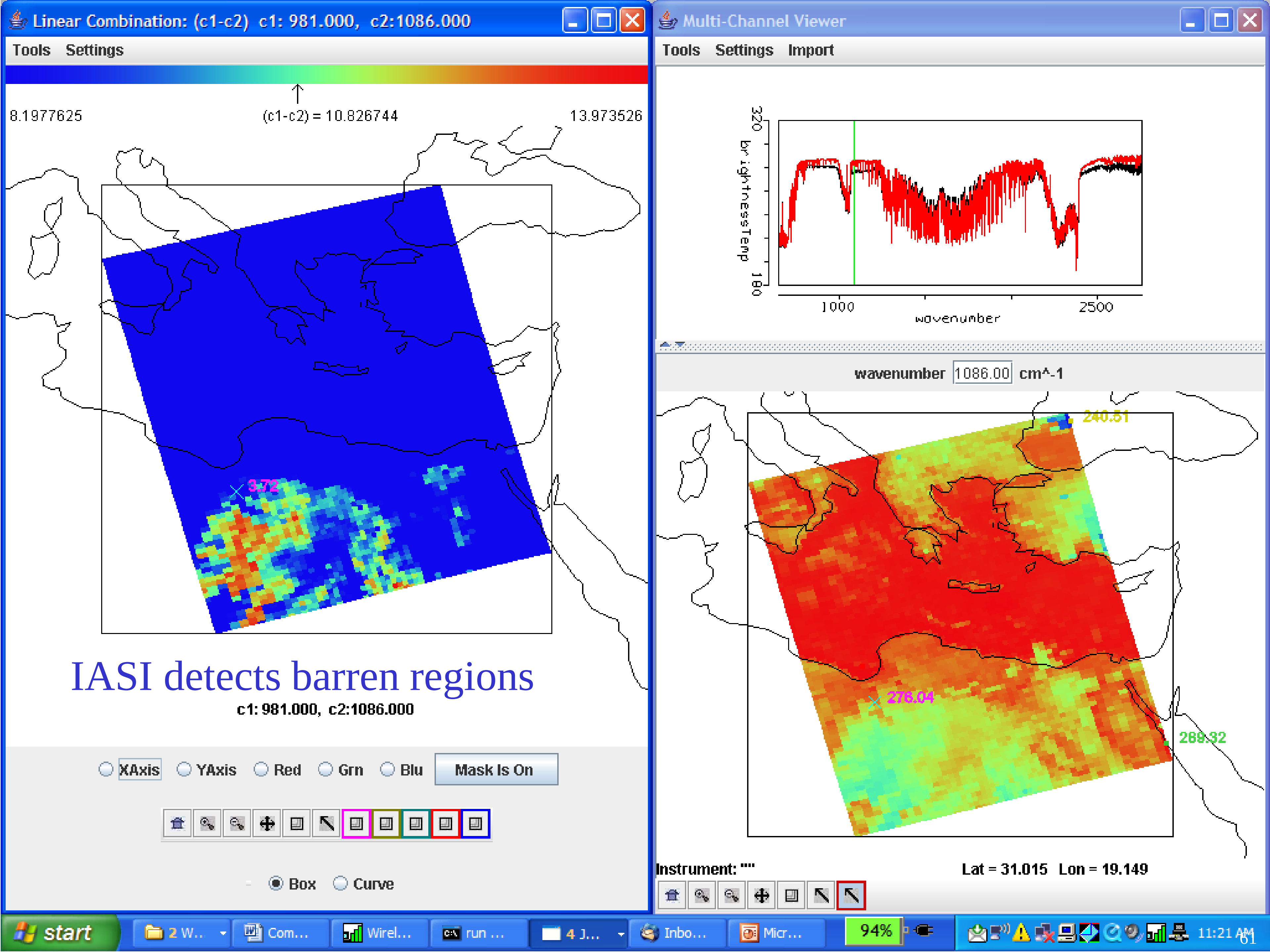
Gregg, Bill, Pei

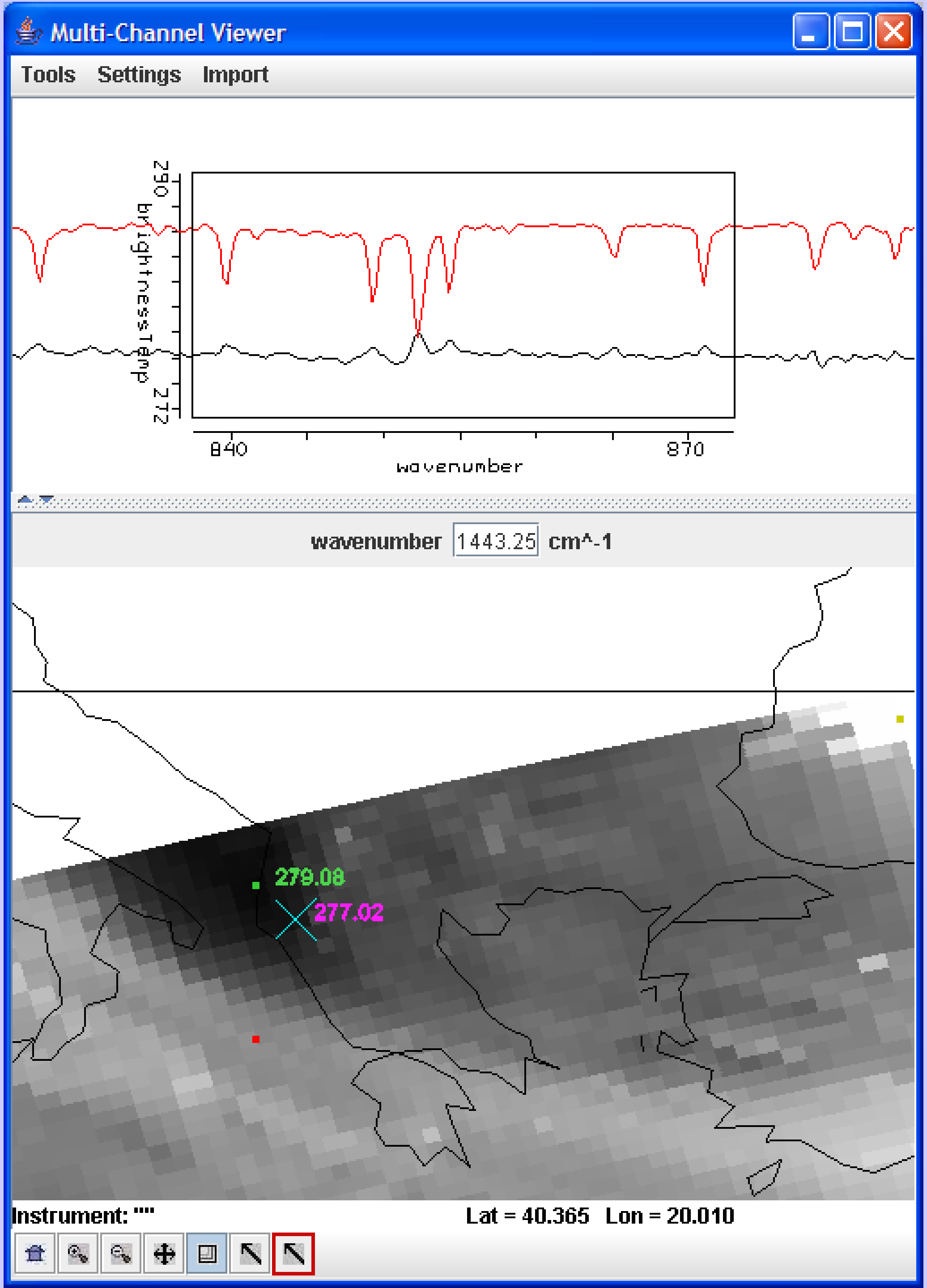



Wavelength (µm)
14.3
13.3
12.5
11.8
11.1
10.5
10.0
9.5
9.1
AIRS Brightness Temperature (K)
320
300
280
260
240
220
200
Wavenumber (cm^{-1})
700
750
800
850
900
950
1000
1050
1100
Desert 03-Mar-2004 14:17 UTC
Dust 03-Mar-2004 14:17 UTC
Water 03-Mar-2004 14:17 UTC
Water Cld 03-Mar-2004 14:17 UTC
Ice Cloud 03-Mar-2004 14:17 UTC
UW/CIMSS


