Satellite Oceanography: Sea-Surface Temperature and Climate Data Records

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Satellite Oceanography

Passive remote sensing – measuring emitted or reflected electromagnetic radiation.

(Active remote sensing – using artificial illumination radars & lidars)
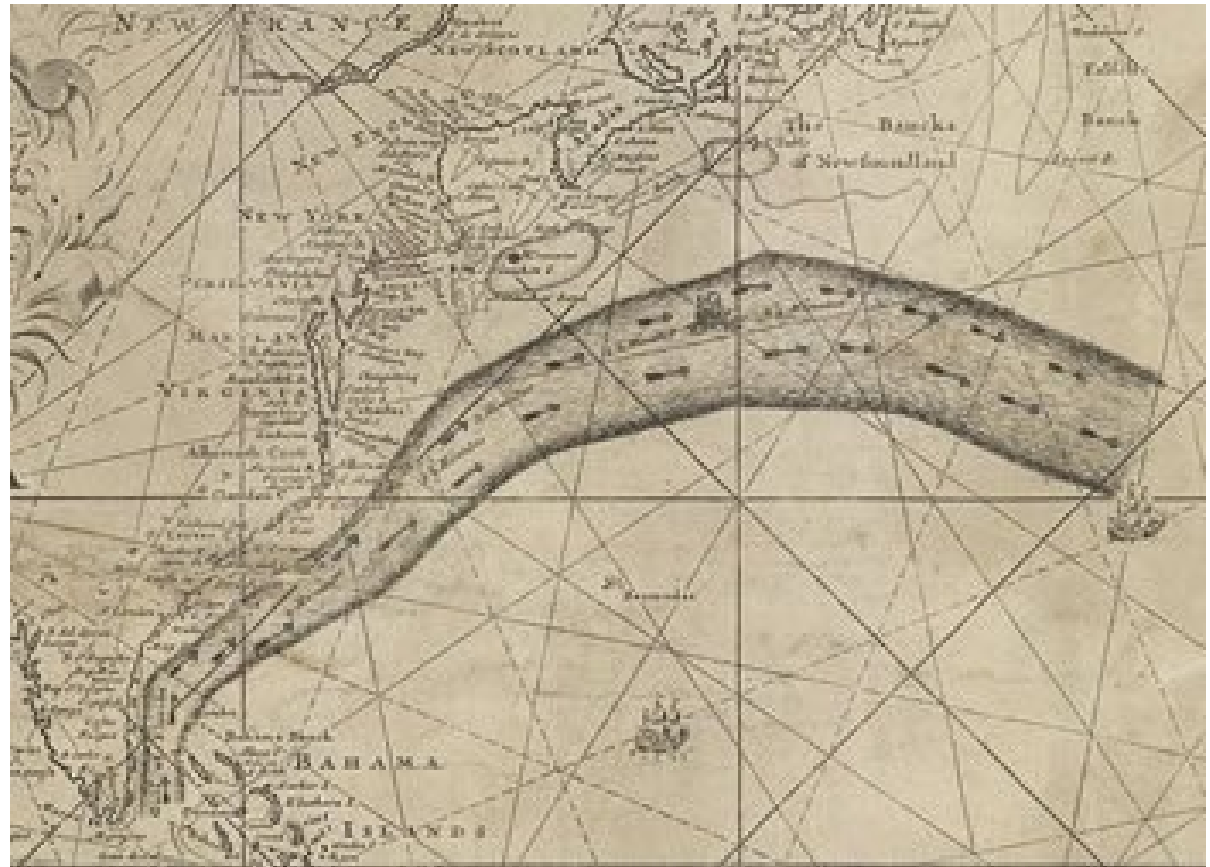
Three lectures:
- Infrared
- Visible
- Microwave

Outline

- Historical perspective.
- Review Planck function, atmospheric transmission....
- Radiometric calibration.
- Instrument descriptions:
  - Line scanners: AVHRR, MODIS, VIIRS.
  - Dual-view conical scanners: (A)ATSR, SLSTR.
- Cloud screening.
- Atmospheric corrections.
- What are oceanographic signals detectable from space.
- What is Sea-Surface Temperature?
- How can we generate an SST Climate Data Record?

Early knowledge of SST variability

In 1770, Benjamin Franklin and Timothy Folger published a chart of North Atlantic Currents, which included a depiction of the Gulf Stream. In addition to the surface flow it was realized there were temperature gradients associated with the Gulf Stream.

Franklin-Folger map is at the US Library of Congress

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SST Variability in IR images

The Gulf Stream is seen as darker water extending to northeast from Cape Hatteras. Very High Resolution Radiometer (VHRR) on the NOAA-3 Satellite, April 28,1974.

(http://www.photolib.noaa.gov/htmls/spac0301.htm)
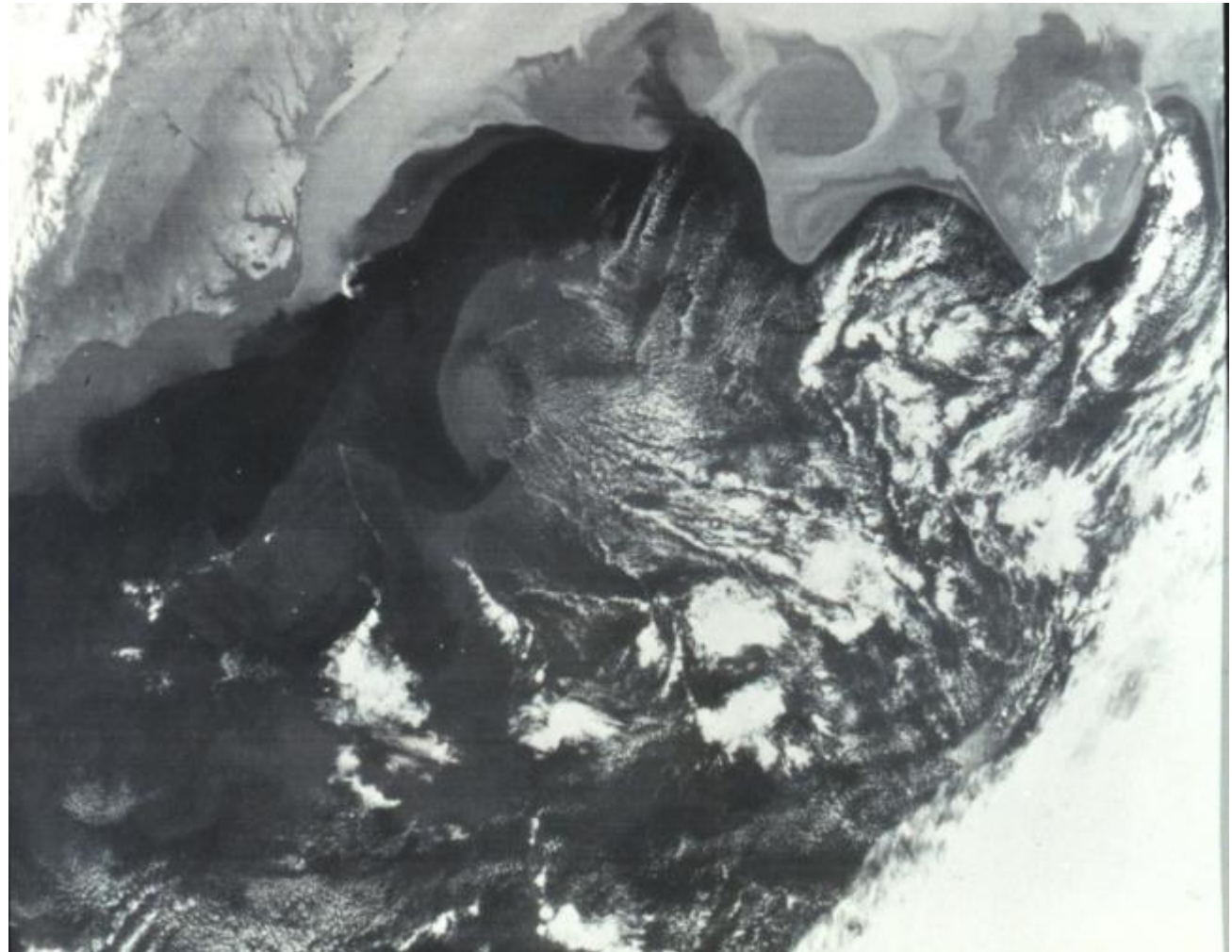
Tropical Instability Waves revealed in satellite IR images

Legeckis, R., 1977: Long Waves in the Eastern Equatorial Pacific Ocean: A View from a Geostationary Satellite. *Science,* **197**, 1179-1181.
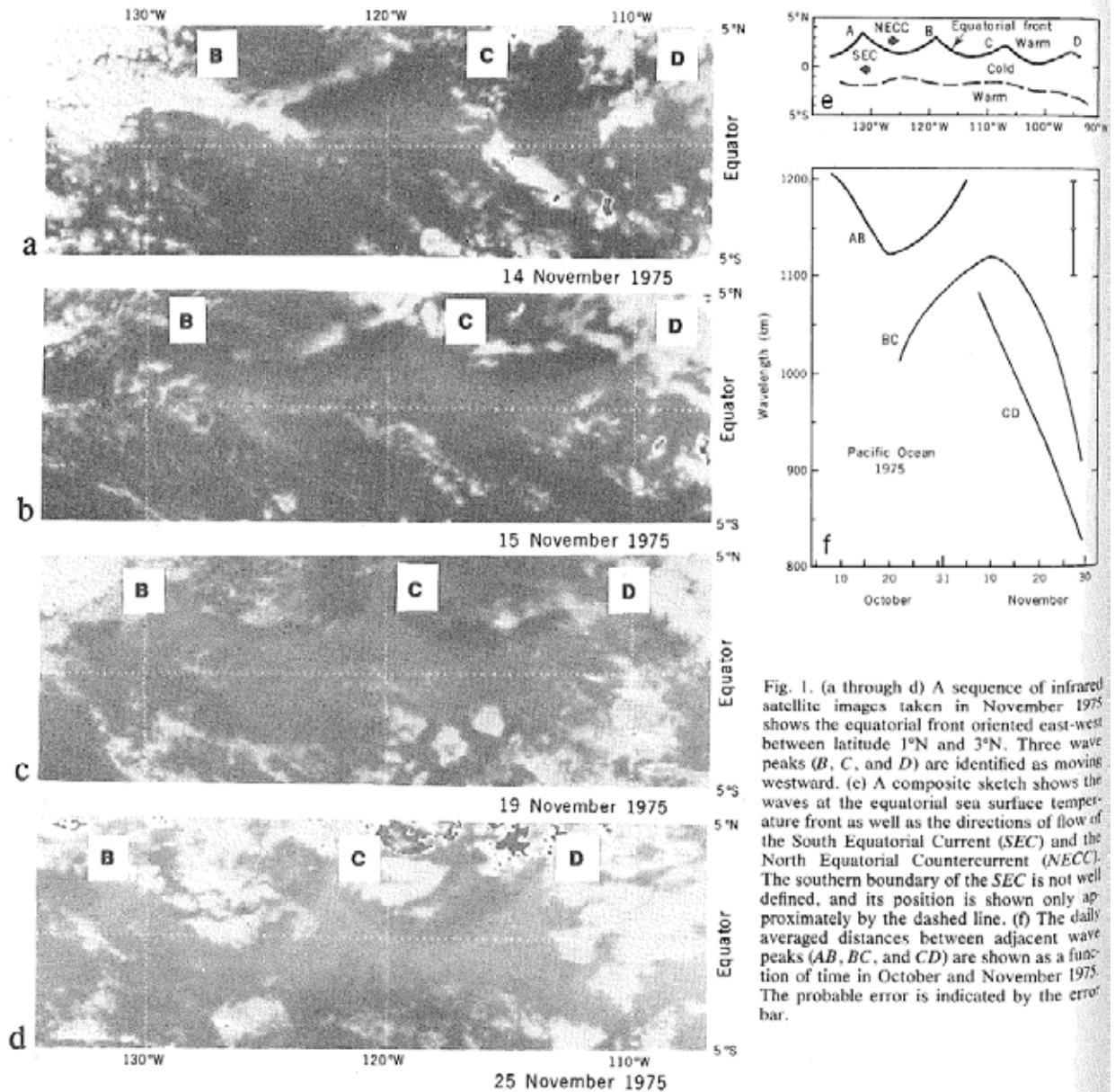

Fig. 1. (a through d) A sequence of infrared satellite images taken in November 1975 shows the equatorial front oriented east-west between latitude 1°N and 3°N. Three wave peaks (*B*, *C*, and *D*) are identified as moving westward. (e) A composite sketch shows the waves at the equatorial sea surface temperature front as well as the directions of flow of the South Equatorial Current (*SEC*) and the North Equatorial Countercurrent (*NECC*). The southern boundary of the *SEC* is not well defined, and its position is shown only approximately by the dashed line. (f) The daily averaged distances between adjacent wave peaks (*AB*, *BC*, and *CD*) are shown as a function of time in October and November 1975. The probable error is indicated by the error bar.
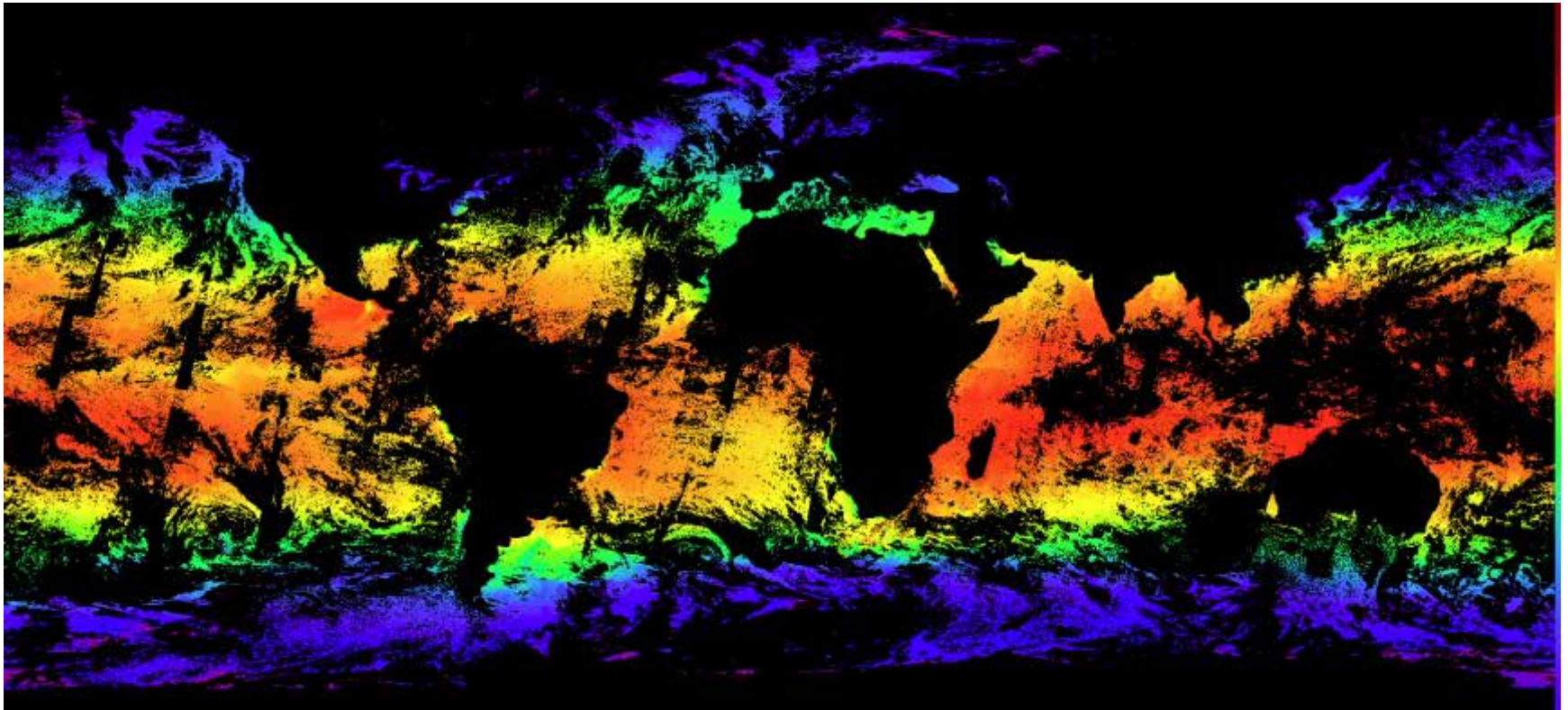
That was then, this is now
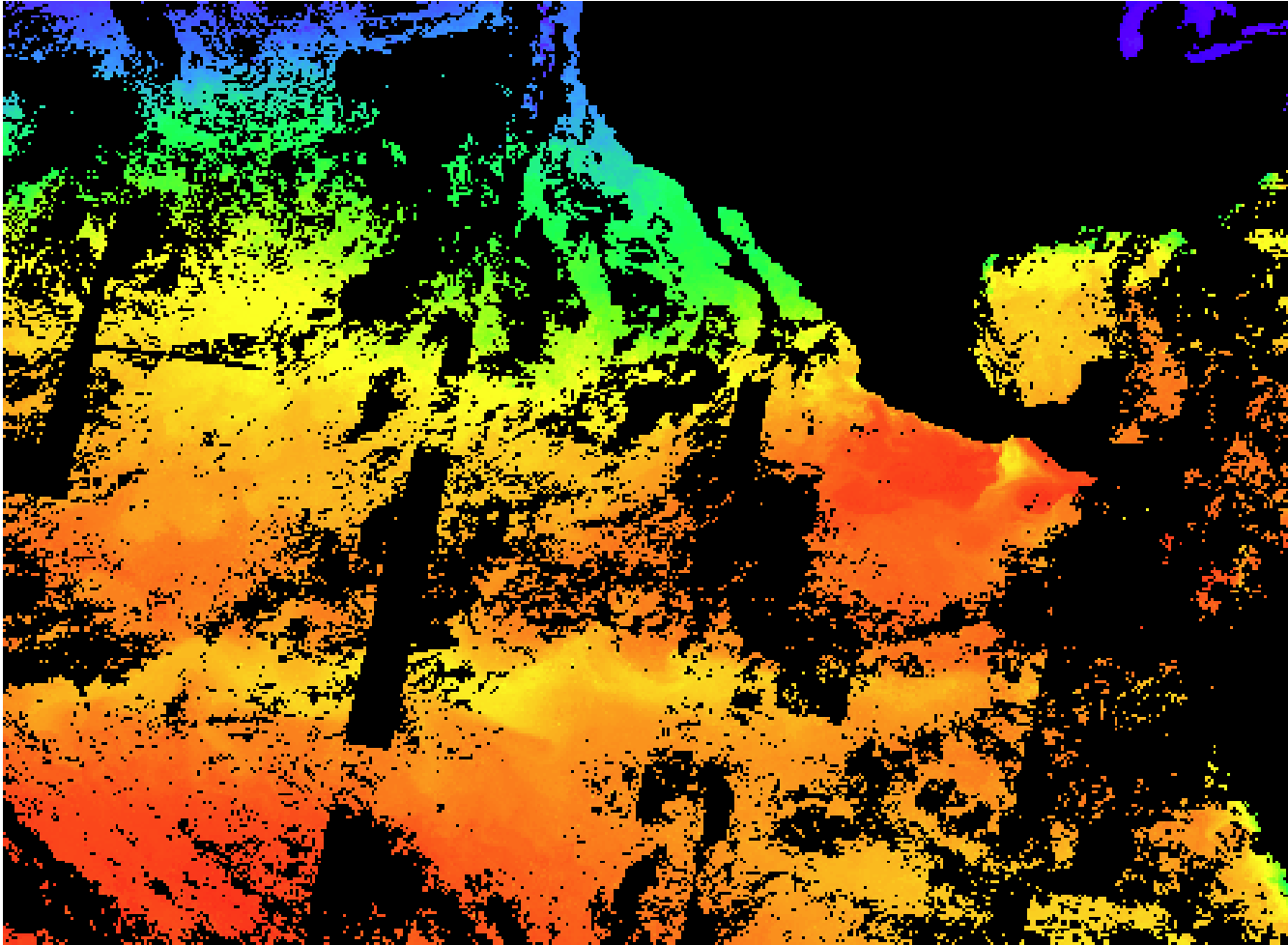
Tropical Instability Waves seen in VIIRS (Visible Infrared Imaging Radiometer Suite on the NASA Suomi-National Polar-orbiting Partnership satellite), February, 2012.

Courtesy Bob Evans et al.

Initial SST fields from VIIRS on NPP

Global 4km VIIRS SST (3.7, 11, 12 µm; night-time) for February 4-6, 2012.
Processed at the native 0.75km resolution and a 4km output pixel generated as the
average of the 'best' quality retrievals within the 4km cell.
SSTs computed using the pre-launch coefficients derived at NGST.

Courtesy Bob Evans et al.

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Planck Function

In searching for a theoretical derivation of blackbody radiation, Planck made the revolutionary assumption that an oscillating atom in the wall of a cavity can exchange energy with the radiation field inside a cavity only in discrete bundles called *quanta* given by $\Delta E = h\nu$, where h is known as *Planck's constant*.

With this assumption, he showed that the radiance being emitted by a blackbody is given by

$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp\left(\dfrac{hc}{\lambda kT}\right) - 1}, \qquad (3$$

where k is Boltzmann's constant, and T is the absolute temperature.

This is the *Planck function*; it earned him the Nobel Prize in 1918. The Planck function is more conveniently written as

$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\exp\left(\dfrac{c_2}{\lambda T}\right) - 1}, \qquad (3.8)$$

where c_1 and c_2 are the first and second radiation constants. Since the radiance from a blackbody is independent of direction, the radiant exitance from a blackbody is simply πB_λ.
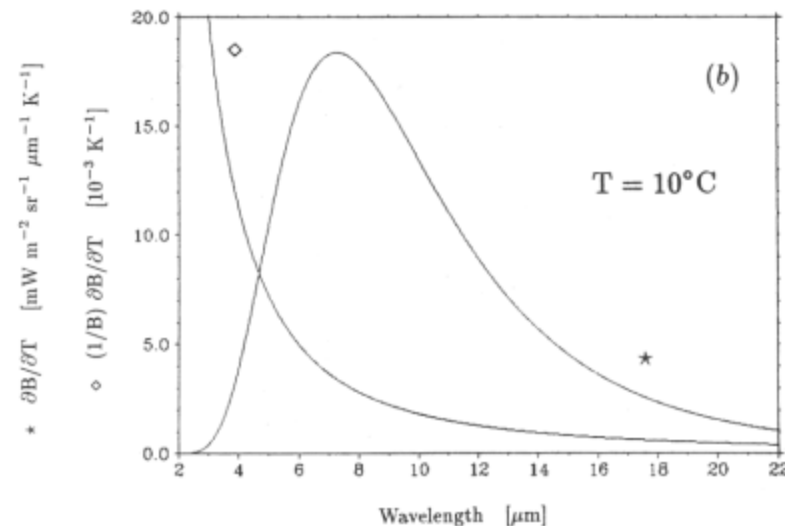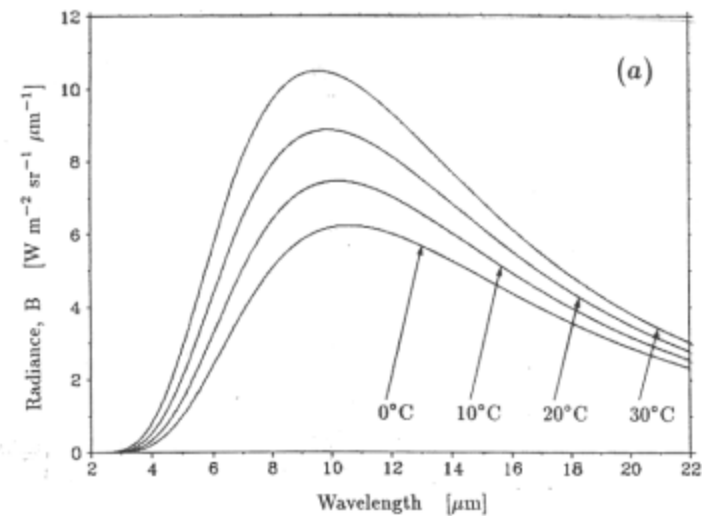
What can happen to a beam of radiation as it passes through the atmosphere ?

There are four processes that can alter the radiation as it passes through an elemental slab of the atmosphere:

– Radiation from the beam can be absorbed by the atmosphere

– Radiation can be scattered out of the beam into other directions

– Radiation can be emitted by the atmosphere

– Radiation can scattered into the beam from other directions

Leads to the Radiative Transfer Equation

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# Applications of infrared radiometry

- Infrared radiometry is used to measure temperature
  - in oceanography this is of the sea surface (SST)
  - in meteorology temperature profiles through the atmosphere can be derived (also humidity profiles, and trace gas concentrations)
  - for land studies land surface temperature (LST) and some information about land cover
- Measurements have to be well-calibrated, using on-board black-body targets.

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Infrared radiometers

- Channels are selected where atmosphere is relatively transparent, for surface temperatures, and where there are spectral gradients in transmissivity for sounding.

- Reflected and scattered solar radiation is not important in thermal infrared window (10 - 12㎛) but leads to contamination in the mid-ir window (3.5 - 4㎛). Thermal measurements available night and day, mid-ir only during the night or when there is confidence in lack of sun-glitter or scattering contamination.

- Scattering may be of importance

    Rayleigh is not significant

    Aerosols may be a problem

- Clouds (scattering and emission) Þ discard data

- Even in atmospheric windows, atmospheric effects (absorption and emission) are very important for quantitative remote sensing. Water vapor is the main concern - very variable in time and space

- In-flight calibration is tractable, using one or two on-board black-body calibration targets.

Atmospheric transmissivity in the infrared

MODIS FM-1 Bands 20, 22, 23, 31 & 32
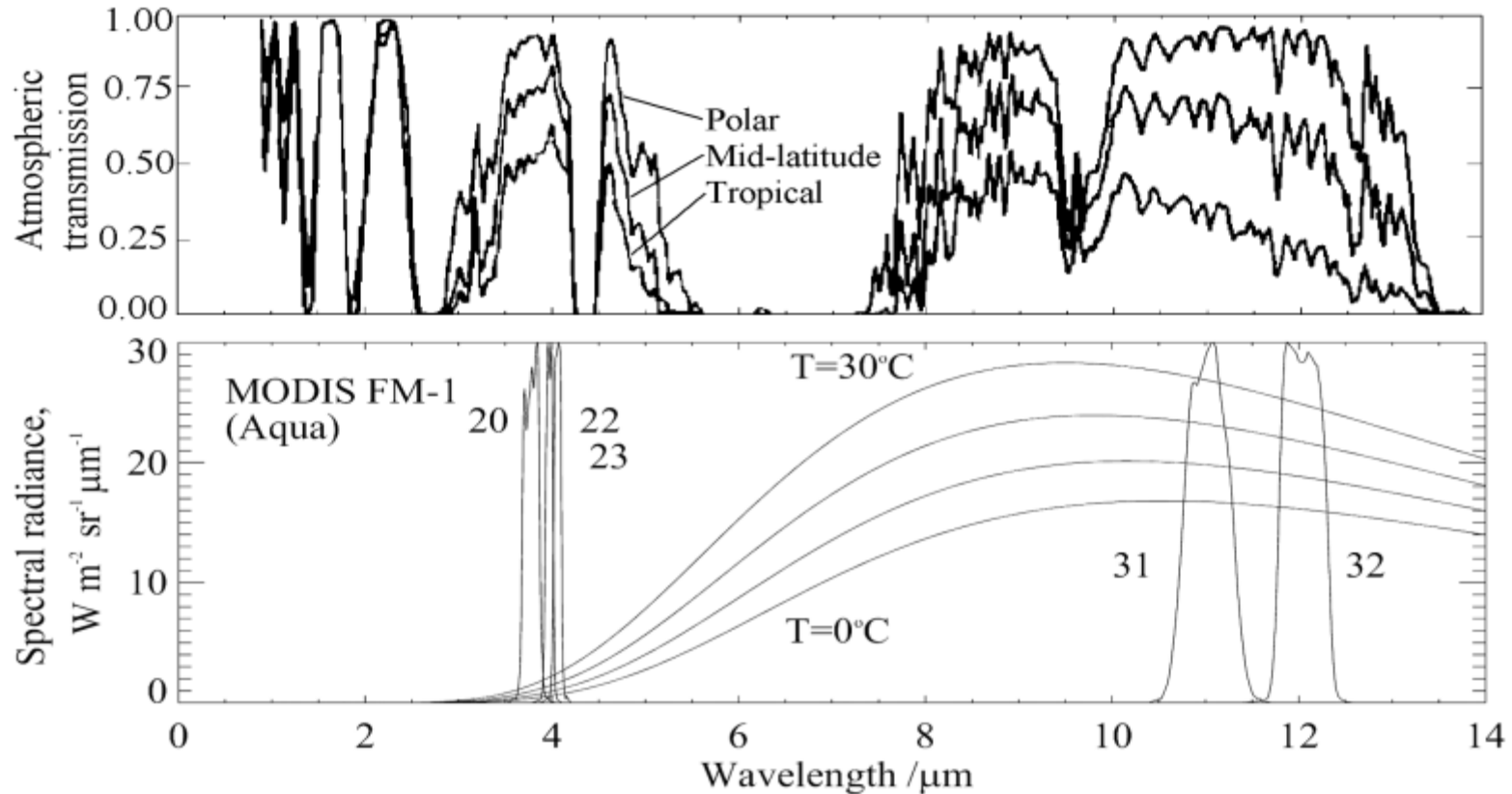
Spectral dependence of the atmospheric transmission for wavelengths of electro-magnetic radiation from about 1 to 14 µm, for three characteristic atmospheres (above), and (below) the black-body emission for temperatures of 0, 10, 20 and 30°C, and the relative spectral response functions of the bands MODIS (Flight Model 1) on *Aqua* used to derive SST.

Satellite infrared radiometers for SST

AVHRR   Broad swath (>3000km), ~1km^2 resolution, operational, 1 blackbody + space view for in-flight calibration, 10-bit digitization, 3 ir SST channels.

MODIS   Broad swath (~2330km), ~1km^2 resolution, 1 bb + space view for in-flight calibration, 12-bit digitization, 5 ir SST channels

VIIRS   Broad swath (>3000km), ~0.75kmxkm resolution, pixel aggregation to try to compensate for pixel growth away from nadir, operational, 1bb + space view for in-flight calibration, 12-bit digitization, 4 ir SST channels

(A)ATSR   Narrow swath (~500km), ~1km^2 resolution, "experimental", 2bb for in-flight calibration, 12-bit digitization, 3 ir SST channels, with two views.

SLSTR   Narrow swath (1675 km (near-nadir view), 750km (backward view)), ~1km^2 resolution, 2bb for in-flight calibration, 12-bit digitization, 3 ir SST channels, with two views.

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Calibration of infrared radiometers

- In-flight measurements every mirror scan of:
  - A black body at a known temperature & view of cold space
  - Or of two on-board black bodies
- These give a two point calibration for converting the digital outputs of the detectors to calibrated channel radiances.
- Integrals of radiance across each channel's relative spectral response functions to convert calibrated channel radiances to brightness temperatures.
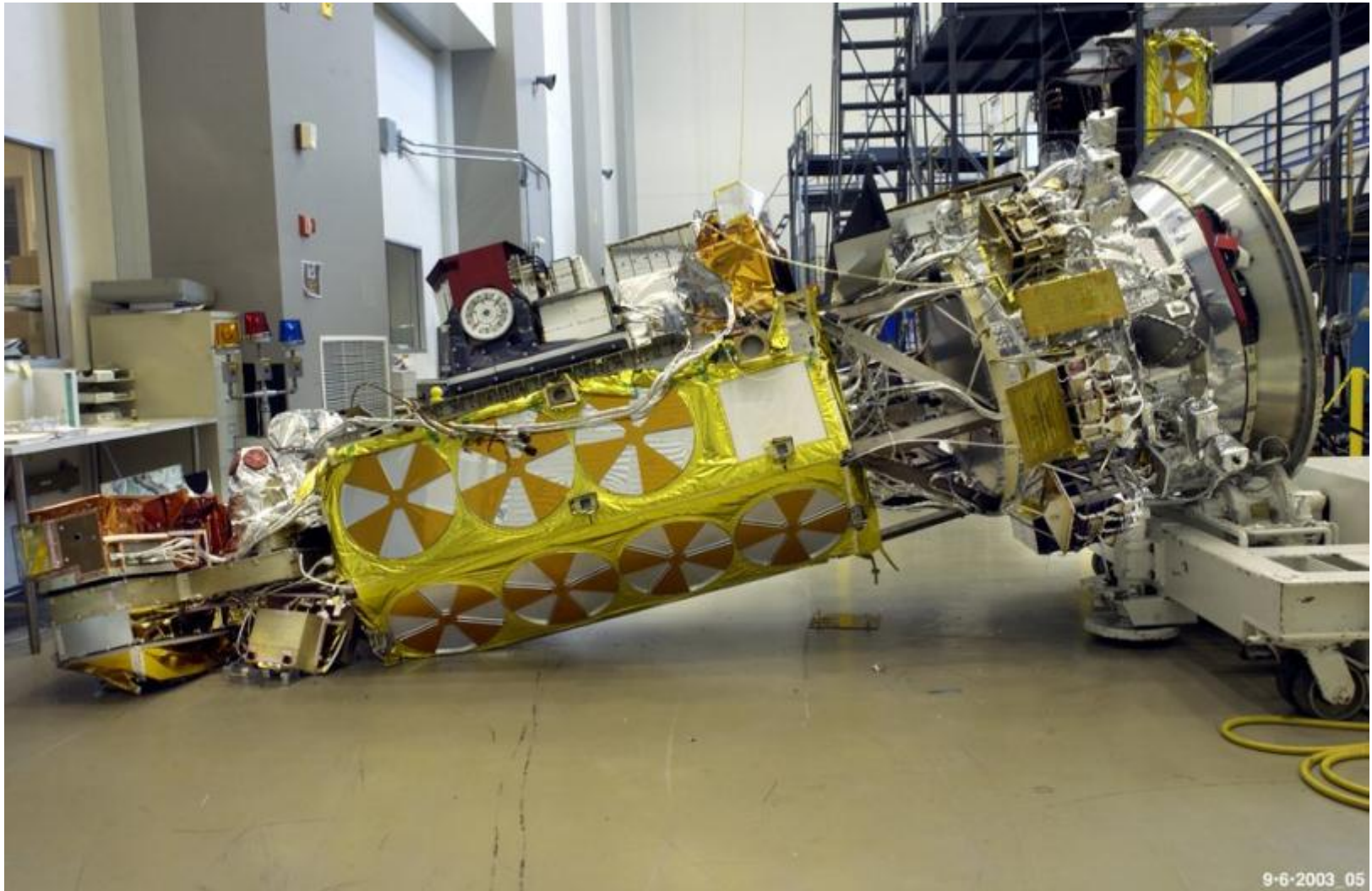
NOAA-nn Polar Orbiters

AVHRR

Advanced
Very **H**igh
Resolution
Radiometer

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NOAA-N* (broken)

9-6-2003_05

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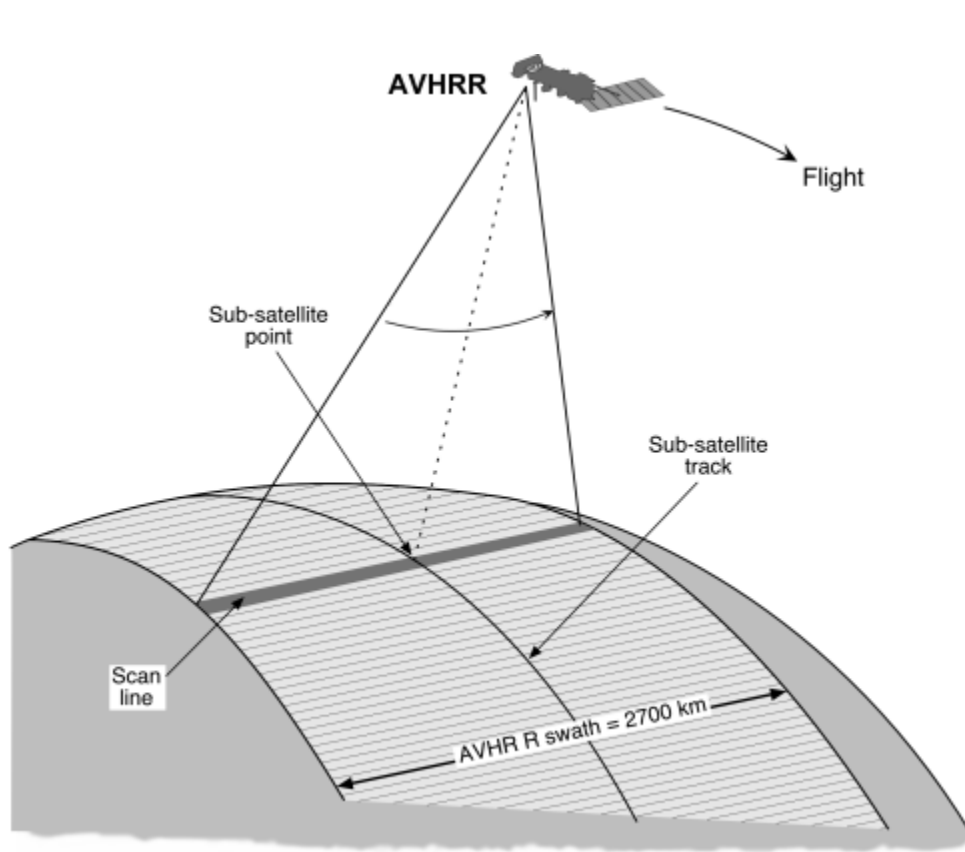30 July - 10 August 2012