Multi-Channel Viewer
Tools Settings Import
IASI detection of dust
320
brightnessTemp
180
1000
2500
wavenumber
wavenumber 1349.75 cm^-1
280.55
270.51
Instrument: ""
Lat = 27.557 Lon = 20.077
Multi-Channel Viewer
Tools Settings Import
IASI detection of cirrus
320
brightnessTemp
180
1000
2500
wavenumber
red spectrum is from nearby clear fov
wavenumber 1349.75 cm^-1
258.26
Instrument: ""
Lat = 36.595 Lon = 17.650
Imaginary Index of Refraction of Ice and Dust
Ice
Dust
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
800
900
1000
1100
1200
1300
wavenumber

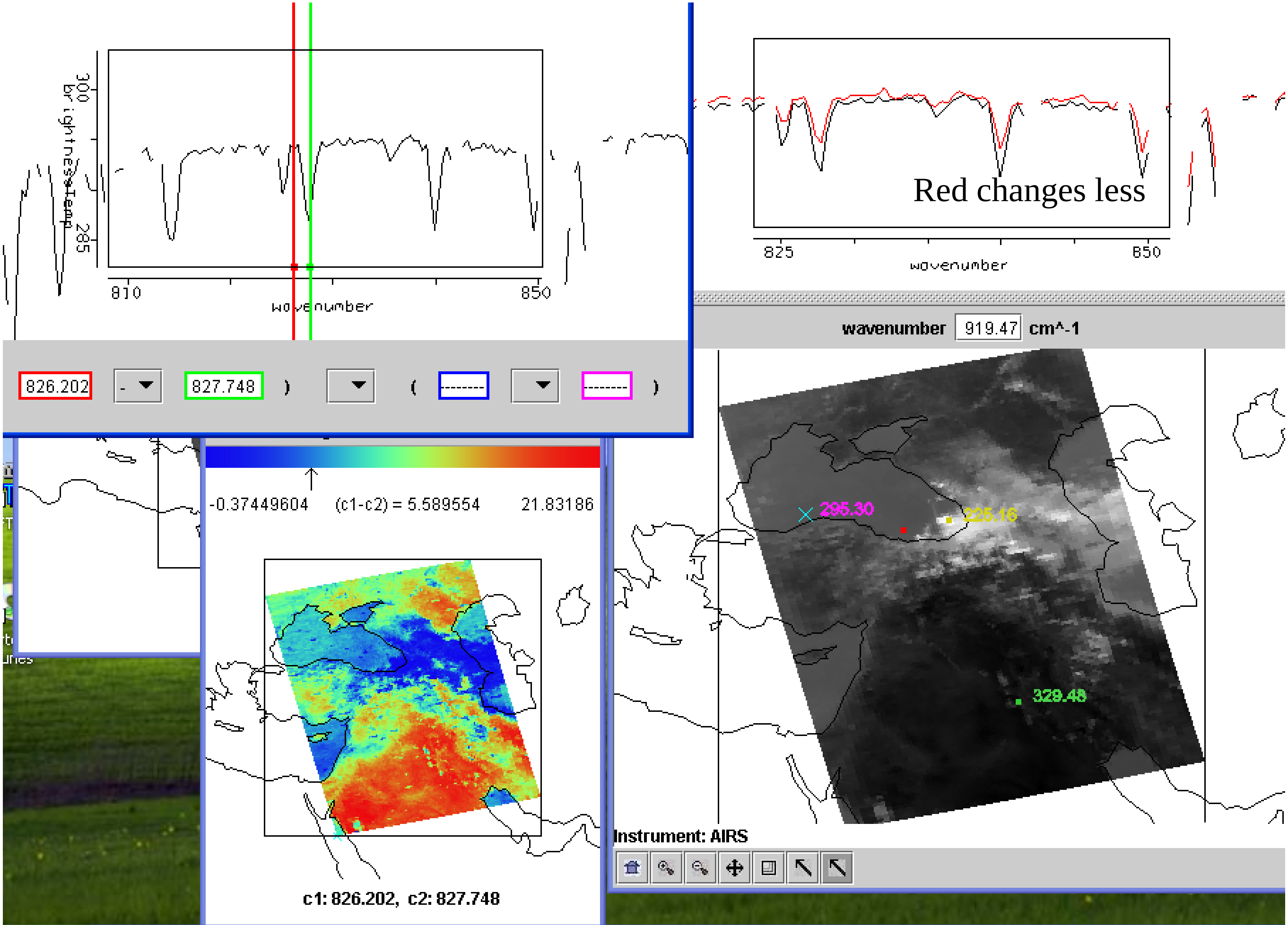
IASI detects barren regions

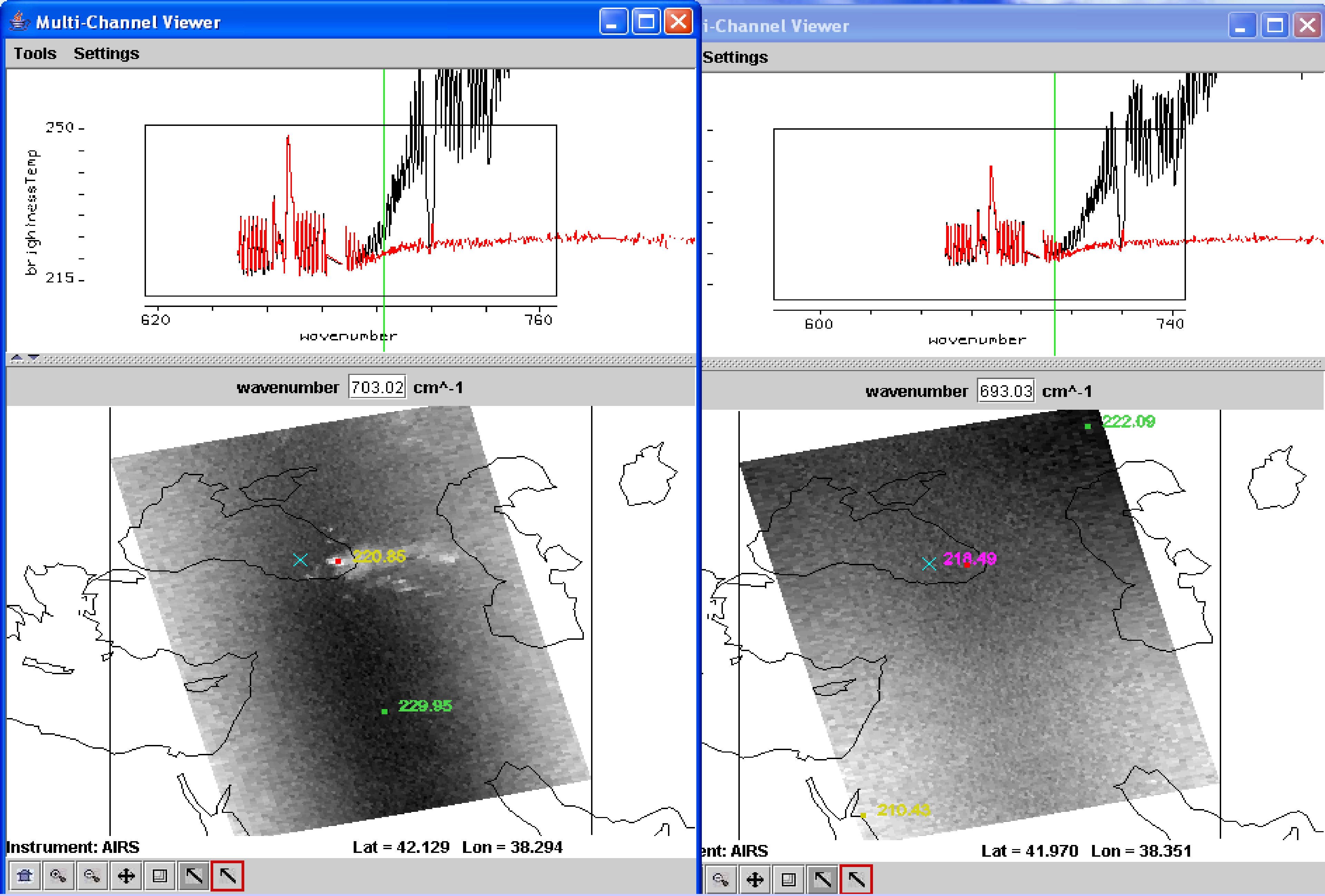




IASI sees
low level inversion
over land

Offline-Online in LW IRW showing low level moisture





Cld and clr spectra in CO2 absorption separate when weighting functions sink to cloud level