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AVHRR-
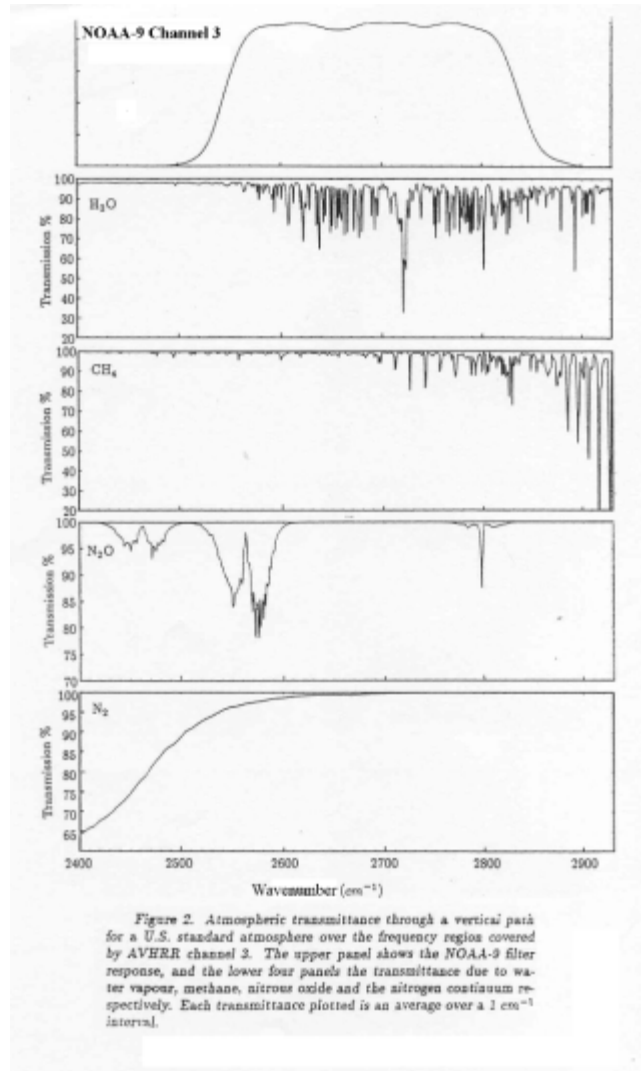# Advanced Very High Resolution Radiometer
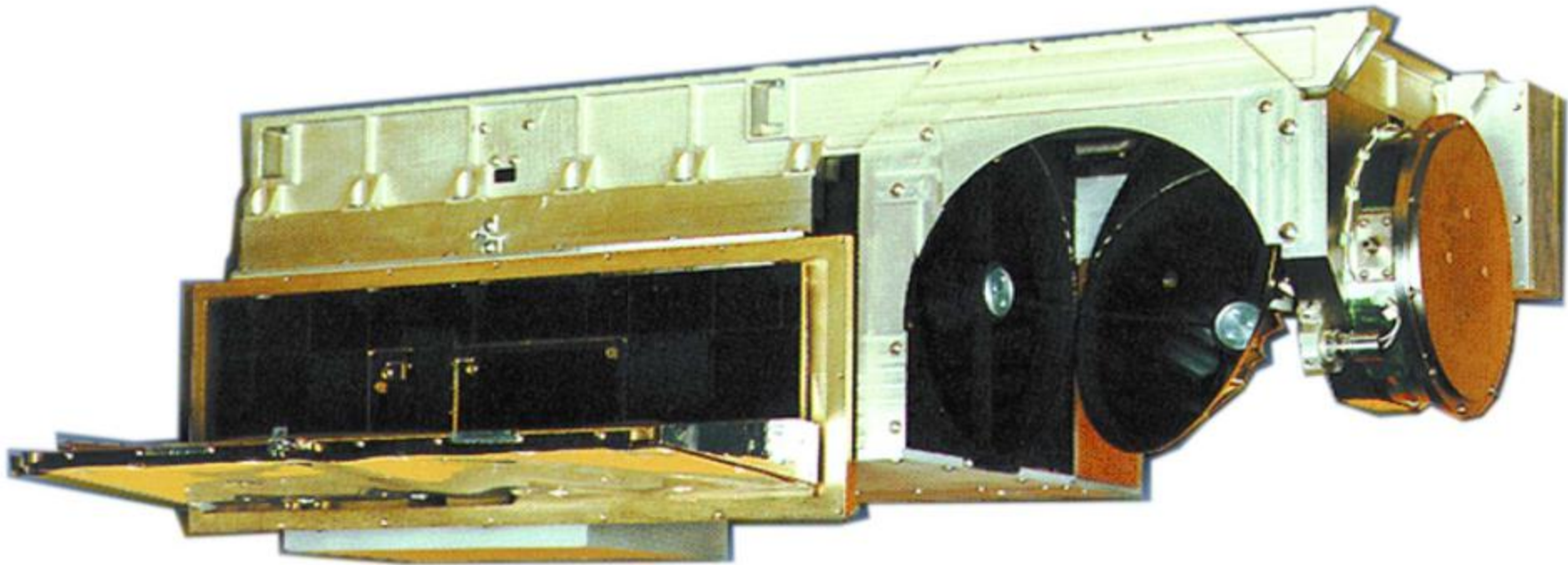
Path length effects and scan patterns
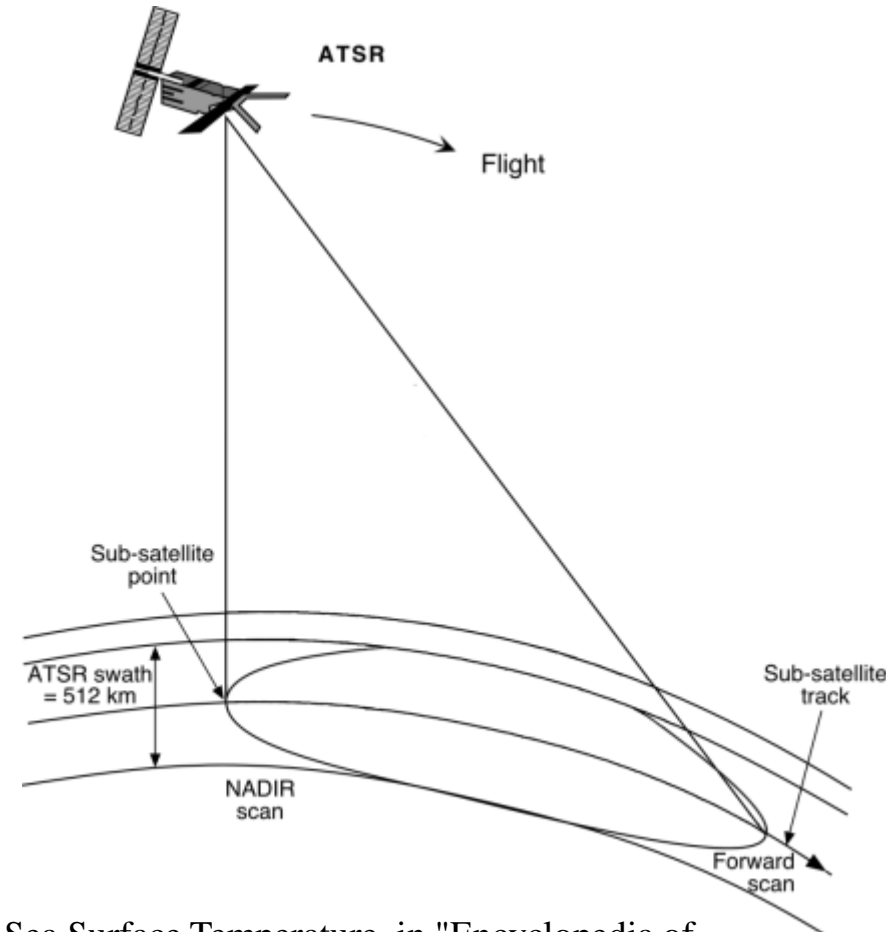
From: Minnett, P. J., 2001. Satellite Remote Sensing of Sea Surface Temperature, in "Encyclopedia of Ocean Sciences" Edited by J. Steele, S. Thorpe and K. Turekian, Academic Press Ltd., London, U.K., pp 2552-2563.

AVHRR gaseous absorption spectra

Figure 2. Atmospheric transmittance through a vertical path for a U.S. standard atmosphere over the frequency region covered by AVHRR channel 3. The upper panel shows the NOAA-9 filter response, and the lower four panels the transmittance due to water vapour, methane, nitrous oxide and the nitrogen continuum respectively. Each transmittance plotted is an average over a 1 cm^{-1} interval.

Figure 3. Atmospheric transmittance through a vertical path for a U.S. standard atmosphere over the frequency region covered by AVHRR channels 4 and 5. The upper panel shows the NOAA-9 filter responses, and the lower four panels the transmittances due to water vapour, carbon dioxide, nitric acid and the CFCs, F11 and F12. Each transmittance plotted is an average over a 1 cm^{-1} interval.

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AVHRR Temperature Deficits

Species	Brightness Temperature Deficits		
	3	4	5
H_2O	0.79	0.83	1.51
CO_2	0.02	0.25	0.07
O_3	0.01	0.01	0.01
CH_4	0.28	–	–
N_2O	0.45	–	–
HNO_3	–	0.06	0.05
N_2	0.13	–	–
F11	–	–	0.15
F12	–	0.18	0.03

Table 5. Calculated AVHRR top of atmosphere brightness temperature deficits (deg K) due to various atmospheric gases for the three infrared channels viewing a black body surface at 287.2K through a U.S. standard atmosphere for a nadir view.

MODIS: MODerate-Resolution Imaging Spectroradiometer

MODIS Web

About MODIS

Mission - Science - Instrument - Technical Specifications

MODIS Technical Specifications

Orbit:	705 km, 10:30 a.m. descending node (AM-1) or 1:30 p.m. ascending node (PM-1), sun-synchronous, near-polar, circular
Scan Rate:	20.3 rpm, cross track
Swath Dimensions:	2330 km (cross track) by 10 km (along track at nadir)
Telescope:	17.78 cm diam. off-axis, afocal (collimated), with intermediate field stop
Size:	1.0 x 1.6 x 1.0 m
Weight:	250 kg
Power:	162.5 W (single orbit average)
Data Rate:	10.8 Mbps (peak daytime); 6.2 Mbps (orbital average)
Quantization:	12 bits
Spatial Resolution:	250 m (bands 1-2) 500 m (bands 3-7) 1000 m (bands 8-36)
Design Life:	6 years

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MODIS Bands - I

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud Properties	3	459 - 479	35.3	243
	4	545 - 565	29.0	228
	5	1230 - 1250	5.4	74
	6	1628 - 1652	7.3	275
	7	2105 - 2155	1.0	110
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420	44.9	880
	9	438 - 448	41.9	838
	10	483 - 493	32.1	802
	11	526 - 536	27.9	754
	12	546 - 556	21.0	750
	13	662 - 672	9.5	910
	14	673 - 683	8.7	1087
	15	743 - 753	10.2	586
	16	862 - 877	6.2	516
Atmospheric Water Vapor	17	890 - 920	10.0	167
	18	931 - 941	3.6	57
	19	915 - 965	15.0	250

MODIS Bands - II

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required NE[delta]T(K)[4]
Surface/Cloud Temperature	20	3.660 - 3.840	0.45(300K)	0.05
	21	3.929 - 3.989	2.38(335K)	2.00
	22	3.929 - 3.989	0.67(300K)	0.07
	23	4.020 - 4.080	0.79(300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17(250K)	0.25
	25	4.482 - 4.549	0.59(275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6.00	150(SNR)
	27	6.535 - 6.895	1.16(240K)	0.25
	28	7.175 - 7.475	2.18(250K)	0.25
	29	8.400 - 8.700	9.58(300K)	0.05
Ozone	30	9.580 - 9.880	3.69(250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55(300K)	0.05
	32	11.770 - 12.270	8.94(300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52(260K)	0.25
	34	13.485 - 13.785	3.76(250K)	0.25
	35	13.785 - 14.085	3.11(240K)	0.25
	36	14.085 - 14.385	2.08(220K)	0.35

[1] Bands 1 to 19 are in nm; Bands 20 to 36 are in μm

[2] Spectral Radiance values are (W/m^2 -μm-sr)

[3] SNR = Signal-to-noise ratio

[4] NE(delta)T = Noise-equivalent temperature difference

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Characteristics of MODIS IR Focal Planes SST Product Input Bands

LWIR — PV HgCdTe / PC HgCdTe — Cold FPAs: (80. 83, 85k)

SWIR/MWIR — PV HgCdTe — ⊕ = OPTICAL AXIS
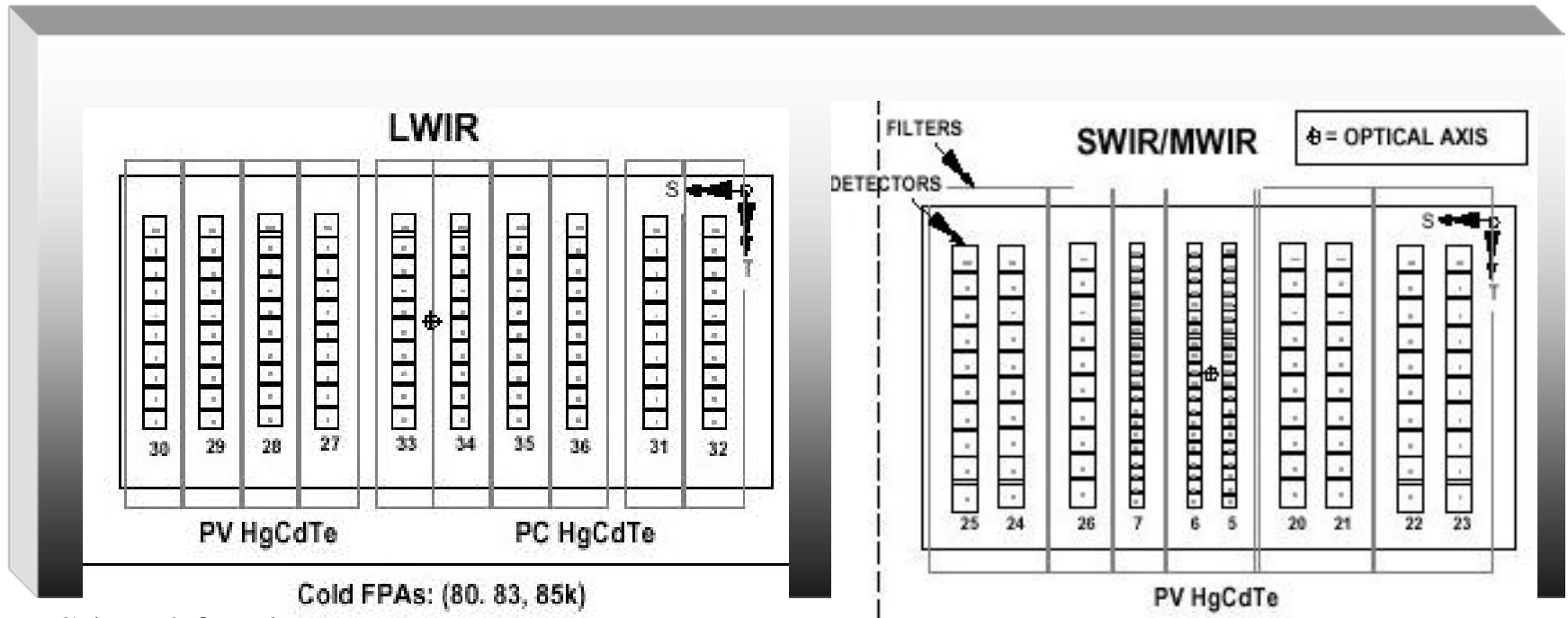
MODIS has 4 focal planes, each band with 10 - 1km detectors:
2 for visible
2 for IR

Band number	Center Wavelength mm	Bandwidth mm	NEDT at T=300K	SNR at T=300K	Saturation Temperature K
Midwave IR					
20	3.7882	0.1826	0.026	9000	333
22	3.9719	0.0882	0.030	837.5	328
23	4.0567	0.0878	0.026	987.5	329
Longwave Thermal IR					
31	11.0144	0.5103	0.024	28088	399
32	12.0282	0.4935	0.040	18245	391

* Averaged over ten detectors in each band

Principal Scan Angles Mapped to Scan Mirror Angles of Incidence
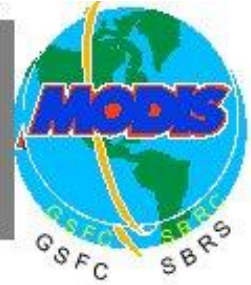
Angle of Incidence changes pixel by pixel with paddle-wheel scan mirror

MODIS Scan Mirror

SD -176.5°
SRCA -152.5°
On_Board BB -129.35°
SV Port -98.425°

Earth Scan Stop (East) 55°
SIS100 45°
NADIR 0°
BCS -45°
Earth Scan Start (West) -55°
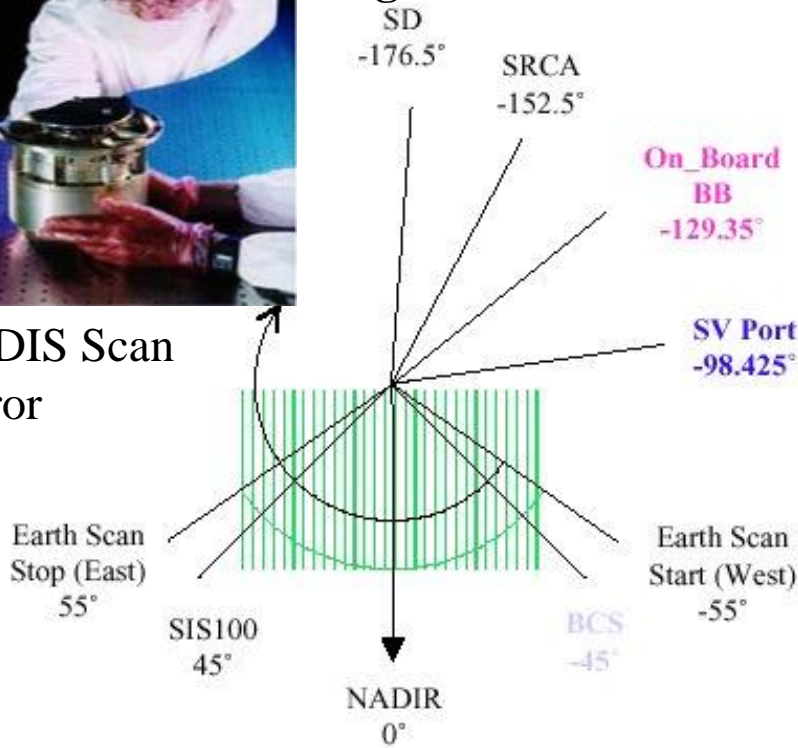
**Principal Scan Angles
(Earth View: -55 to 55)**

SRCA -38.2°
SD -50.3°
On_Board BB -26.7°
SV Port -11.2°
Normal
Earth Scan Start 10.5°
BCS 15.5°
NADIR 38°
SIS100 60.5°
Earth Scan Stop 65.5°