MW

ATMS Design Challenge

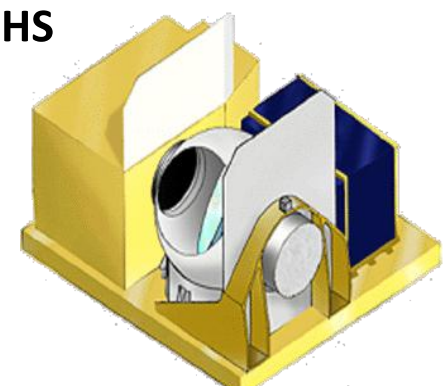
AMSU-A1

- 73x30x61 cm
- 67 W
- 54 kg
- 3-yr life

AMSU-A2

- 75x70x64 cm
- 24 W
- 50 kg
- 3-yr life

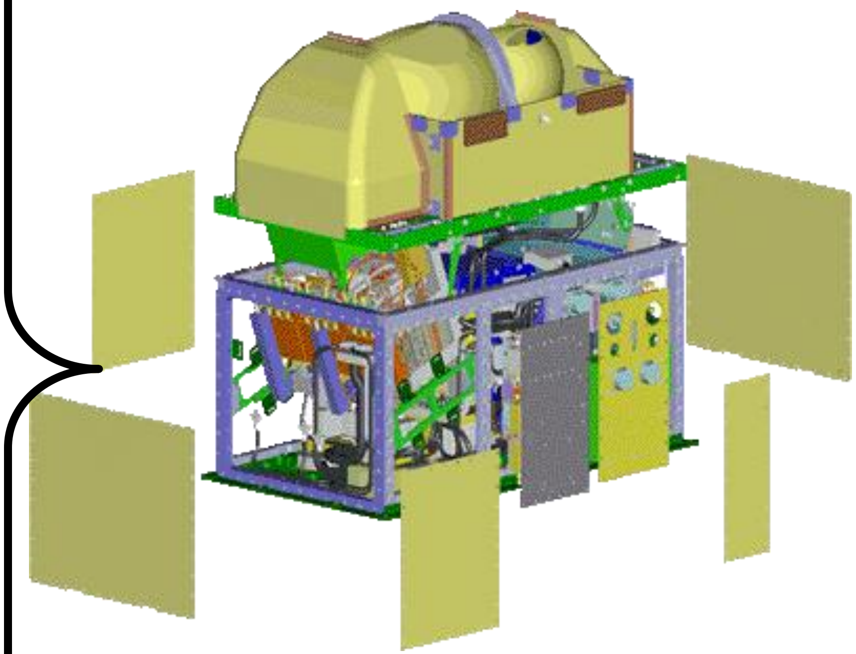
MHS



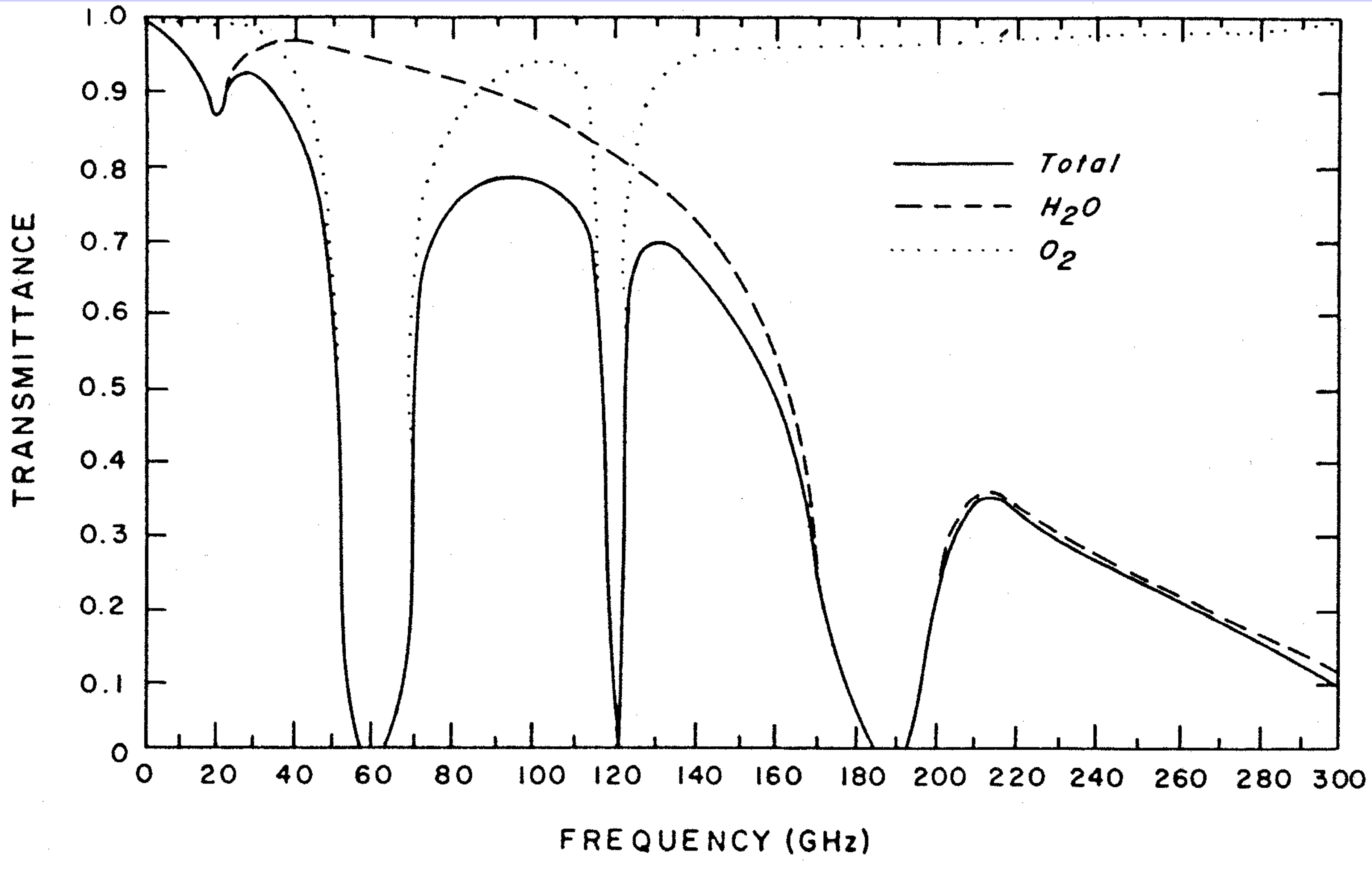
- 75x56x69 cm
- 61 W
- 50 kg
- 4-yr life

Figure courtesy NGES, Azusa, CA

Reduce the volume by 3x



- 70x40x60 cm
- 110 W
- 85 kg
- 8 year life



TRANSMITTANCE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
FREQUENCY (GHz)
Total
H_2O
O_2

Radiation is governed by Planck's Law

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} - 1] \}$$

In microwave region $c_2/\lambda T << 1$ so that

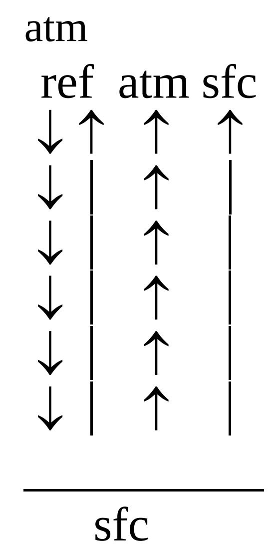
$$e^{c_2/\lambda T} = 1 + c_2/\lambda T + \text{second order}$$

And classical Rayleigh Jeans radiation equation emerges

$$B_\lambda(T) \approx [c_1 / c_2] [T / \lambda^4]$$

Radiance is linear function of brightness temperature.

Microwave Form of RTE



$$I_\lambda^{sfc} = \varepsilon_\lambda B_\lambda(T_s)\,\tau_\lambda(p_s) + (1-\varepsilon_\lambda)\,\tau_\lambda(p_s) \int_o^{p_s} B_\lambda(T(p)) \frac{\partial \tau'_\lambda(p)}{\partial \ln p}\, d \ln p$$

$$I_\lambda = \varepsilon_\lambda B_\lambda(T_s)\,\tau_\lambda(p_s) + (1-\varepsilon_\lambda)\,\tau_\lambda(p_s) \int_o^{p_s} B_\lambda(T(p)) \frac{\partial \tau'_\lambda(p)}{\partial \ln p}\, d \ln p$$

$$+ \int_{p_s}^{o} B_\lambda(T(p)) \frac{\partial \tau_\lambda(p)}{\partial \ln p}\, d \ln p$$

In the microwave region $c_2/\lambda T << 1$, so the Planck radiance is linearly proportional to the temperature

$$B_\lambda(T) \approx [c_1 / c_2]\,[T / \lambda^4]$$

So

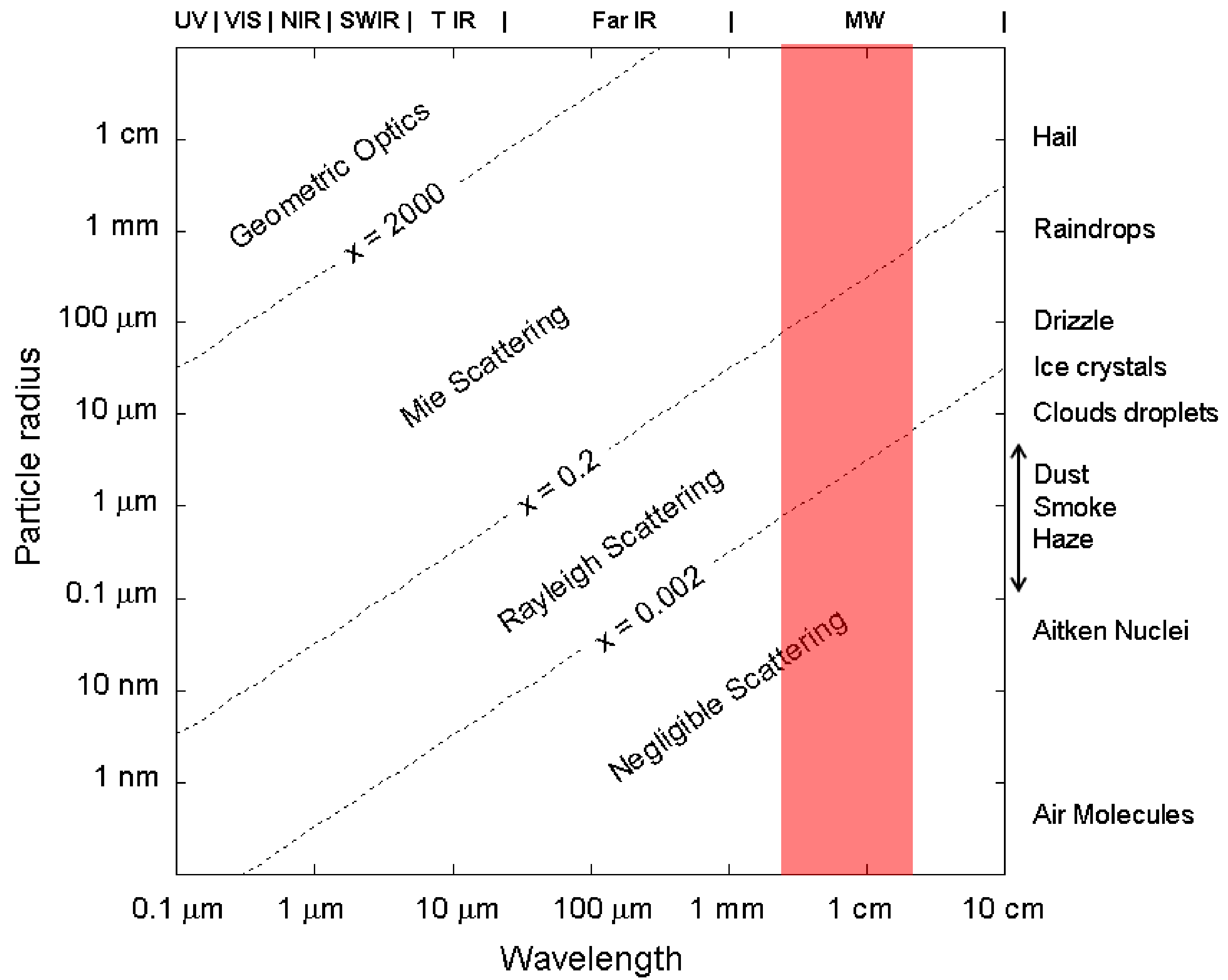
$$T_{b\lambda} = \varepsilon_\lambda T_s(p_s)\,\tau_\lambda(p_s) + \int_{p_s}^{o} T(p)\, F_\lambda(p) \frac{\partial \tau_\lambda(p)}{\partial \ln p}\, d \ln p$$

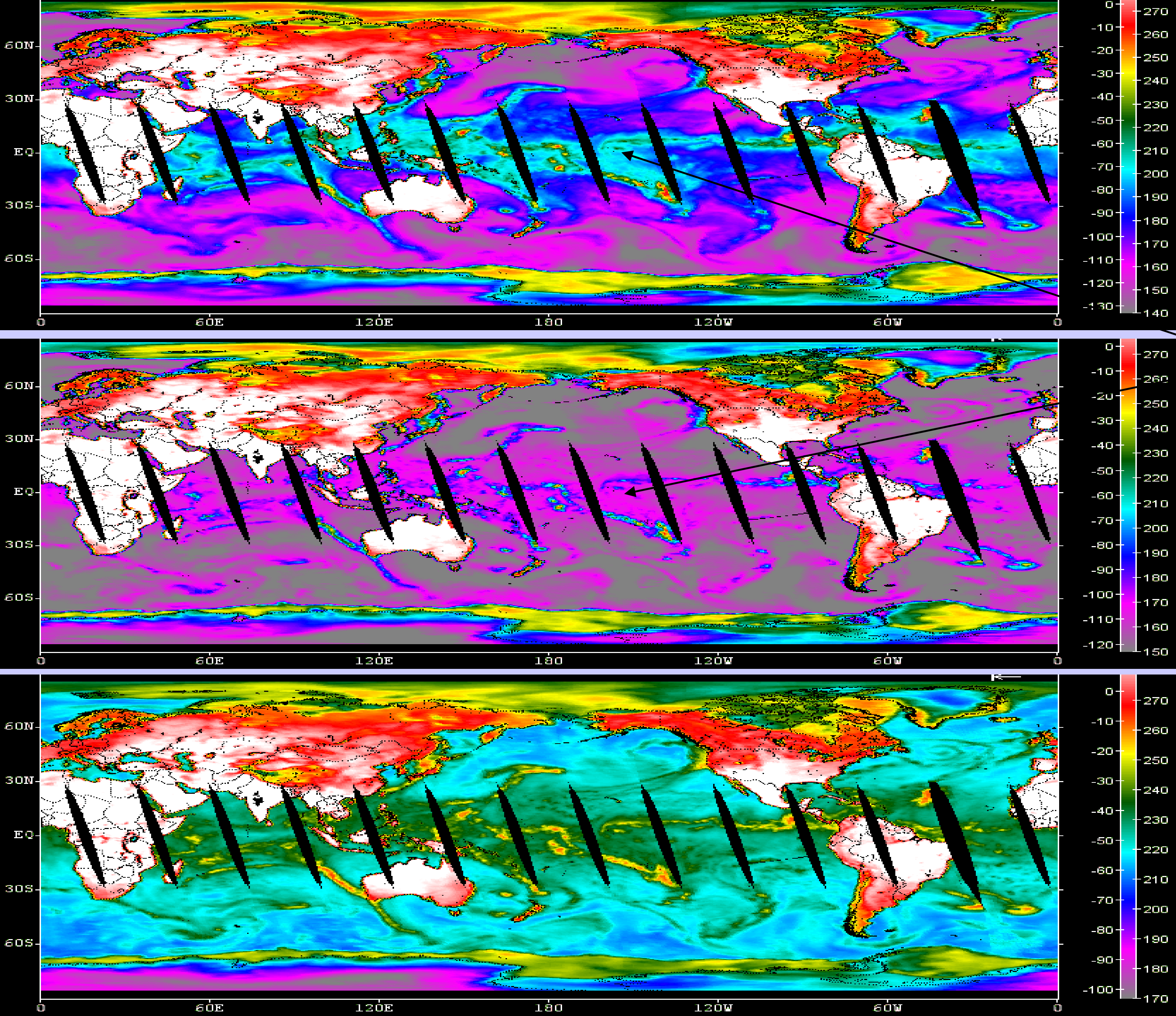
where

$$F_\lambda(p) = \left\{ 1 + (1 - \varepsilon_\lambda) \left[\frac{\tau_\lambda(p_s)}{\tau_\lambda(p)}\right]^2 \right\} .$$