SCAN MIRROR
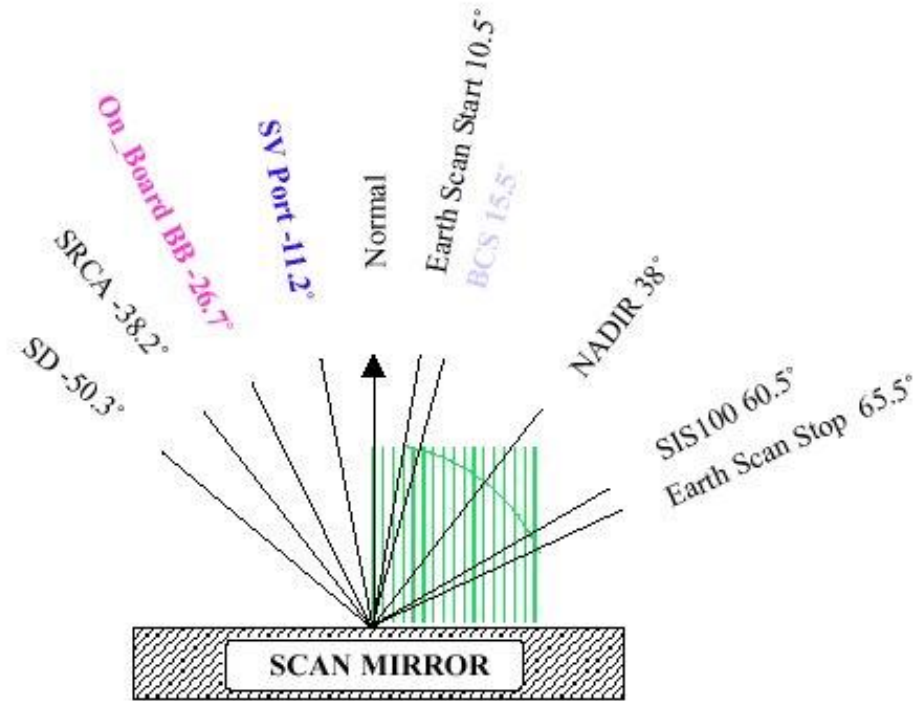
**Angles of Incidence
(Earth View: 10.5 to 65.5)**

VIIRS Components

Electronics module (EM) & cables refined to minimize EMI

MODIS-heritage Solar Diffuser screen redesigned to minimize solar modulation

MODIS-heritage blackbody relocated to minimize Earth shine

MODIS-heritage Solar Diffuser Stability Monitor refined to improve performance

4-mirror anastigmat All-reflective Aft optics imager

3-Mirror Anastigmat Rotating telescope refined to eliminate modulated instrument background (MIB)

- Constant-speed rotating telescope
- Simple all-reflective diamond point turned bolt-together optics
- Proven emissive/reflective calibration

Passive Cryoradiator

Cold FPA Dewar Assembly

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VIIRS SST RSRs

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VIIRS pixel aggregation

GSD: Ground Sampling Distance
HSI: Horizontal Sampling Interval

(A)ATSR

- ATSR – Along-Track Scanning Radiometer
  - ASTR on ERS-1
  - ATSR-2 on ERS-2
  - AATSR (Advanced ATSR) on Envisat
  - SLSTR (Sea Land Surface Temperature Radiometer) on Sentinal-3a to be launched in 2014.
- Only spacecraft radiometers optimized for SST measurements

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Advanced Along Track Scanning Radiometer

- Imaging radiometer
- Designed to measure global SST at the levels of precision and accuracy required for climate research (better than 0.3 K; 1σ)
- Contributes to 20 year unbroken record of accurate SST measurements on a global scale

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AATSR Principles of Operation

- 7 spectral channels
  - 3 IR (3.7 µm, 11 µm, 12 µm)
  - 4 Vis/NIR (0.55 µm, 0.67 µm, 0.87 µm, 1.6 µm)
- 500 km swath
- 1 km IFOV at nadir
- Dual view (nadir and 55° to nadir)
- On board calibration
  - 2 on-board black bodies for IR calibration
  - VISCAL unit for visible channel calibration
- Stirling Cycle Coolers, cooling low noise detectors to 80K, for optimum signal-to-noise ratios

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AATSR - SCAN GEOMETRY
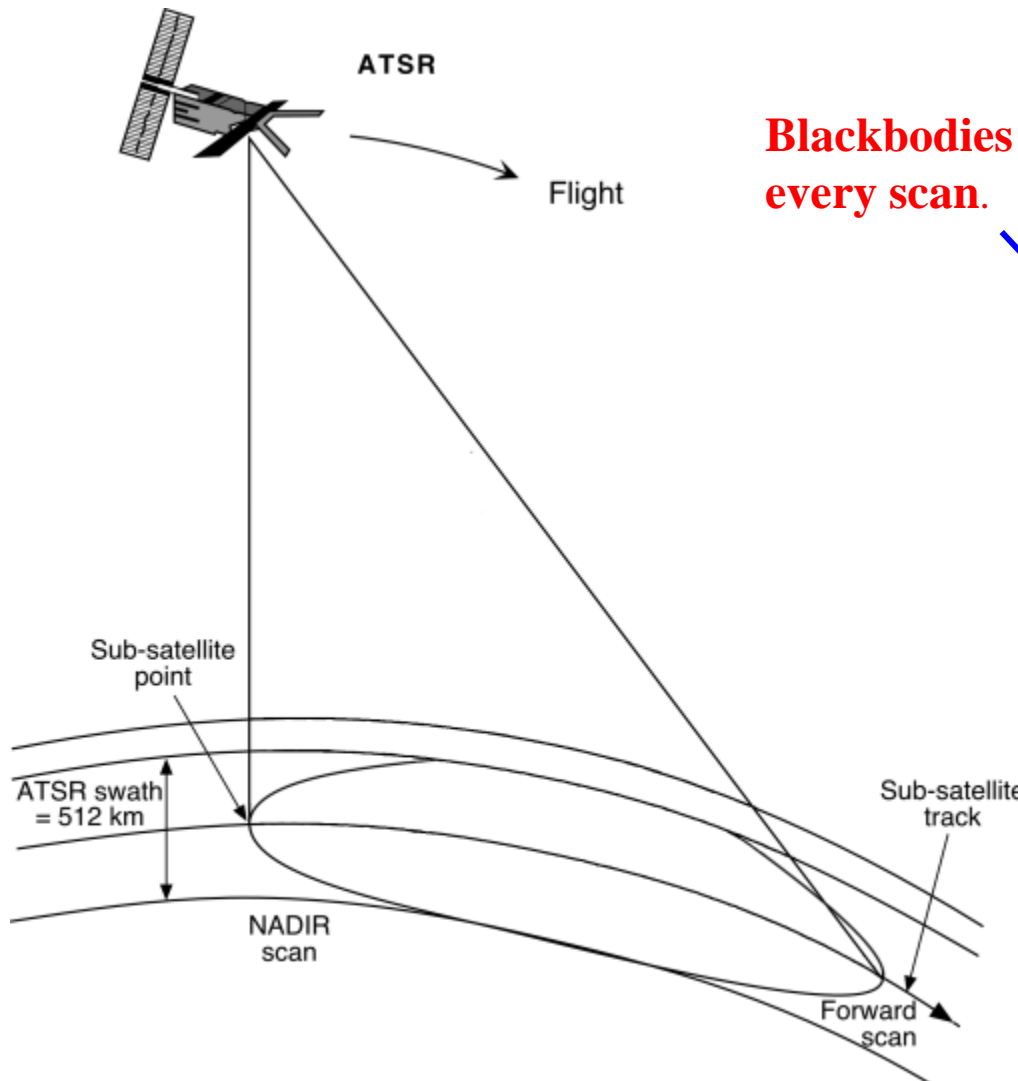
Blackbodies viewed every scan.
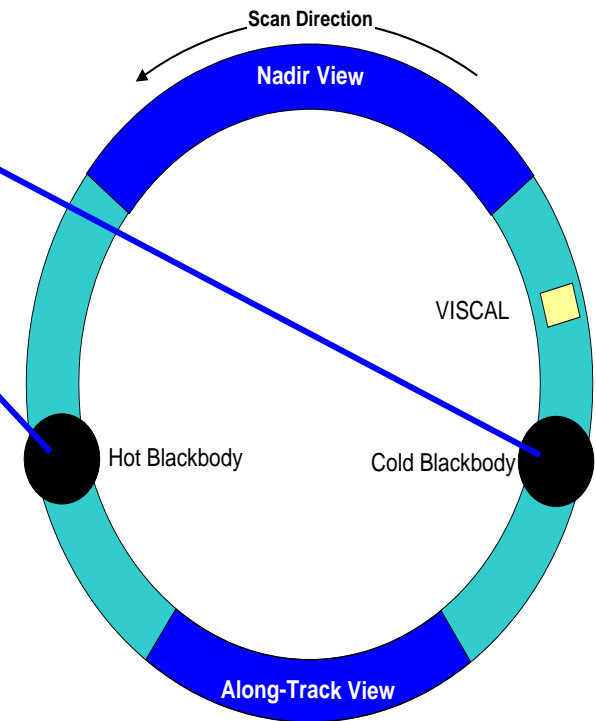
Sea and Land Surface Temperature Radiometer - SLSTR

- SLSTR has been designed to measure SST and Land Surface Temperature with an **equivalent baseline performance to ENVISAT AATSR.**

- Designed to **extend and improve the (A)ATSR** series but maintains fundamental concepts and elements of the original.

- SLSTR is an IR self-calibrating instrument using on-board calibration blackbody cavities.
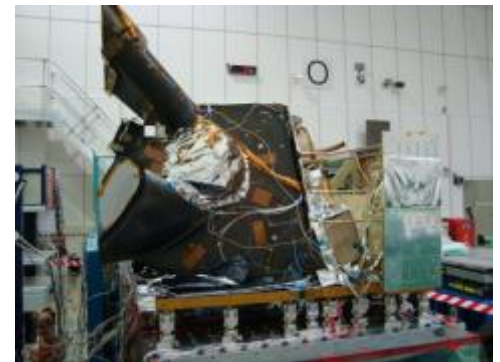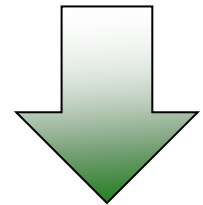
SLSTR scan geometry

- Uses two scan mechanisms and a flip mirror to enable wider swath.

- Nadir swath is offset to cover OLCI swath.

- One VIS channel (865nm) is used for co-registration with OLCI swath.

- Oblique view 55° inclination maintains a longer atmospheric path length compared to nadir for better atmospheric correction.

SLSTR

Direction of flight

55°

Oblique (rear) swath scanner footprint (740 km swath)

Nadir swath scanner footprint (1400 km swath)

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S3 SLSTR: Spectral Bands

SLSTR Spectral transmission table (SRF)
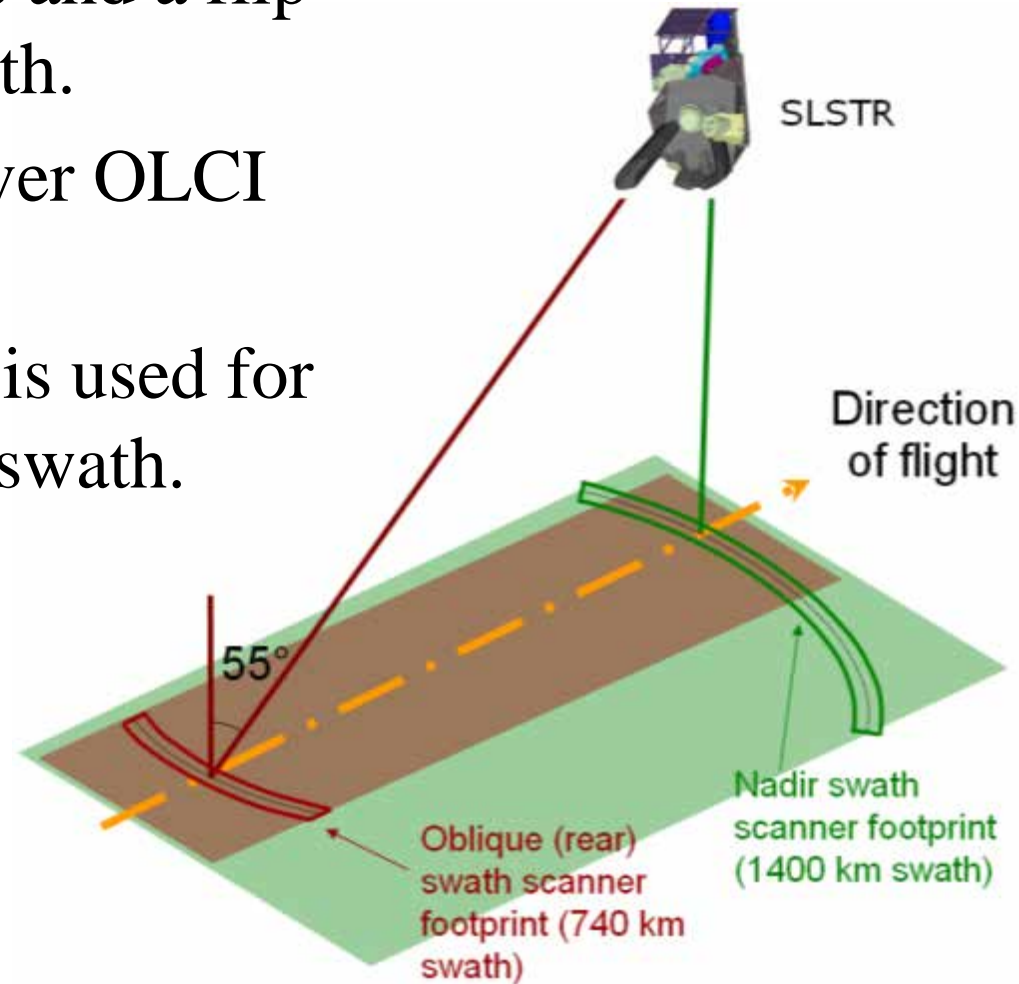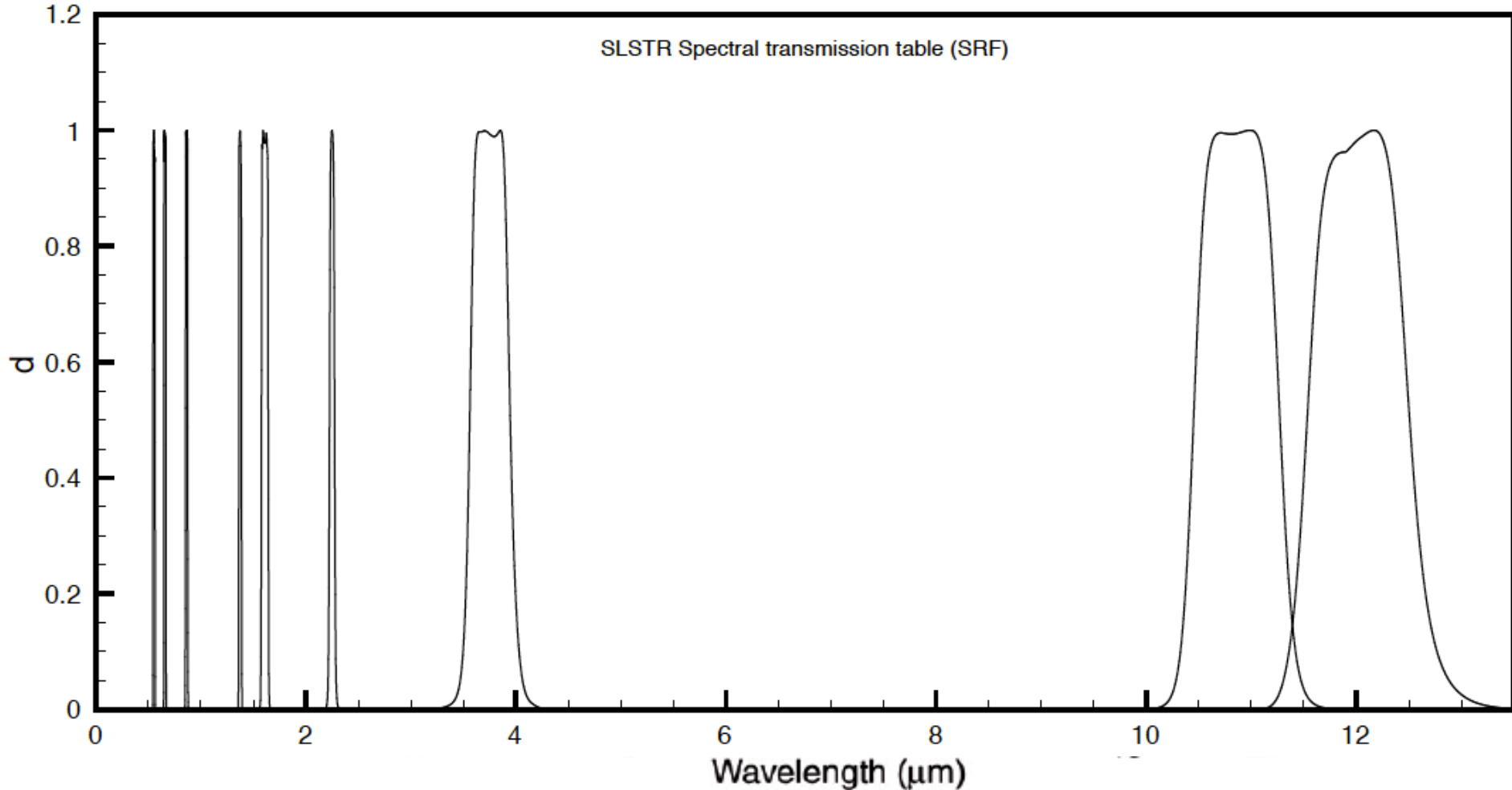
Cloud Screening for SST

- Spectral and textural information are powerful means for cloud screening (classification problem – cloud-free and cloud-contaminated).

- Several layers of tests needed to identify all pixels contaminated by clouds e.g. temperature thresholds, reflected sunlight (during the day), "spatial coherence", channel differences (fog and cirrus).

- Problems remain with marine stratus, fog, cirrus, and partially cloud-filled pixels.

- Undetected aerosols remain a problem.