Scattering of MW radiation

- Scattering regimes





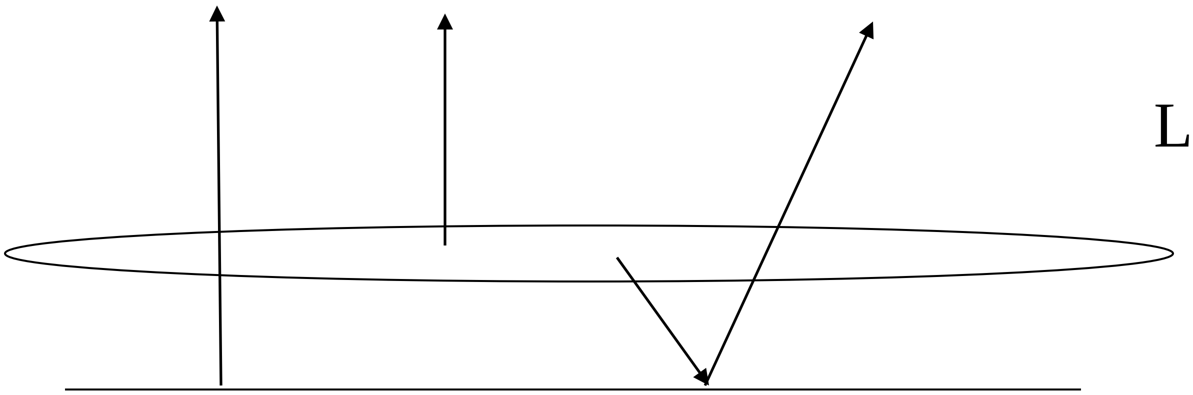
AMSU

23.8 dirty window

atm Q warms BT

31.4 window

50.3 GHz



Low mist over ocean

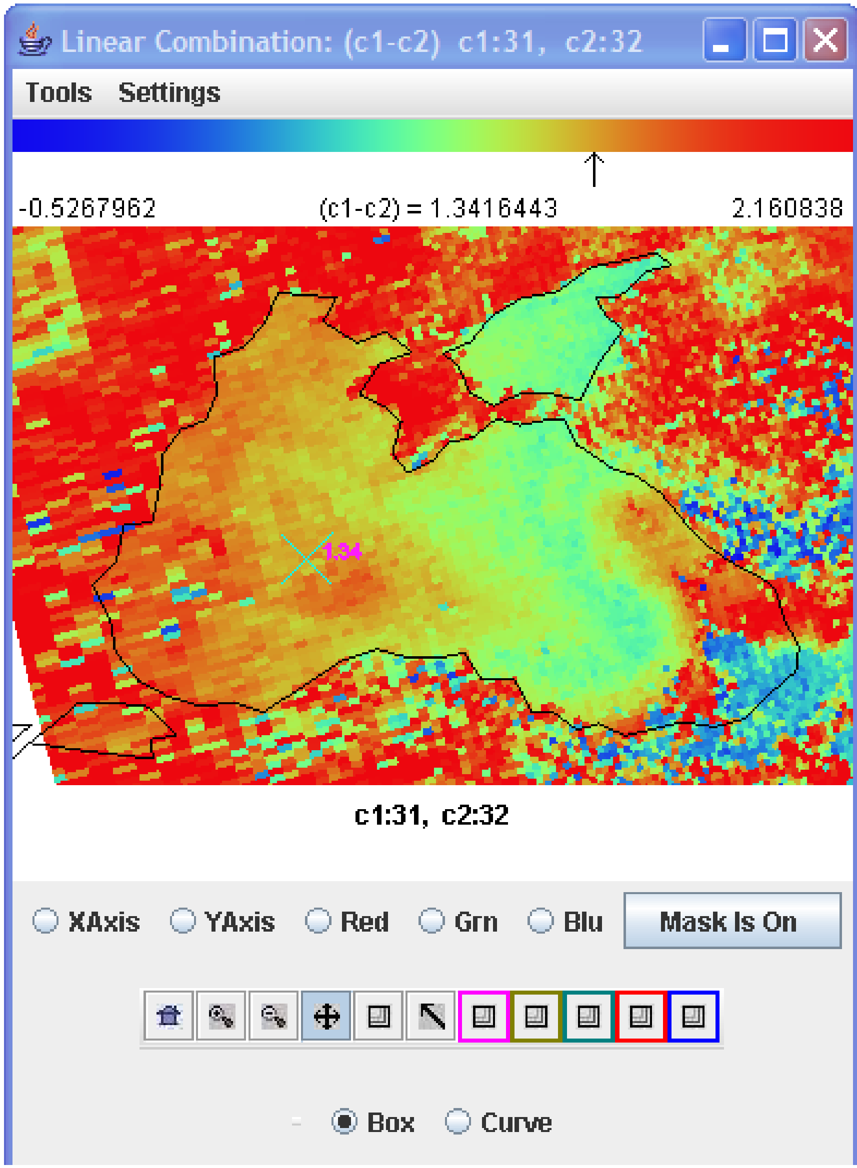
$$T_b = \varepsilon_s T_s (1-\sigma_m) + \sigma_m T_m + \sigma_m (1-\varepsilon_s)(1-\sigma_m) T_m$$

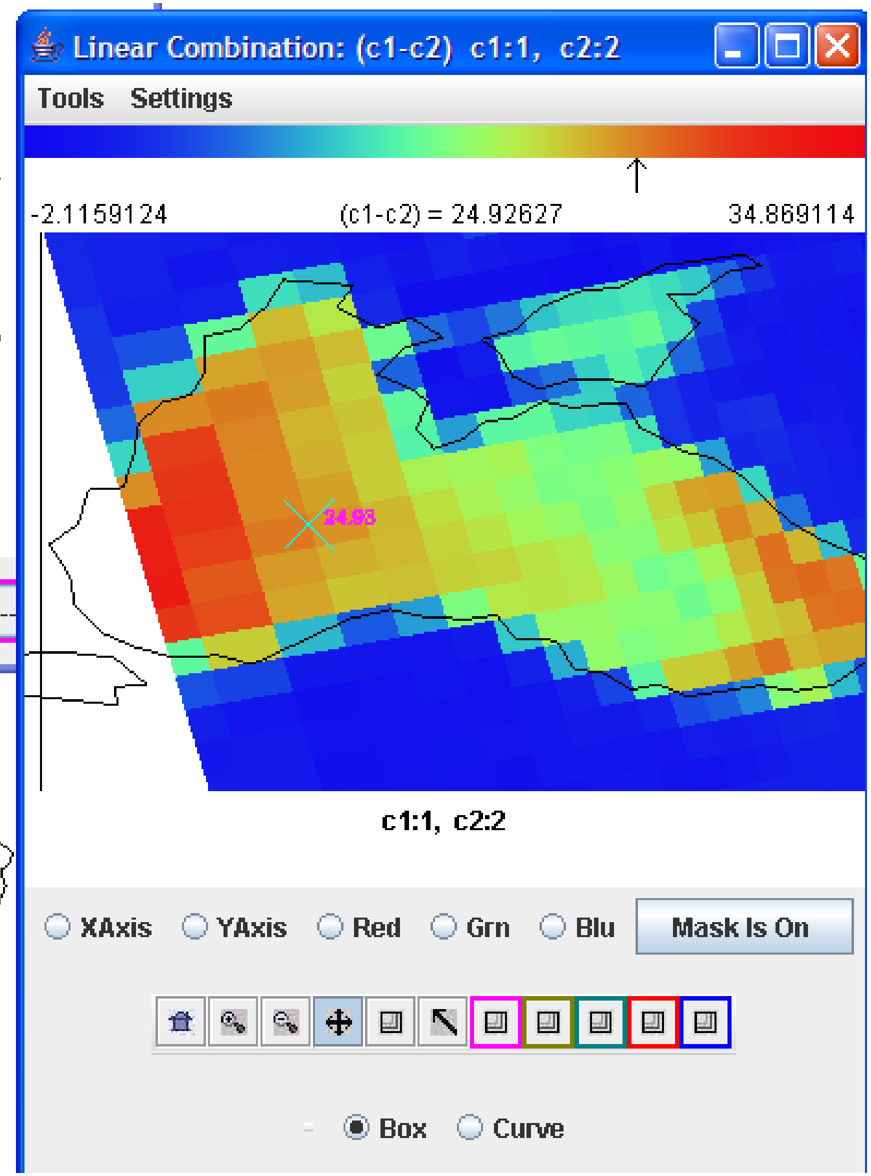
So

$$\Delta T_b = -\varepsilon_s \sigma_m T_s + \sigma_m T_m + \sigma_m (1-\varepsilon_s)(1-\sigma_m) T_m$$

For $\varepsilon_s \sim 0.5$ and $T_s \sim T_m$ this is always positive for $0 < \sigma_m < 1$

MW split window has larger signal for low level moisture than IR split window





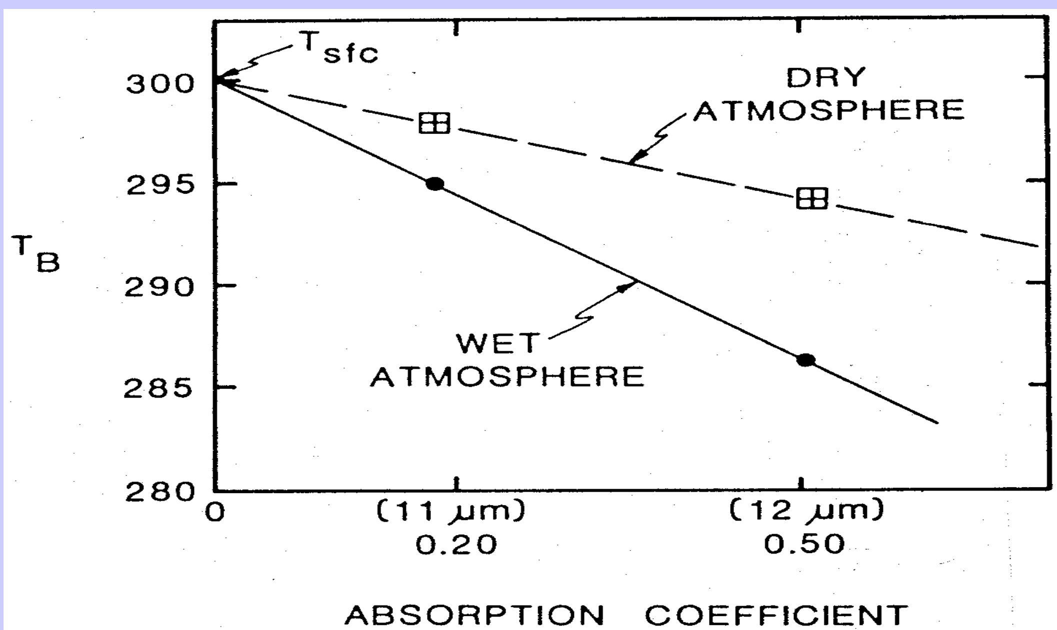
Moisture

Moisture attenuation in atmospheric windows varies linearly with optical depth.

$$\tau_\lambda = e^{-k_\lambda u} = 1 - k_\lambda u$$

For same atmosphere, deviation of brightness temperature from surface temperature is a linear function of absorbing power. Thus moisture corrected SST can inferred by using split window measurements and extrapolating to zero k_λ

Moisture content of atmosphere inferred from slope of linear relation.

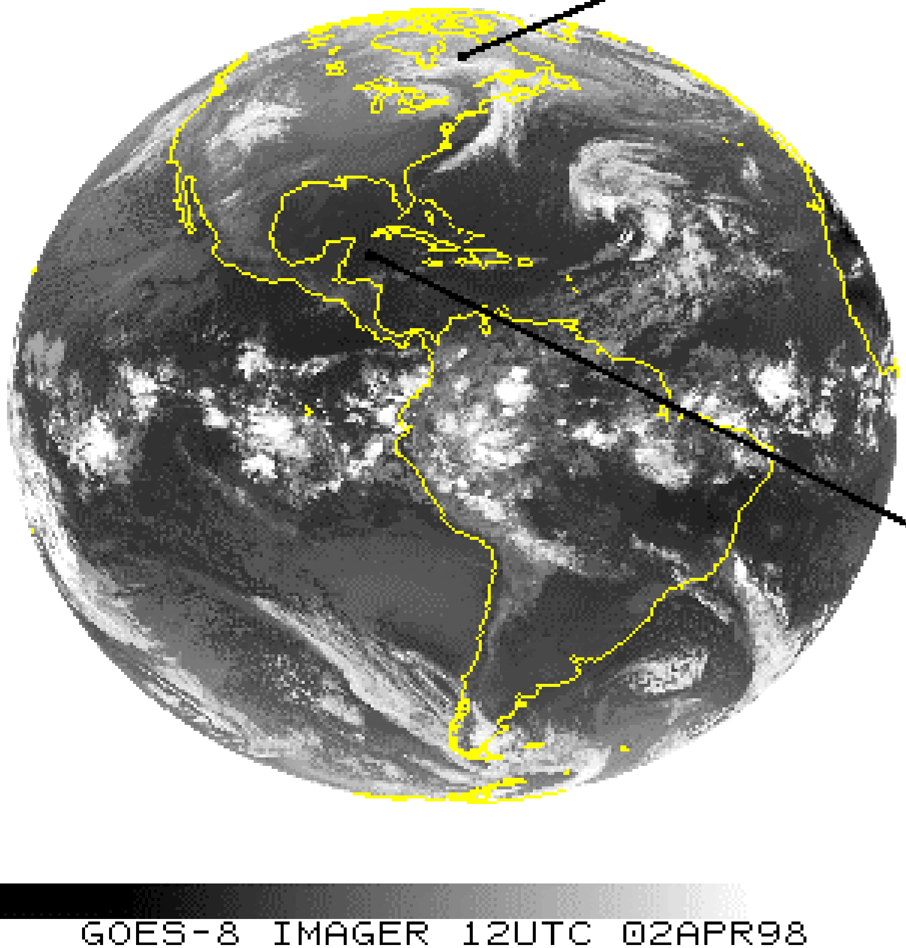


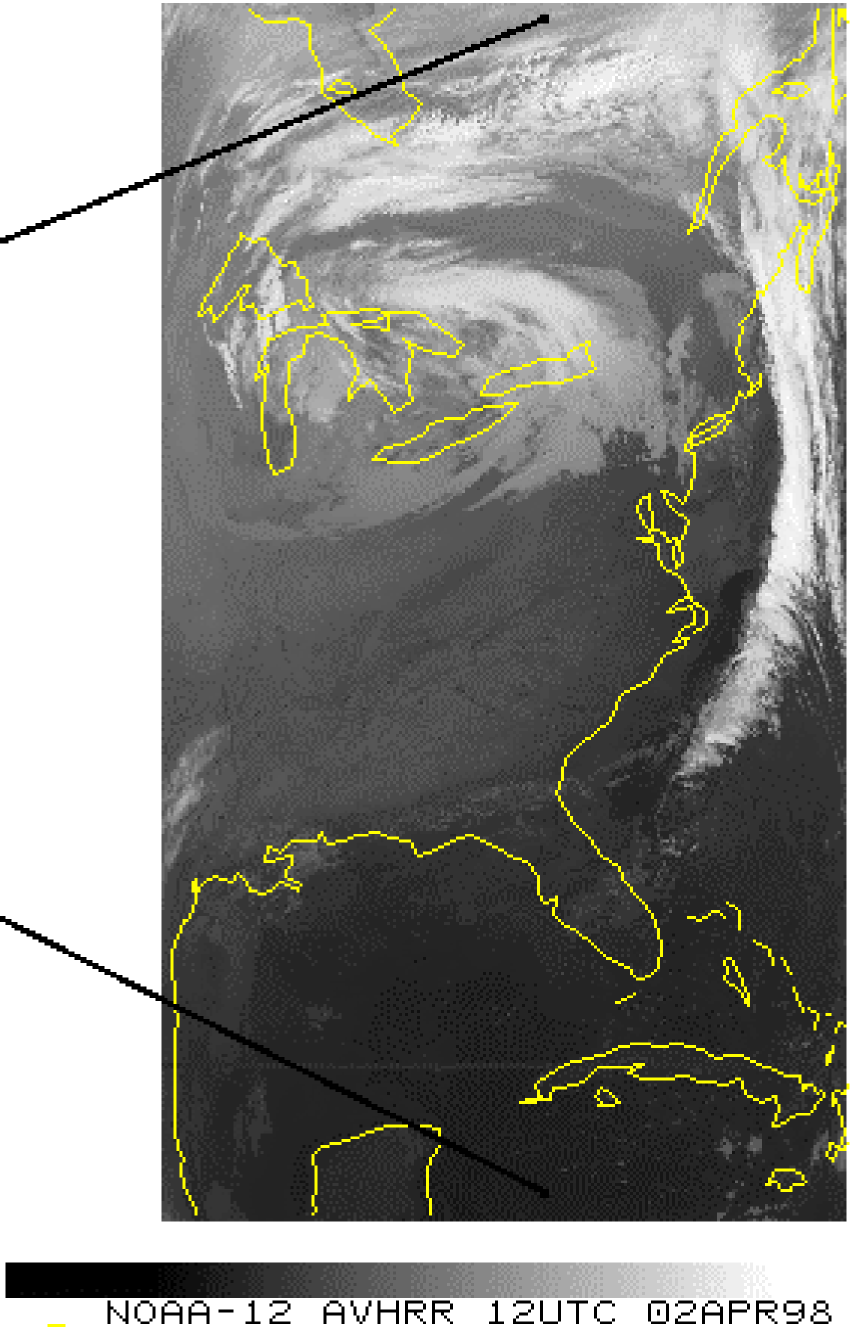
Accuracy of Satellite Derived Met Parameters