- Better to have false positives than false negatives.
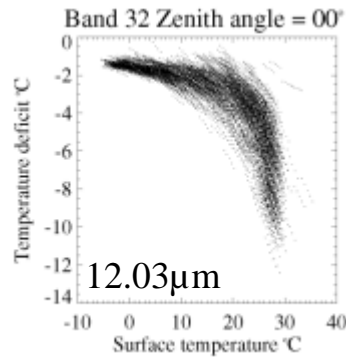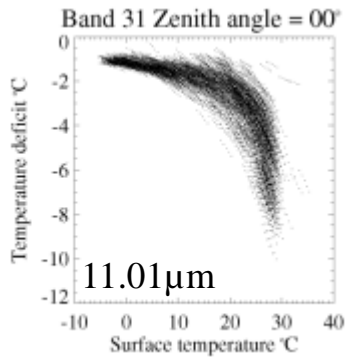
AVHRR Pathfinder SST cloud screening (1)
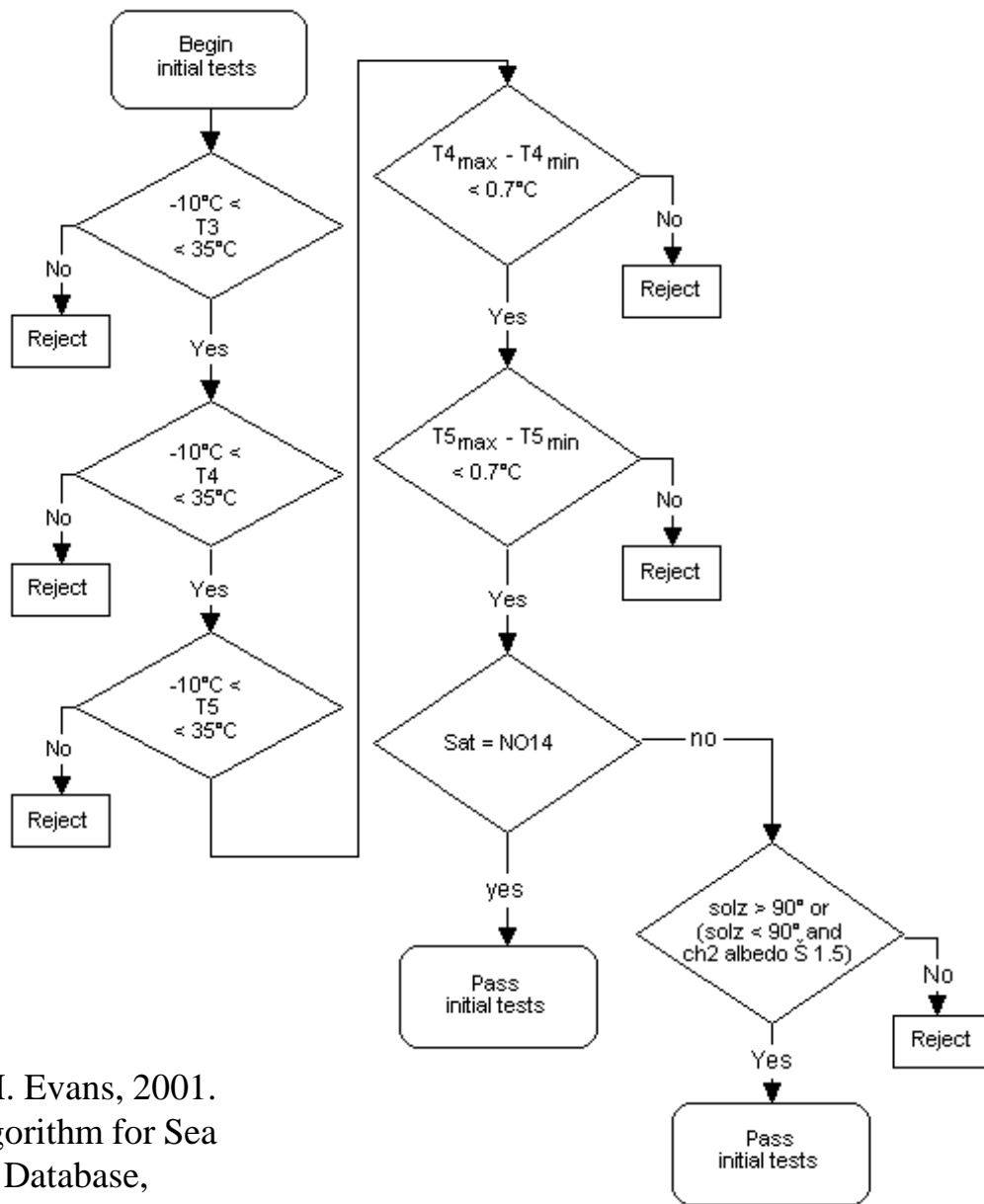
From: Kilpatrick, K. A., G.P.Podesta and R. H. Evans, 2001.
Overview of the NOAA/NASA Pathfinder algorithm for Sea
Surface Temperature and associated Matchup Database,
Journal of Geophysical Research, 106, 9179-9198

AVHRR Pathfinder SST cloud screening (2)

Thresholds tuned to NOAA-14 AVHRR

From: Kilpatrick, K. A., G.P.Podesta and R. H. Evans, 2001. Overview of the NOAA/NASA Pathfinder algorithm for Sea Surface Temperature and associated Matchup Database, Journal of Geophysical Research, 106, 9179-9198

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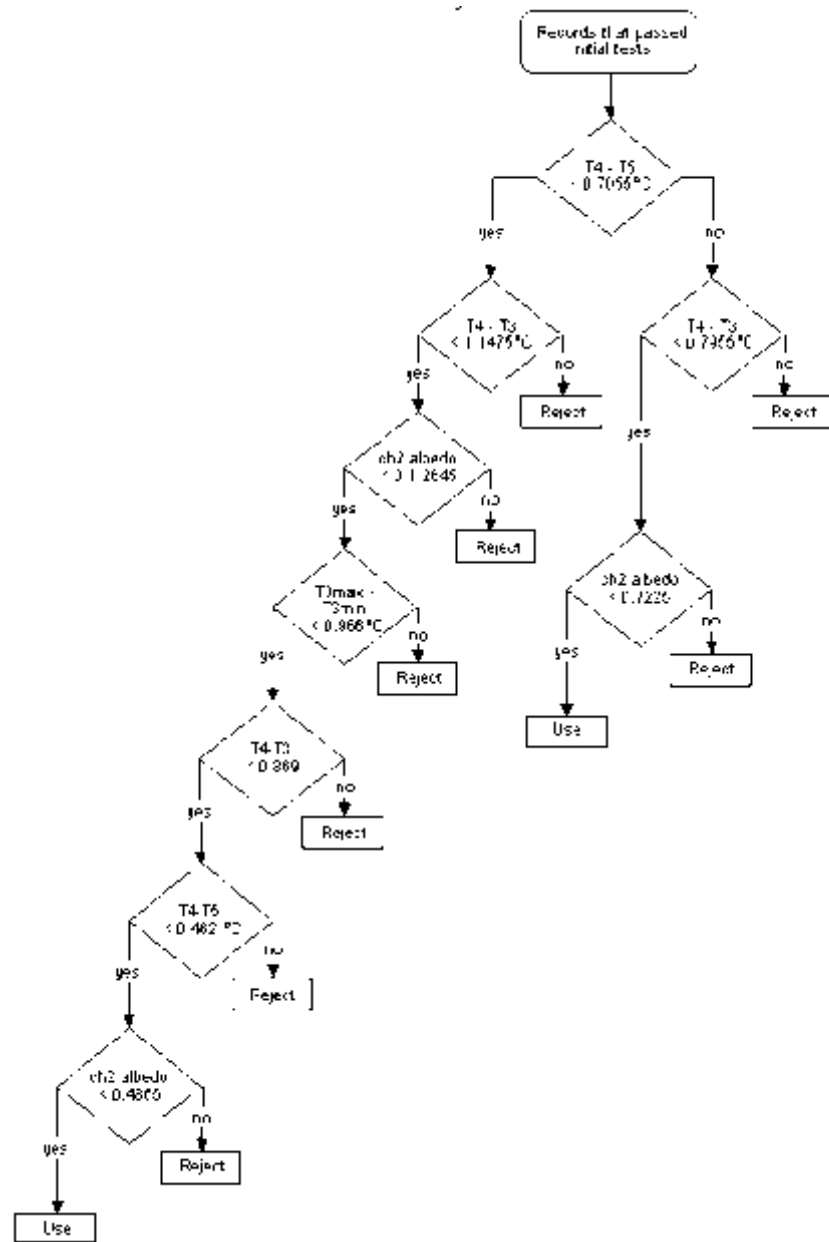
Predicted MODIS brightness temperatures at satellite height

Temperature deficit
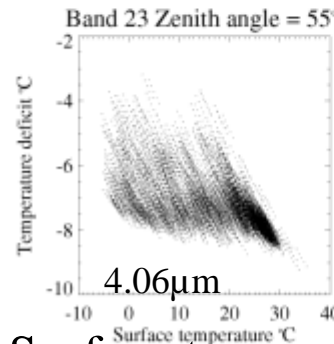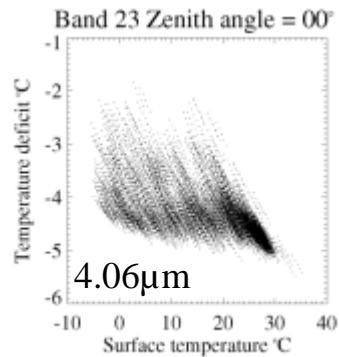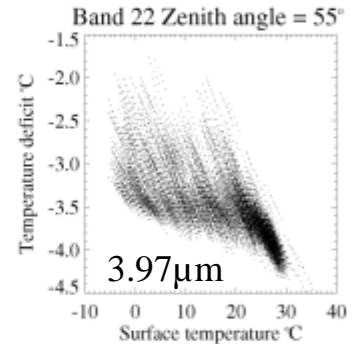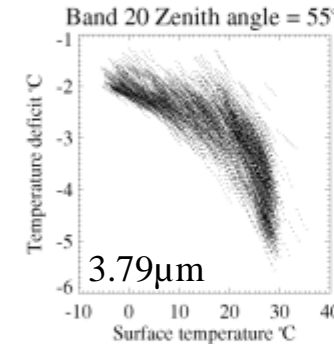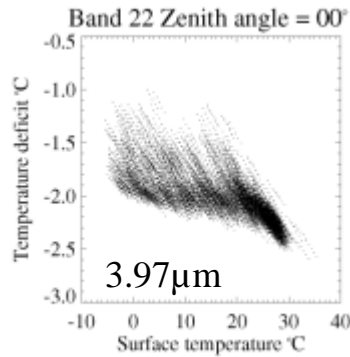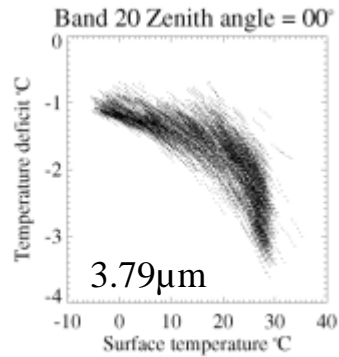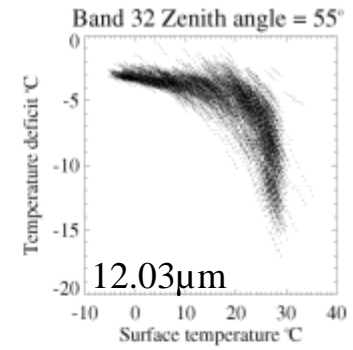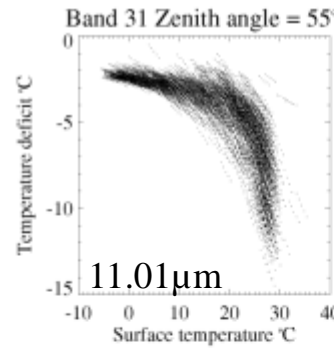
At nadir

Change in BT with surface T relatively small for bands 22, 23 - significantly larger for bands 20, 31, 32

At edge of swath

N=13950

Surface temperature range, -10 to 40°C

The SST atmospheric correction algorithms

The form of the daytime and night-time algorithm for measurements in the long wave atmospheric window is:

$$SST = c_1 + c_2 * T_{11} + c_3 * (T_{11}-T_{12}) * T_{sfc} + c_4 * (\sec(\theta)-1)* (T_{11}-T_{12})$$

where T_n are brightness temperatures measured in the channels at n mm wavelength, T_{sfc} is a 'climatological' estimate of the SST in the area, and θ is the satellite zenith angle. This is based on the Non-Linear SST algorithm.

[Walton, C. C., W. G. Pichel, J. F. Sapper and D. A. May (1998). "The development and operational application of nonlinear algorithms for the measurement of sea surface temperatures with the NOAA polar-orbiting environmental satellites." Journal of Geophysical Research **103** 27,999-28,012.]

The MODIS night-time algorithm, using two bands in the 4mm atmospheric window is:

$$SST4 = c_1 + c_2 * T_{3.9} + c_3 * (T_{3.9}-T_{4.0}) + c_4 * (\sec(\theta)-1)$$

Note, the coefficients in each expression are different. They can be derived in three ways:
- empirically by regression against SST values derived from another validated satellite instrument
- empirically by regression against SST values derived surface measurements from ships and buoys
- theoretically by numerical simulations of the infrared radiative transfer through the atmosphere.
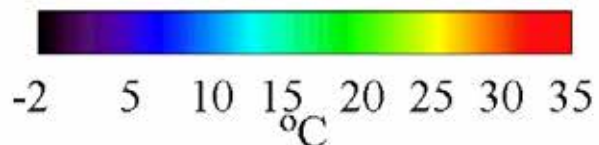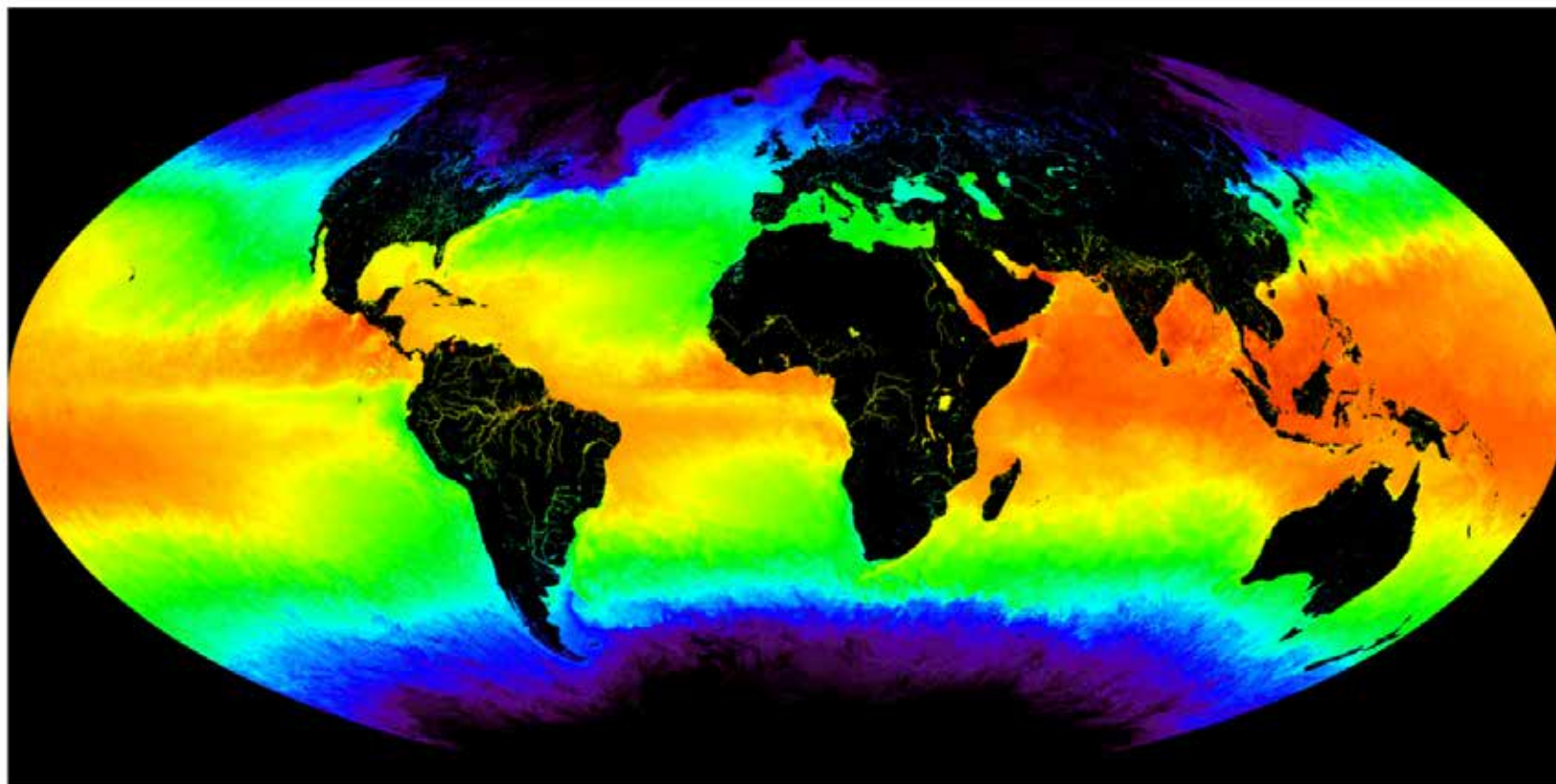
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MODIS SST

Typical oceanographic thermal signals

- The El Niño SST signal is an example of a large SST signal and is typically ~3-4K; temperature differences across large ocean fronts are similar. If satellite data are to be used to study such features, the accuracy of the retrieved SSTs should be at one order of magnitude smaller than the signal ~0.3K.
- For climate studies:
  - Accuracy 0.1K.
  - Stability 0.04K/decade.

  (Ohring, G., B. Wielicki, et al. (2005). "Satellite Instrument Calibration for Measuring Global Climate Change: Report of a Workshop." Bulletin of the American Meteorological Society 86(9): 1303-1313).

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What is SST?

- SST is a variable function of time and space, determined by integrated fluxes (including insolation), turbulent mixing, and advection (including upwelling).

- "SST" depends on how and where measured:
  - Heat flux between ocean and atmosphere leads to a skin layer at the ocean surface
  - Absorption of insolation can lead to surface gradients, especially in low winds.

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SST & the thermal skin layer

- The skin layer exists as a consequence of heat exchange from ocean to atmosphere.

- The skin layer is a 'bottleneck' in the heat flow from ocean to atmosphere, and it is this flow of heat that drives evaporation and sensible heat flow.

- The skin-bulk temperature difference, can be a significant fraction of the conventional air-sea temperature difference.

- SST could be an indicator of climate change, and satellite radiometers a global thermometer.

.

What is SST? –skin *vs.* bulk

The optical depth of sea water at infrared wavelengths is < 1mm. The **source of the infrared signal** used in remote sensing is the **skin layer** of the ocean, which is generally cooler than the subsurface layer because of heat flow from the ocean to the atmosphere.

The **conventional** meaning of **SST** is the temperature measured at a **depth of a meter** or more by a contact thermometer; the so-called bulk temperature.

At the levels of accuracy at which SST needs to be, and can be, measured from space, skin and subsurface temperatures are not the same.