T(p) within 1.5 C of raobs for 1 km layers
SST within 0.5 C of buoys
Q(p) within 15-20% of raobs for 2 km layers
TPW with 3 mm of ground based MW
TO3 within 30 Dobsons of ozone profilers
LI adjusted 3 C lower (for better agreement with raobs)
    gradients in space and time more reliable than absolute
AMVs within 7 m/s (upper trop) and 5 m/s (lower trop)
CTPs within 50 hPa of lidar determination
Geopotential heights within 20 to 30 m
    for 500 to 300 hPa
For TC, Psfc within 6 hPa and Vmax within 10 kts
    (from MW ΔT250)
Trajectory forecast 72 hour error reduction about 10%

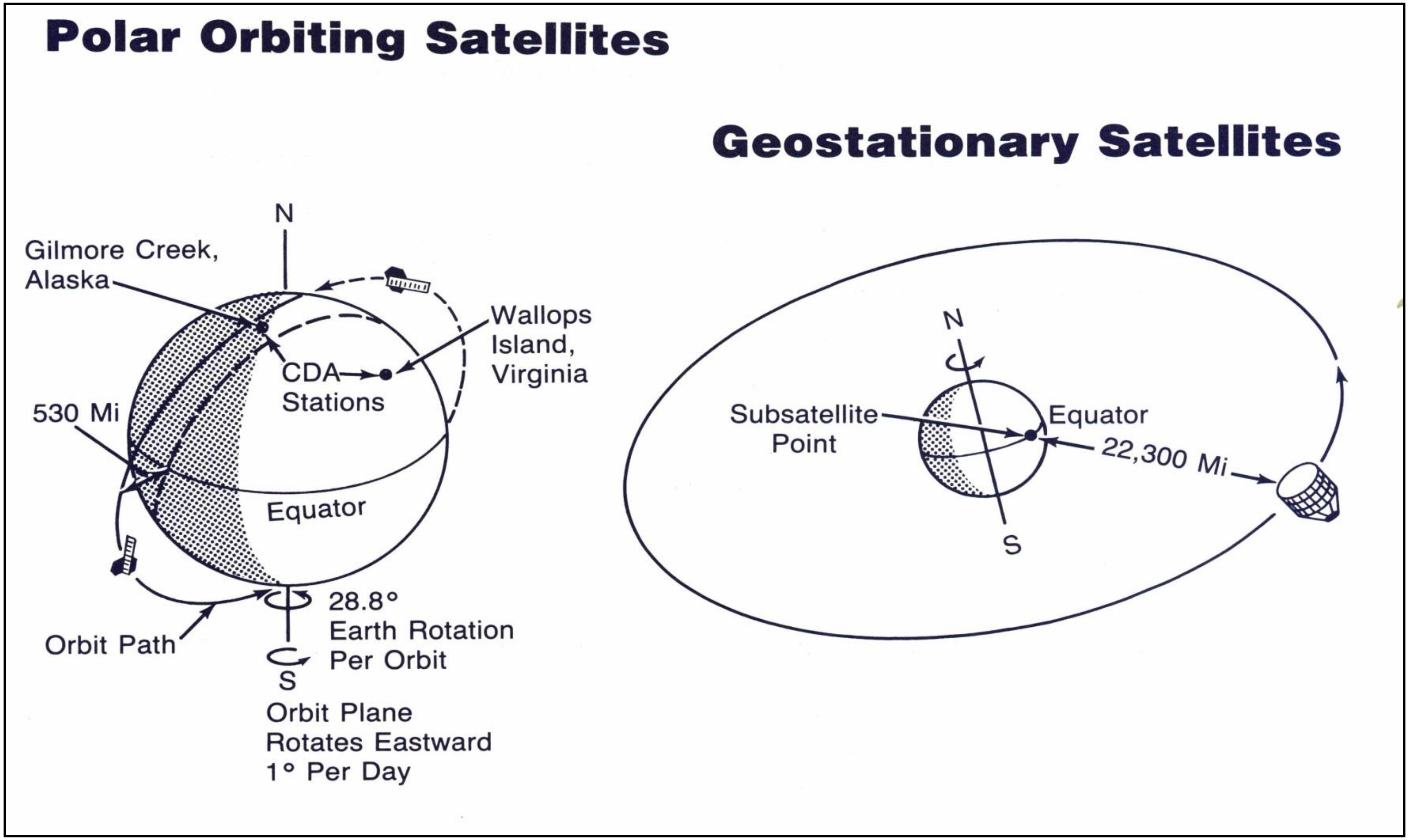
Geo vs Leo

GEO vs LEO





Polar (LEO) & Geostationary (GEO) Orbits



Comparison of geostationary (geo) and low earth orbiting (leo) satellite capabilities

Geo	Leo
observes process itself (motion and targets of opportunity)	observes effects of process
repeat coverage in minutes ($\Delta t \leq 15$ minutes)	repeat coverage twice daily ($\Delta t = 12$ hours)
near full earth disk	global coverage
best viewing of tropics & mid-latitudes	best viewing of poles
same viewing angle	varying viewing angle
differing solar illumination	same solar illumination
visible, NIR, IR imager (1, 4 km resolution)	visible, NIR, IR imager (1, 1 km resolution)
IR only sounder (8 km resolution)	IR and microwave sounder (1, 17, 50 km resolution)
filter radiometer	filter radiometer, interferometer, and grating spectrometer
diffraction more than leo	diffraction less than geo

Access to Data and HYDRA

Access to visualization tools and data

For hydra2 ftp://ftp.ssec.wisc.edu/rink/hydra2/

For MODIS data and quick browse images
http://rapidfire.sci.gsfc.nasa.gov/realtime

For MODIS data http://ladsweb.nascom.nasa.gov/

For AIRS data http://daac.gsfc.nasa.gov/

For VIIRS, CrIS, and ATMS data, orbit tracks, guide
http://www.nsof.class.noaa.gov
http://www.ssec.wisc.edu/datacenter/npp/
http://www.class.ncdc.noaa.gov/notification/faq_npp.htm

See tutorial "How do I order NPP data in CLASS (11/28/11)"

The Big Picture

Key Areas of Uncertainty in Understanding Climate & Global Change

* Earth's radiation balance and the influence of clouds on radiation and the hydrologic cycle

* Oceanic productivity, circulation and air-sea exchange

* Transformation of greenhouse gases in the lower atmosphere, with emphasis on the carbon cycle

* Changes in land use, land cover and primary productivity, including deforestation

* Sea level variability and impacts of ice sheet volume

* Chemistry of the middle and upper stratosphere, including sources and sinks of stratospheric ozone