Schematic Temperature Profiles
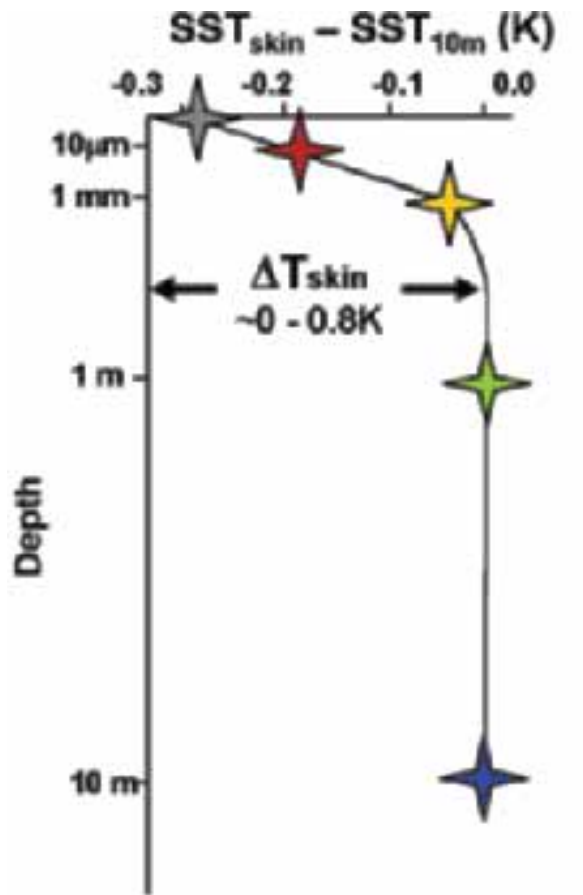
(a) Night time situation, light wind
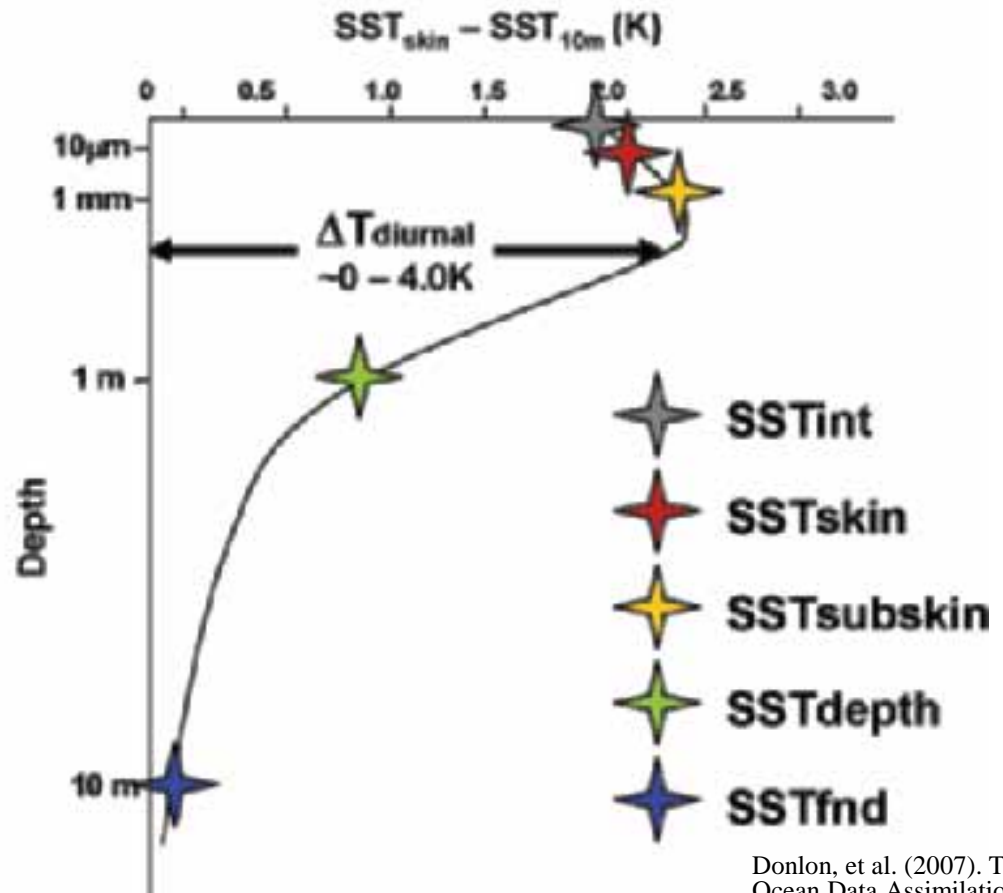
(b) Day time situation, strong solar radiation and light winds

Donlon, et al. (2007). The Global Ocean Data Assimilation Experiment High-resolution Sea Surface Temperature Pilot Project. *Bulletin of the American Meteorological Society, 88, 1197-1213*

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Wind speed dependence of diurnal & skin effects

As wind speed increases, magnitude of diurnal heating decreases and peak moves to later in the afternoon
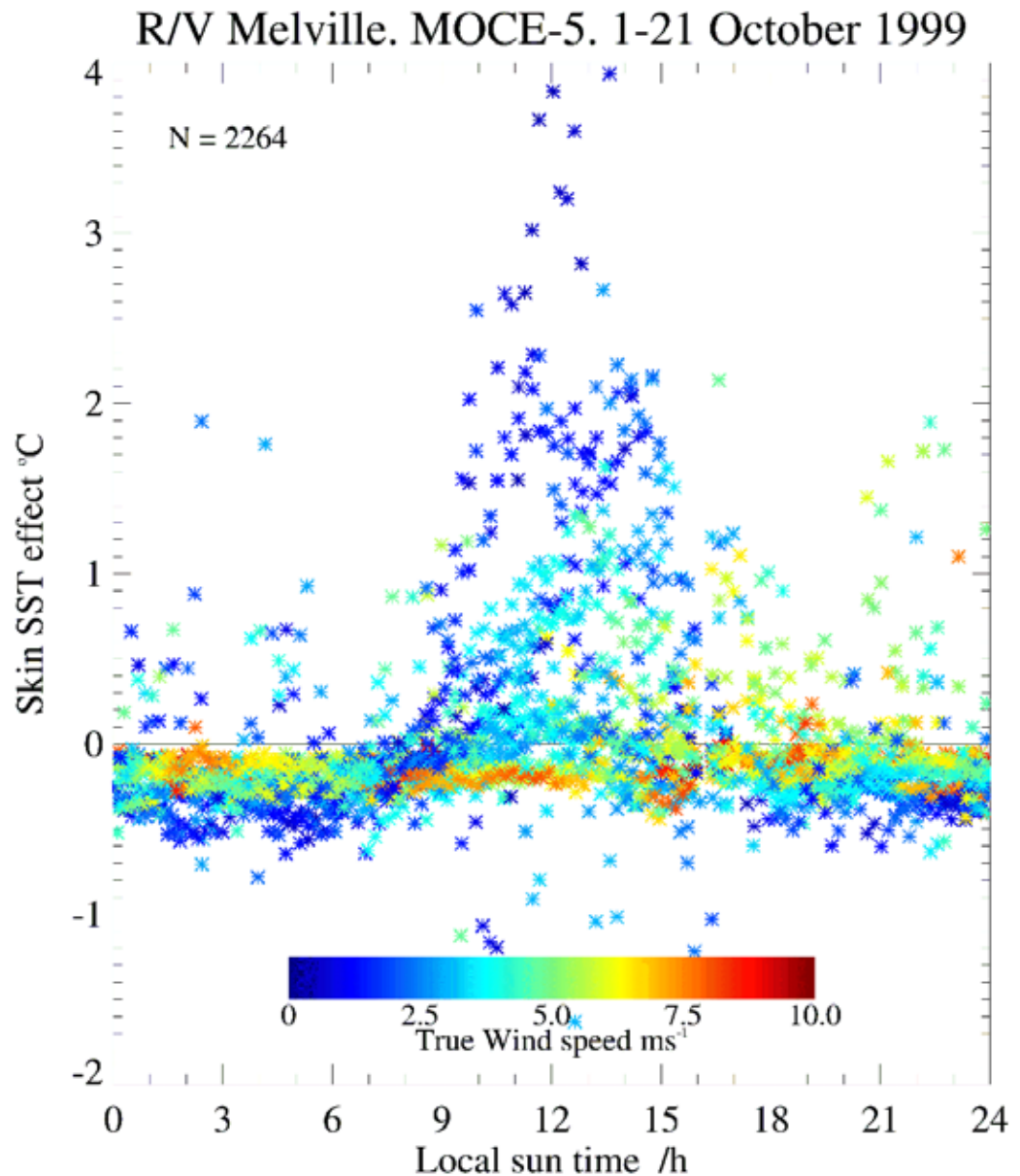
See: Minnett, P. J. (2003). "Radiometric measurements of the sea-surface skin temperature - the competing roles of the diurnal thermocline and the cool skin." International Journal of Remote Sensing **24**(24): 5033-5047

R/V Melville. MOCE-5. 1-21 October 1999

N = 2264

Skin SST effect °C

True Wind speed ms⁻¹

Local sun time /h

Wind speed dependence of diurnal & skin effects

As wind speed increases, magnitude of diurnal heating decreases and peak moves to later in the afternoon

Terra and Aqua overpass times.

R/V Melville. MOCE-5. 1-21 October 1999

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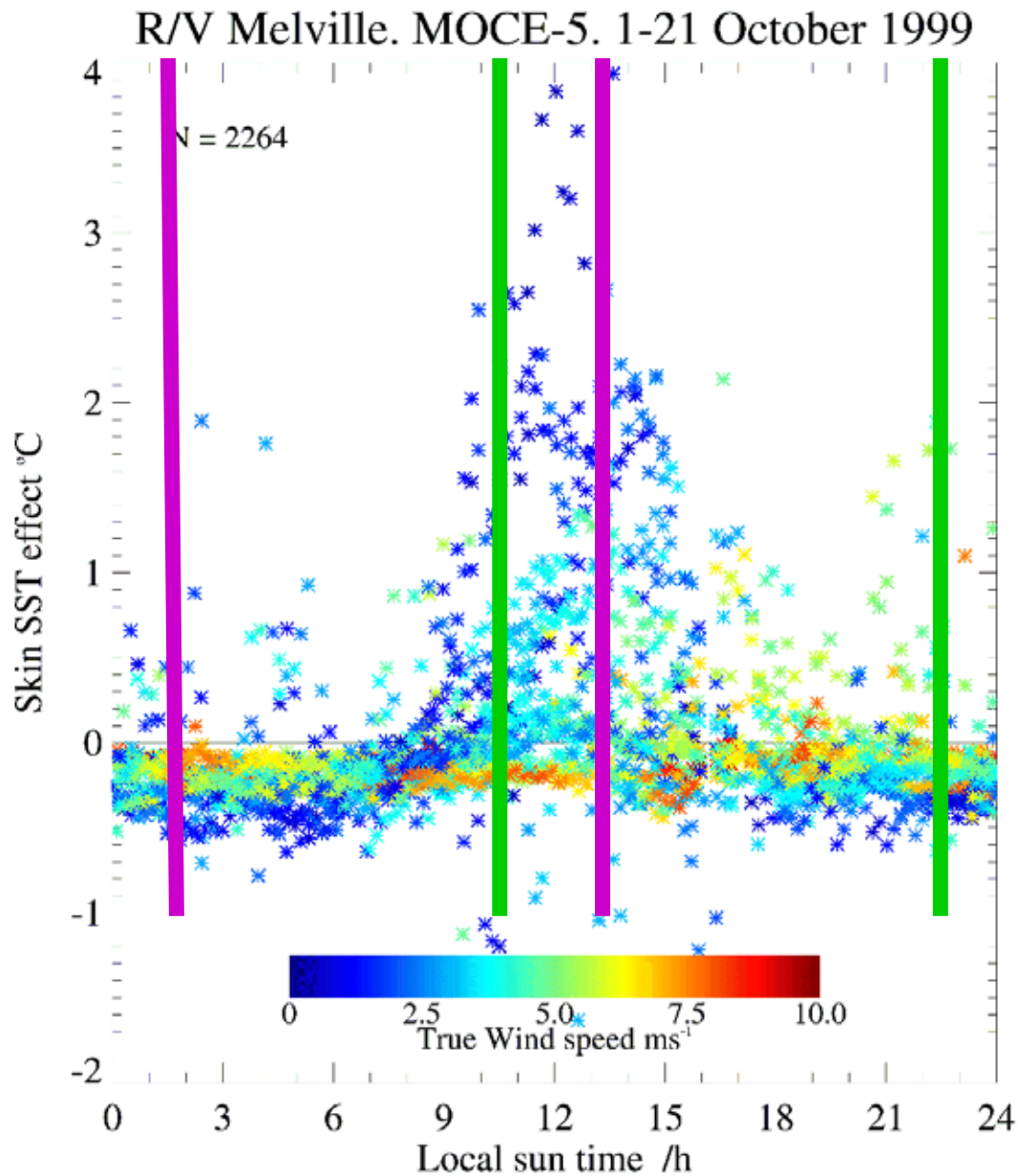
Wind speed dependence of the skin effect

Note collapse of envelope at moderate to high wind speeds > 7ms^{-1}, asymptotic value ~ -0.15K.

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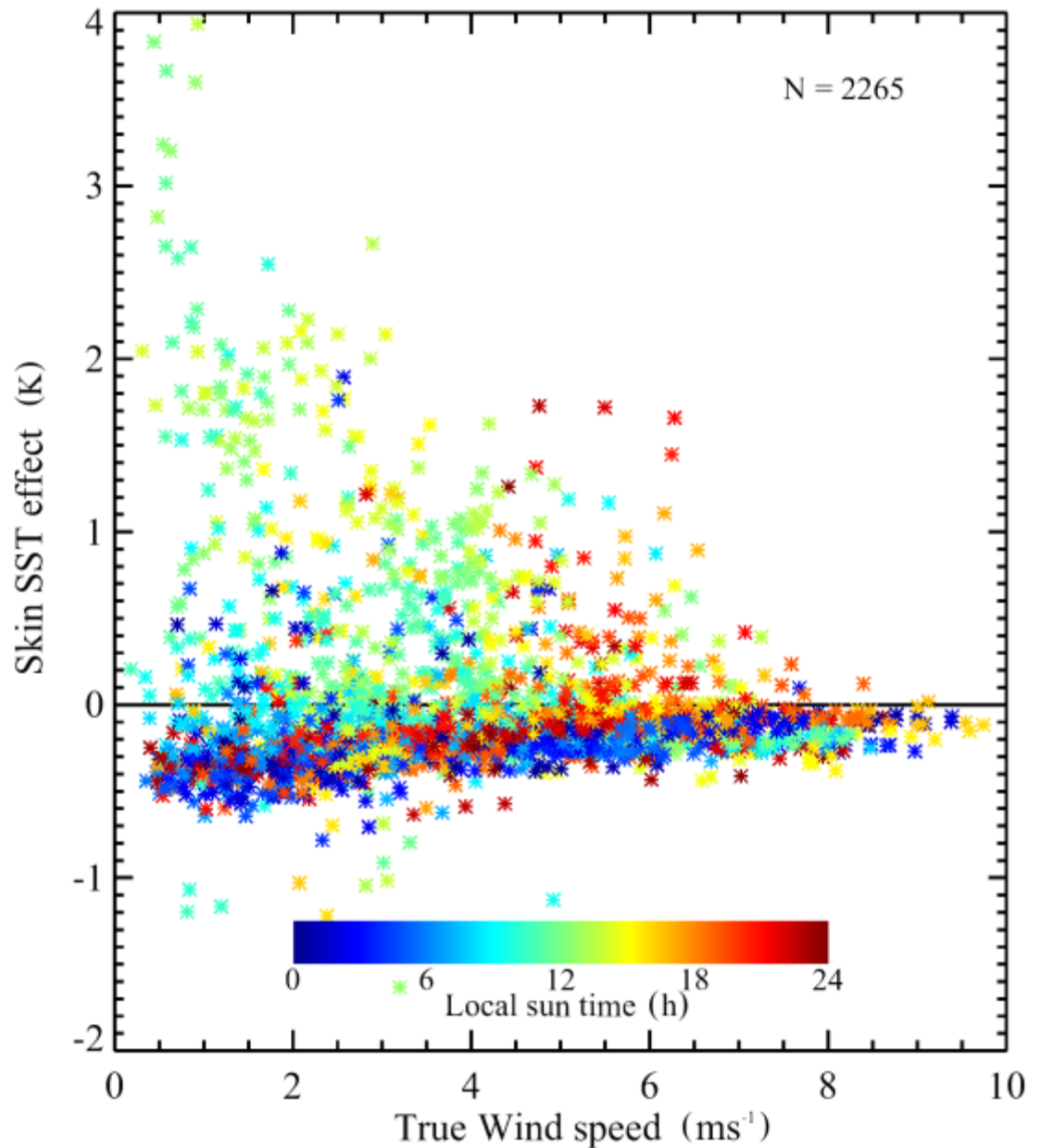
Measurements of Diurnal Warming

- Skin SST measured by M-AERI
- Bulk SST by a thermosalinograph at a depth of ~3m
- Winds and insolation measured on the ships

From Gentemann, C. L. and P. J. Minnett, 2008: Radiometric measurements of ocean surface thermal variability. *Journal of Geophysical Research*, **113,** C08017. doi:10.1029/2007JC004540.
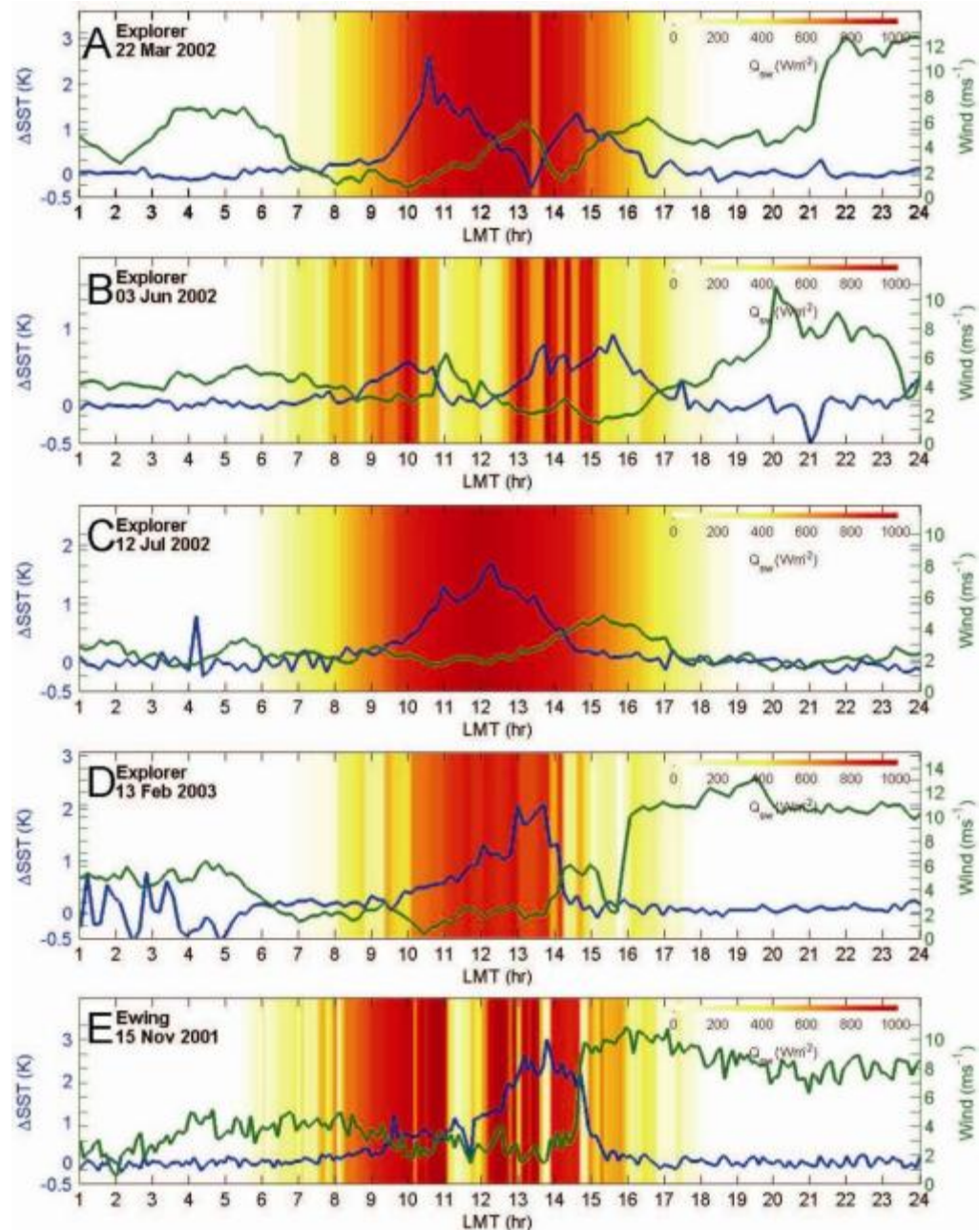
Examples of large amplitude diurnal heating

Large amplitude diurnal heating is identified in independent satellite data.