* Volcanic eruptions and their role in climate change

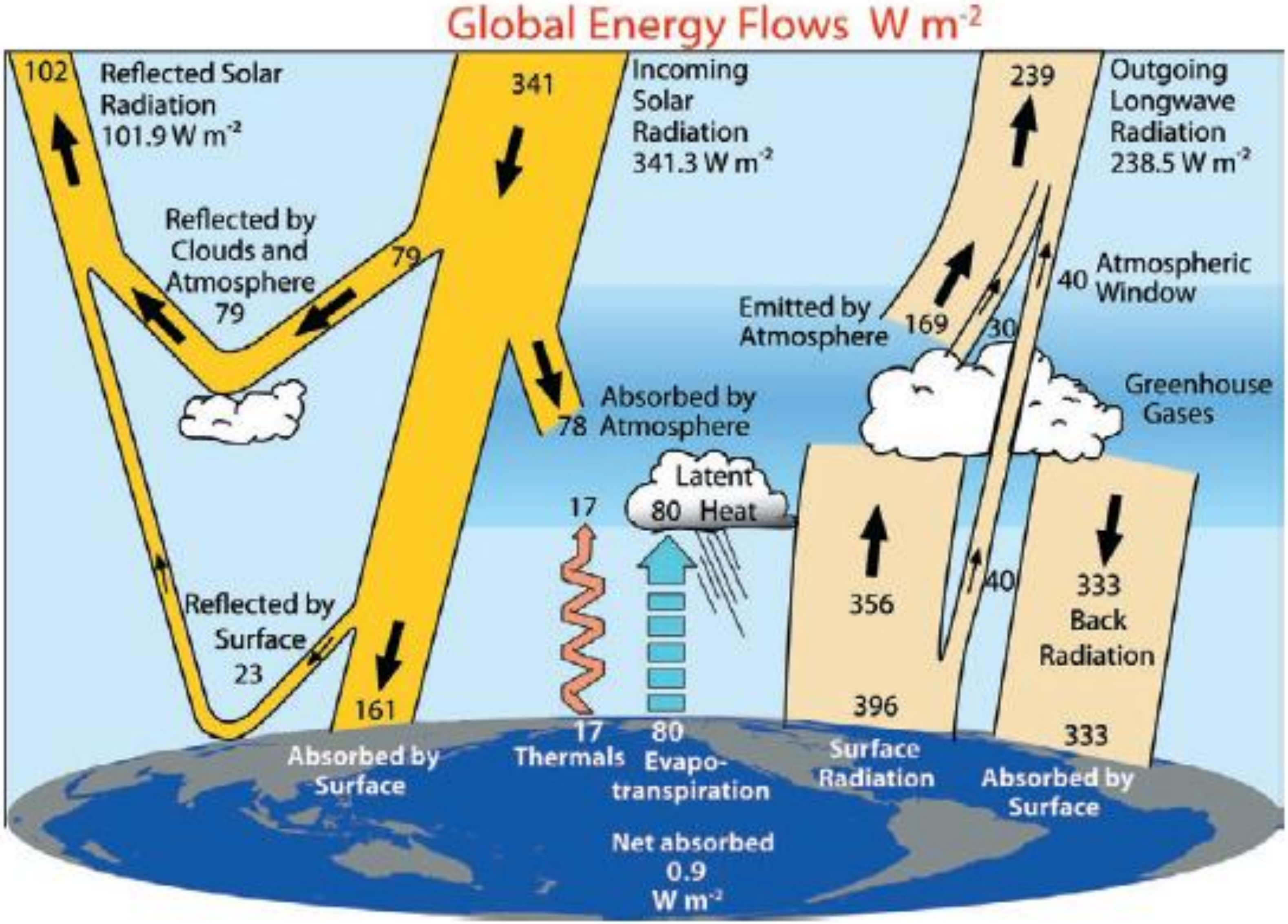
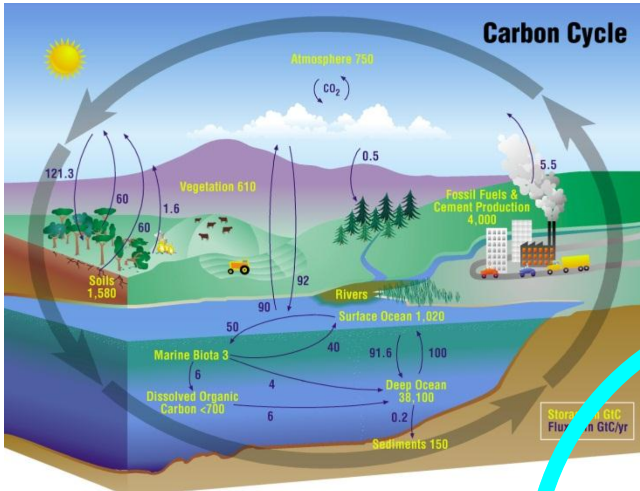
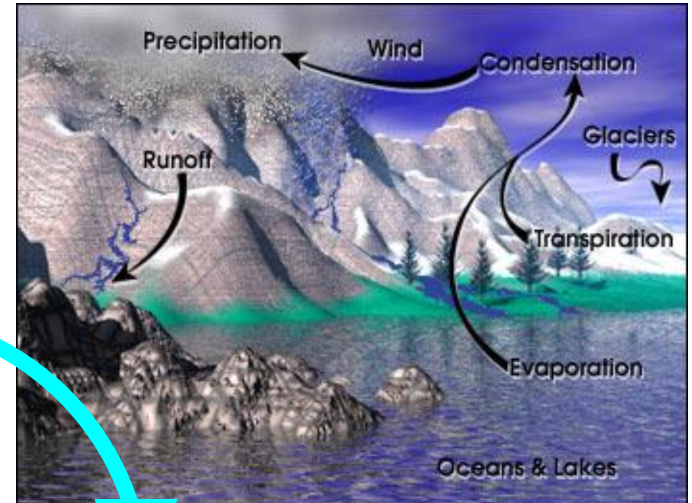


FIG. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m^{-2}). The broad arrows indicate the schematic flow of energy in proportion to their importance.

Trenberth et al, BAMS 2009

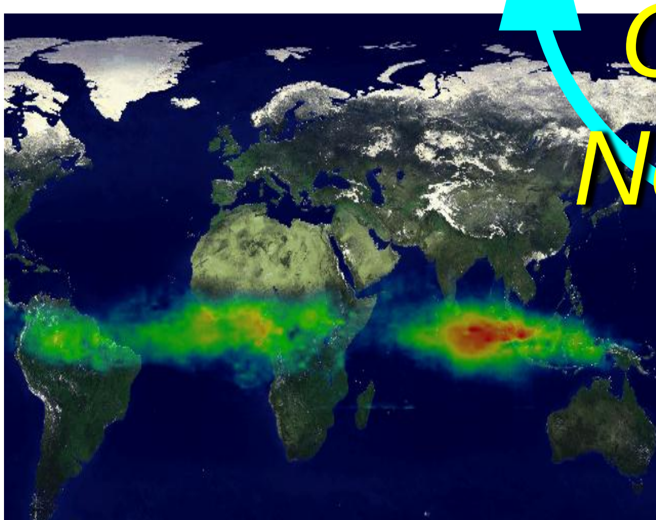
Major Climate System Elements

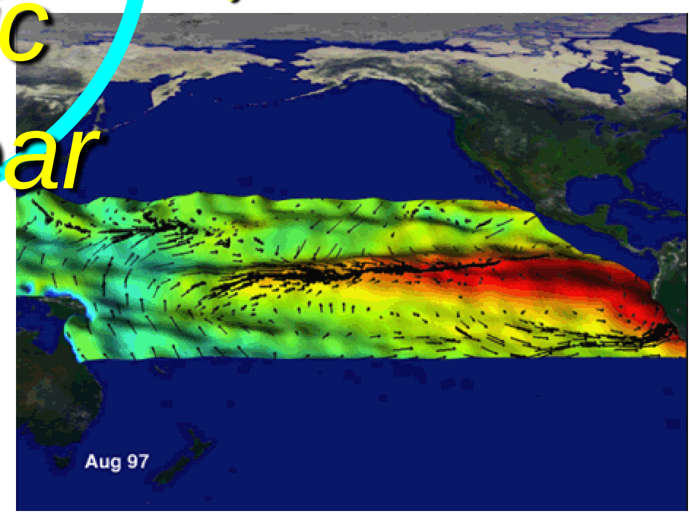




Coupled
Chaotic
Nonlinear

Atmosphere and Ocean Dynamics





Spectral Signatures