From Gentemann, C. L., P. J. Minnett, P. LeBorgne, and C. J. Merchant, 2008: Multi-satellite measurements of large diurnal warming events. *Geophysical Research Letters*, 35, L22602. doi:10.1029/2008GL035730
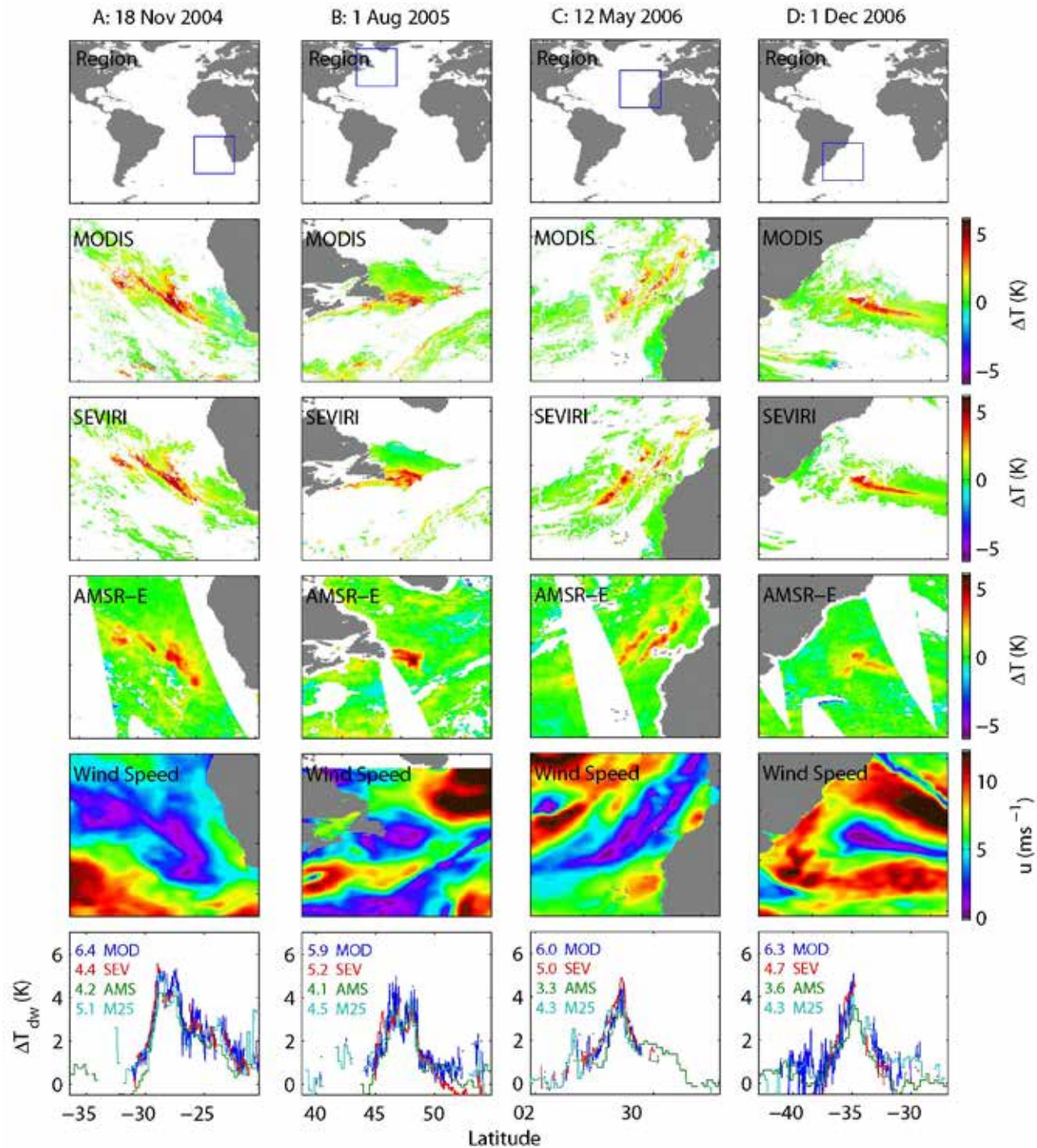
Large amplitude diurnal heating

SEVIRI (Spinning Enhanced Visible and Infrared Imager) is on the Meteosat 8 & 9 – geostationary satellites.

Images generated every hour.

Symbols are where diurnal heating >6K

Background color is number of days in the year where wind <1ms^{-1} at 14:00 LST.

From Gentemann, C. L., P. J. Minnett, P. LeBorgne, and C. J. Merchant, 2008: Multi-satellite measurements of large diurnal warming events. *Geophysical Research Letters*, **35,** doi:10.1029/2008GL035730

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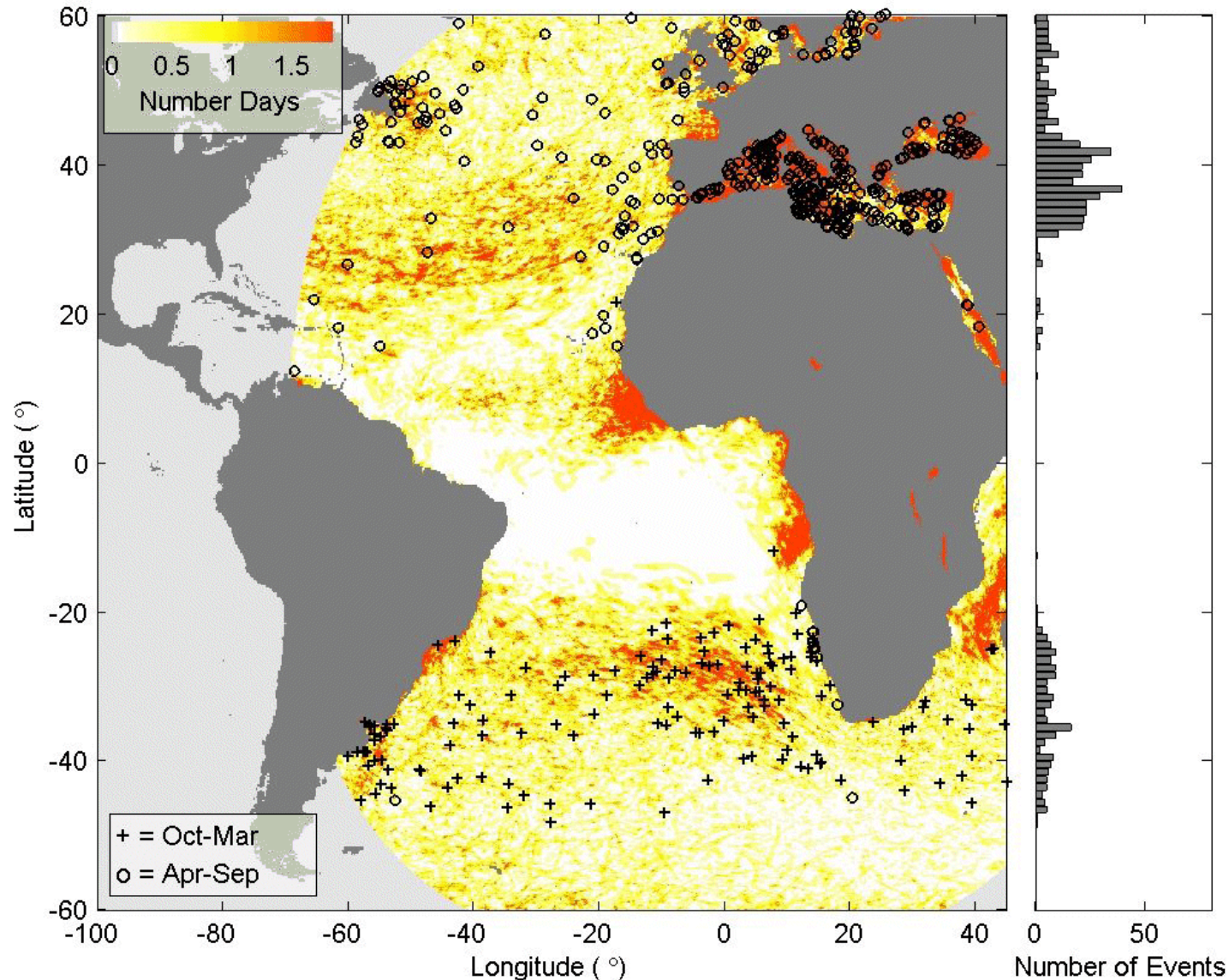
Uncertainty estimates
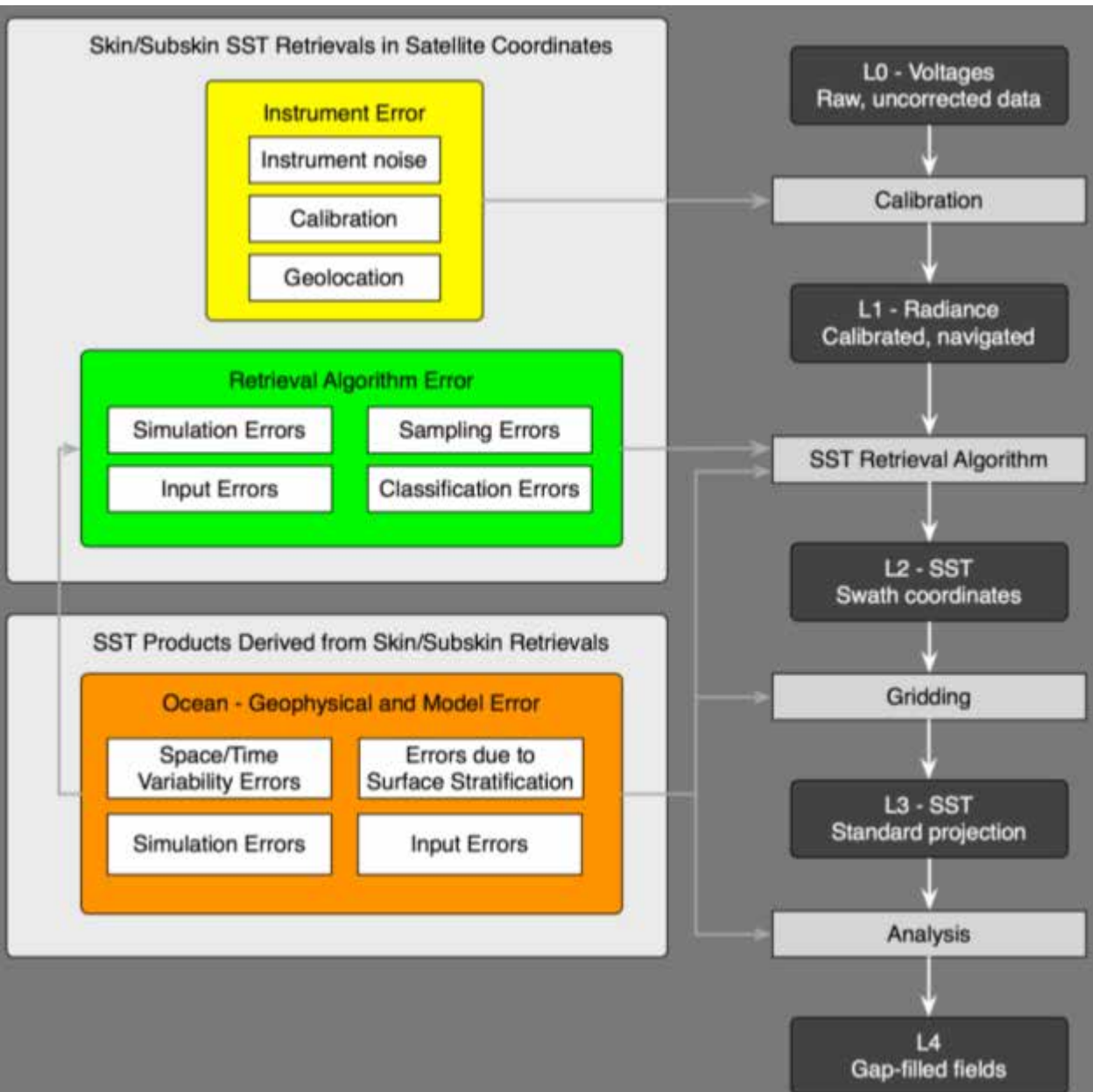
Good estimates of error, or uncertainties, are needed for data assimilation, and to assess significance of trends.

Each processing step is prone to additional error sources.

From Cornillon et al, 2010, Sea-Surface Temperature Error Budget White Paper. (http://www.ssterrorbudget.org/ISSTST/)

Uncertainty estimates
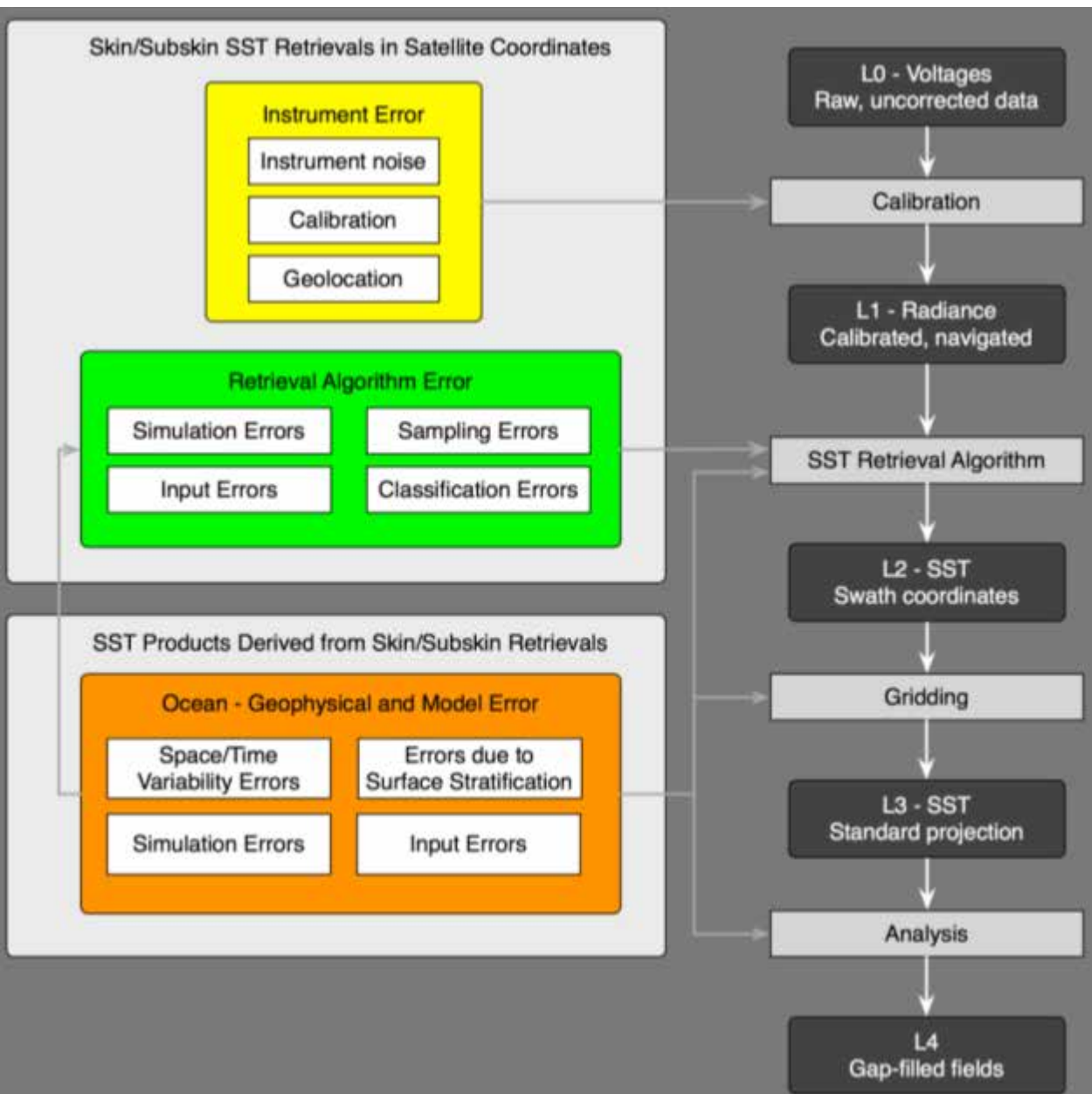
L2 is where the uncertainties in the SST retrievals by comparison with independent measurements.

L4 fields are used to initialize climate models, and in other climate studies.

Climate Data Records

- What does "Climate Data Record" mean?
- What is the path to a CDR of SST?
- Can we generate a CDR of SST?

Reference to SI units

The First Recommendation of the 20th Conférence Générale des Poids et Mesures :

"that those responsible for studies of Earth resources, the environment, human well-being and related issues ensure that measurements made within their programs are in terms of well-characterized SI units so that they are reliable in the long term, are comparable world-wide and are linked to other areas of science and technology through the world's measurement system established and maintained under the Convention du Mètre"

See http://www.bipm.org/jsp/en/ListCGPMResolution.jsp?CGPM=20

Laying the foundations

- Provides a basis for consistent long-term records from a variety of sources

- Provides consistency between different groups making related measurements

- For satellite-derived sea-surface temperature, it provides a mechanism for consistent time series to be generated over multiple missions.

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Essential Climate Variables

Essential Climate Variables
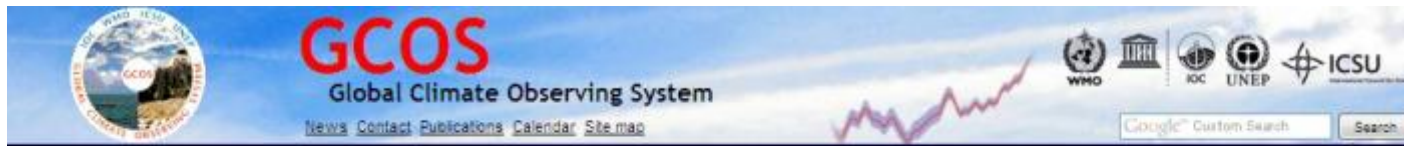
News
About GCOS
▾ Climate Observation Needs
UNFCCC and GCOS
UNFCCC Guidelines
GCOS Reports to UNFCCC
▶ Essential Climate Variables
Climate Monitoring Principles

Sea-surface temperature.

Outreach
Contact

GCOS Essential Climate Variables

The Essential Climate Variables (ECVs;) are required to support the work of the UNFCCC and the IPCC. All ECVs are technically and economically feasible for systematic observation. It is these variables for which international exchange is required for both current and historical observations. Additional variables required for research purposes are not included in this table. It is emphasized that the ordering within the table is simply for convenience and is not an indicator of relative priority. Currently, there are 44 ECVs plus soil moisture recognized as an emerging ECV.

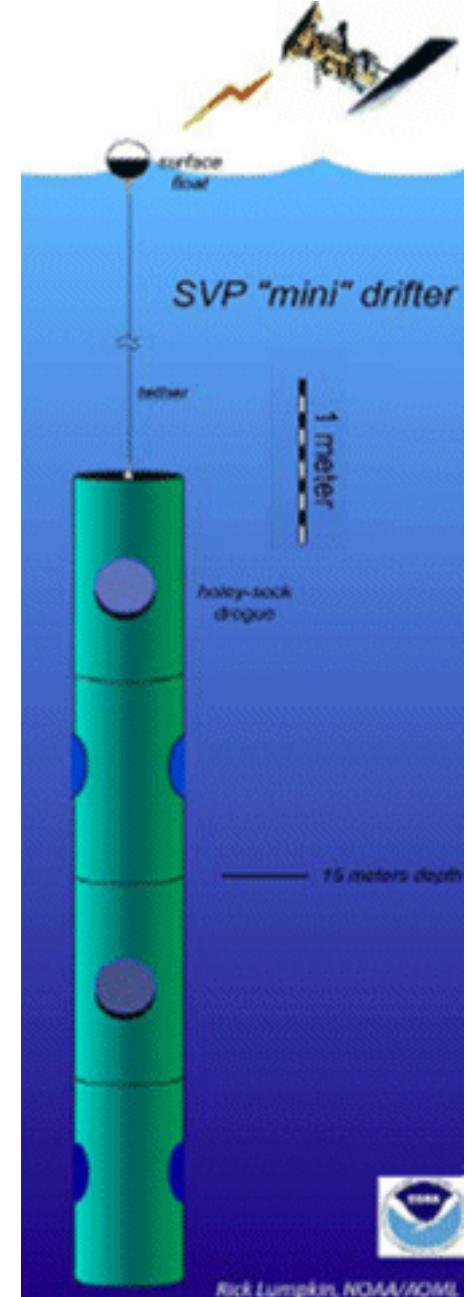| Domain	Essential Climate Variables
(Atmospheric over land, sea and ice)	**Surface:** Air temperature, Precipitation, Air pressure, Surface radiation budget, Wind speed and direction, Water vapour. **Upper-air:** Earth radiation budget (including solar irradiance), Upper-air temperature (including MSU radiances), Wind speed and direction, Water vapour, Cloud properties. **Composition:** Carbon dioxide, Methane, Ozone, Other long-lived greenhouse gases[1], Aerosol properties.
Oceanic	**Surface:** Sea-surface temperature, Sea-surface salinity, Sea level, Sea state, Sea ice, Current, Ocean colour (for biological activity), Carbon dioxide partial pressure. **Sub-surface:** Temperature, Salinity, Current, Nutrients, Carbon, Ocean tracers, Phytoplankton.
Terrestrial[2]	River discharge, Water use, Ground water, Lake levels, Snow cover, Glaciers and ice caps, Permafrost and seasonally-frozen ground, Albedo, Land cover (including vegetation type), Fraction of absorbed photosynthetically active radiation (fAPAR), Leaf area index (LAI), Biomass, Fire disturbance, Soil moisture[3].

Climate Data Records

- National Academy of Sciences Report (*NRC, 2000*): "*a data set designed to enable study and assessment of long-term climate change, with 'long-term' meaning year-to-year and decade-to-decade change. Climate research often involves the detection of small changes against a background of intense, short-term variations.*"

- "*Calibration and validation should be considered as a process that encompasses the entire system, from the sensor performance to the derivation of the data products. The process can be considered to consist of five steps:*
  - *instrument characterization,*
  - *sensor calibration,*
  - *calibration verification,*
  - *data quality assessment, and*
  - *data product validation.*"

How can we generate SST CDRs?

- Satellite radiometers may be well-calibrated and well-characterized prior to launch, but is this sustained through launch and on orbit?

- Satellite instruments are not recovered for post-deployment re-calibration…

- Accurate brightness temperatures measured in space do not necessarily mean accurate SSTs, as effects of imperfect atmospheric corrections dominate.

- SST CDRs require SI traceability: can only be achieved through validation programs.

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Temperature measurements from drifting buoys

- Deployed from ships and aircraft.
- Telemeter data via satellite links.
- Measure SST and P_o
- Satellites determine position.
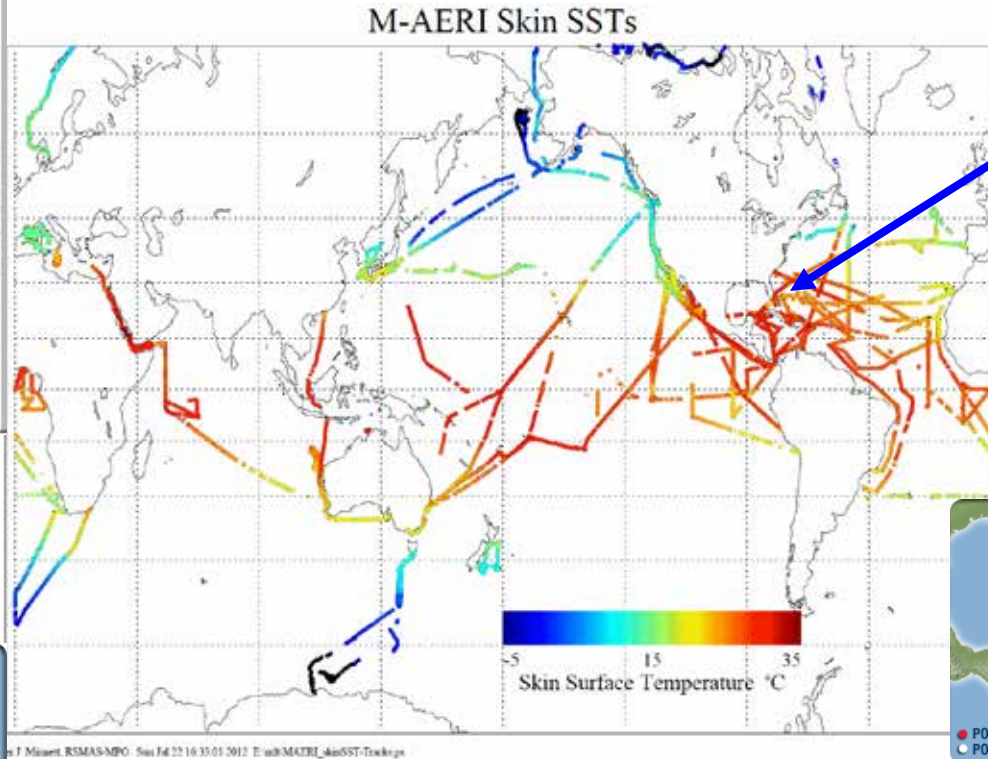- Changes in positions from day-to-day give surface currents; often with a drogue.

SVP "mini" drifter

surface float

tether

1 meter

holey-sock drogue

15 meters depth

Rick Lumpkin, NOAA/AOML

Drifting buoys

Before   &   After

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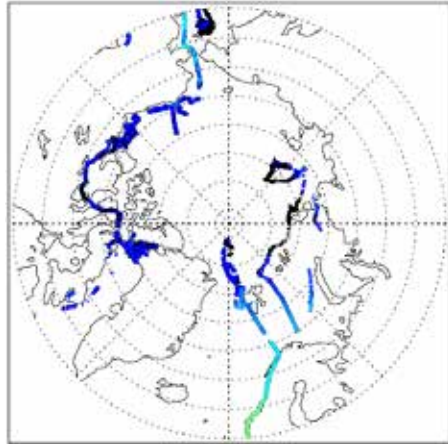
M-AERI cruises for MODIS, AATSR & AVHRR validation

Explorer of the Seas

Explorer of the Seas: near continuous operation December 2000 – December 2007.

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ISAR cruises for MODIS, AATSR & AVHRR validation

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·eesa
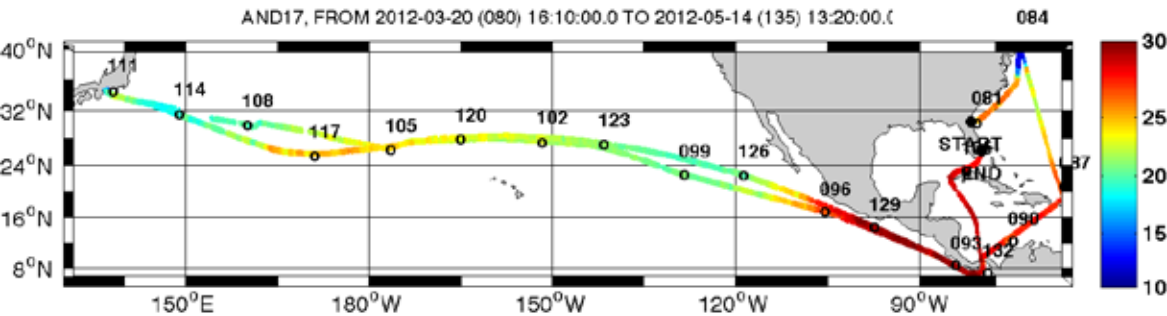
International radiometer workshops

- There have been three international workshop on infrared radiometry held at RSMAS, University of Miami.
  - The first was held prior to the launch of *Terra*
  - The second in 2001, before the launch of *Aqua*
  - The third took place in May 2009, under the auspices of the GEO/CEOS (Group on Earth Observations / Committee on Earth Observation Satellites)
- The data from the third workshop were analyzed at the National Physical Laboratory (NPL), Teddington, UK, and the results have been published in reports of the NPL
- Through the participation of NIST these workshops provide traceability to national radiometric and thermodynamic temperature standards through the characterization of the laboratory radiometers used to assess the validity of the internal calibration of the radiometers used at sea. This traceability to SI standards is achieved by using the NIST Transfer Radiometer (TXR)
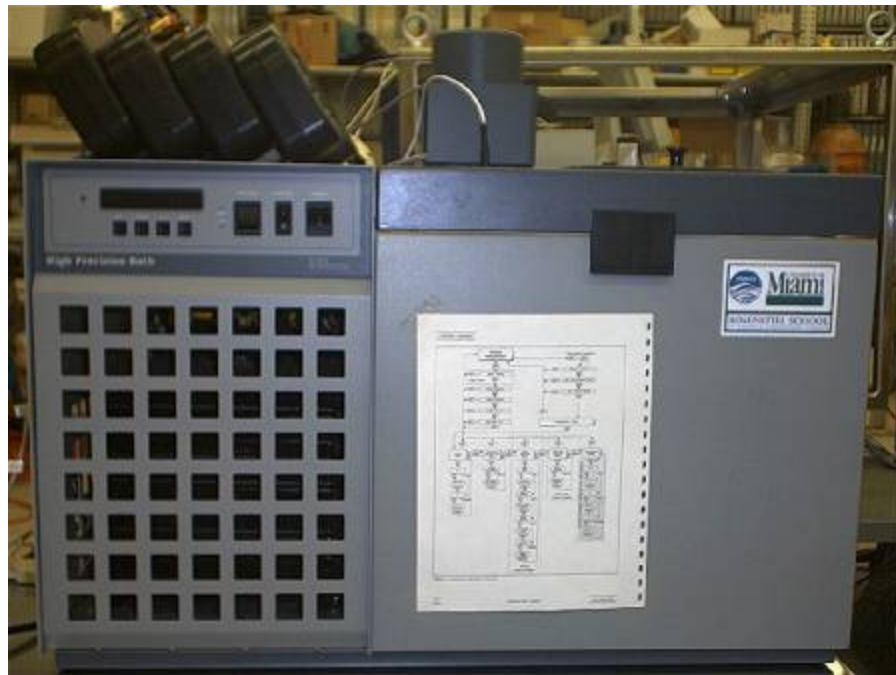
The NIST EOS TXR
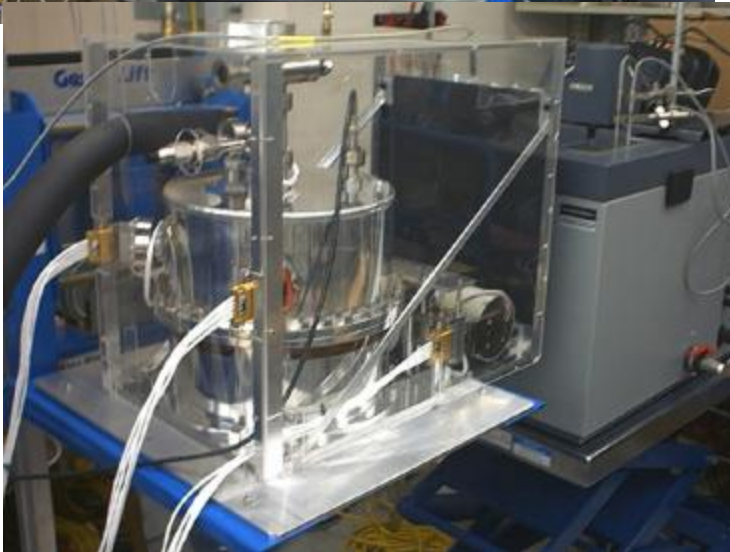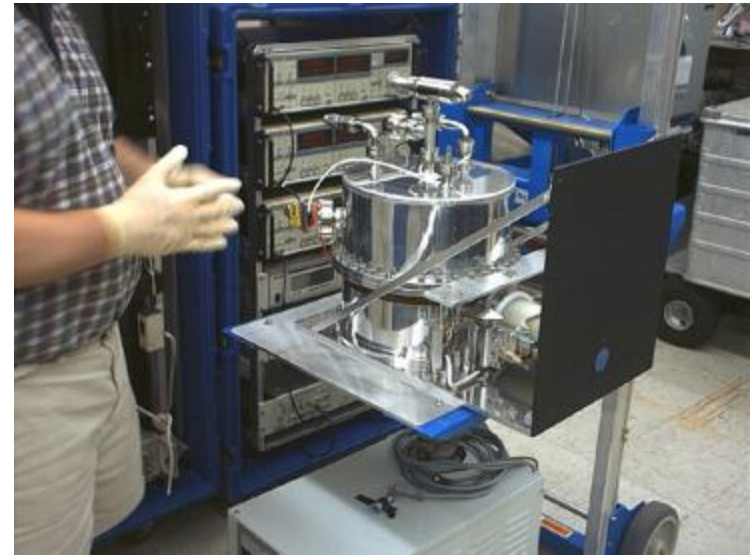
Unique EOS Standard
Cryogenic detectors (liquid N_2)
$\lambda = 5$ & $10 \mu m$

Rice, J. P. and B. C. Johnson, 1998. The NIST
EOS Thermal-Infrared Transfer Radiometer,
Metrologia, 35, 505-509.

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NIST water-bath black-body calibration target

See: Fowler, J. B., 1995. A third generation water bath based blackbody source, *J. Res. Natl. Inst. Stand. Technol.*, 100, 591-599
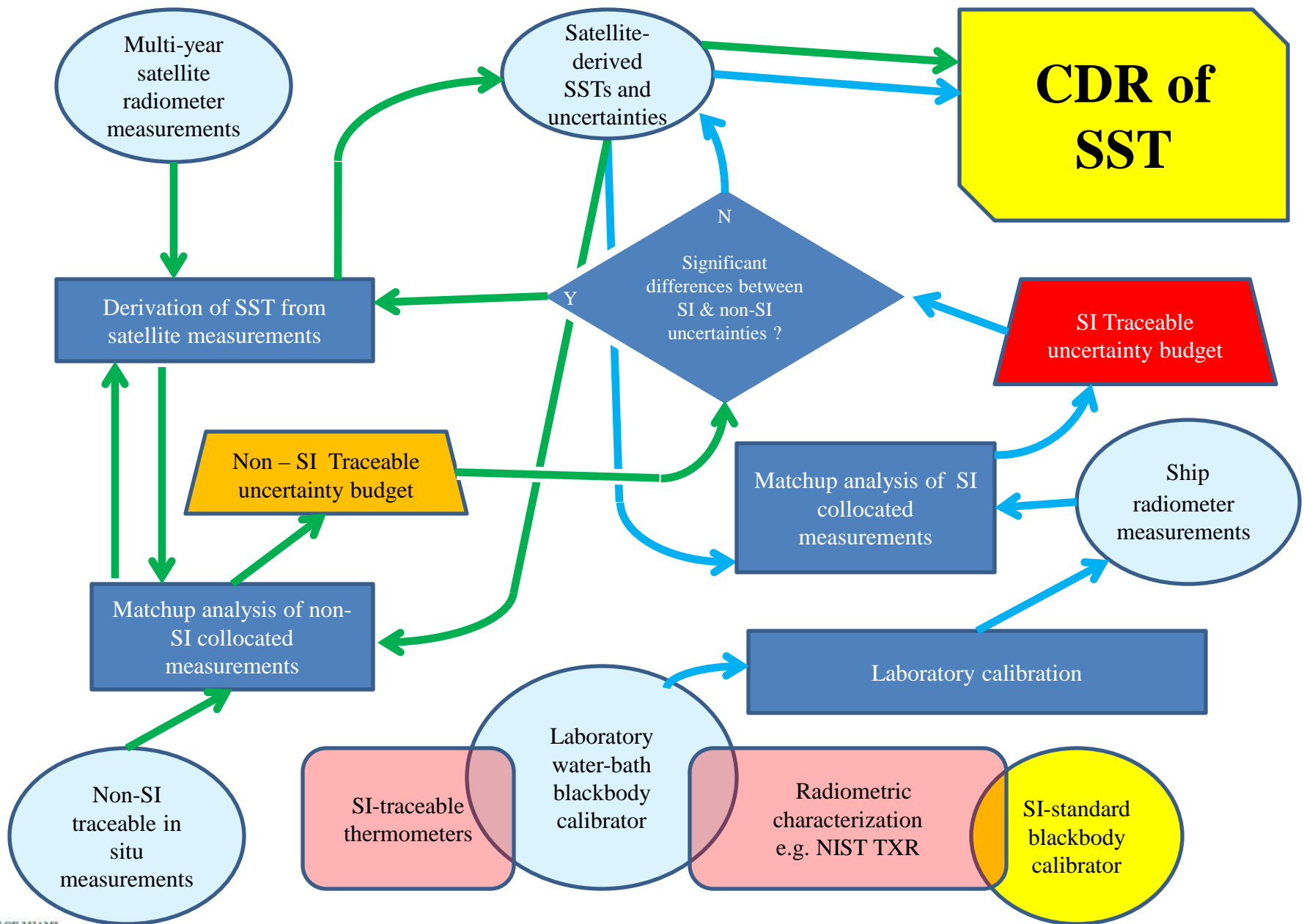
SST radiometers - 2009
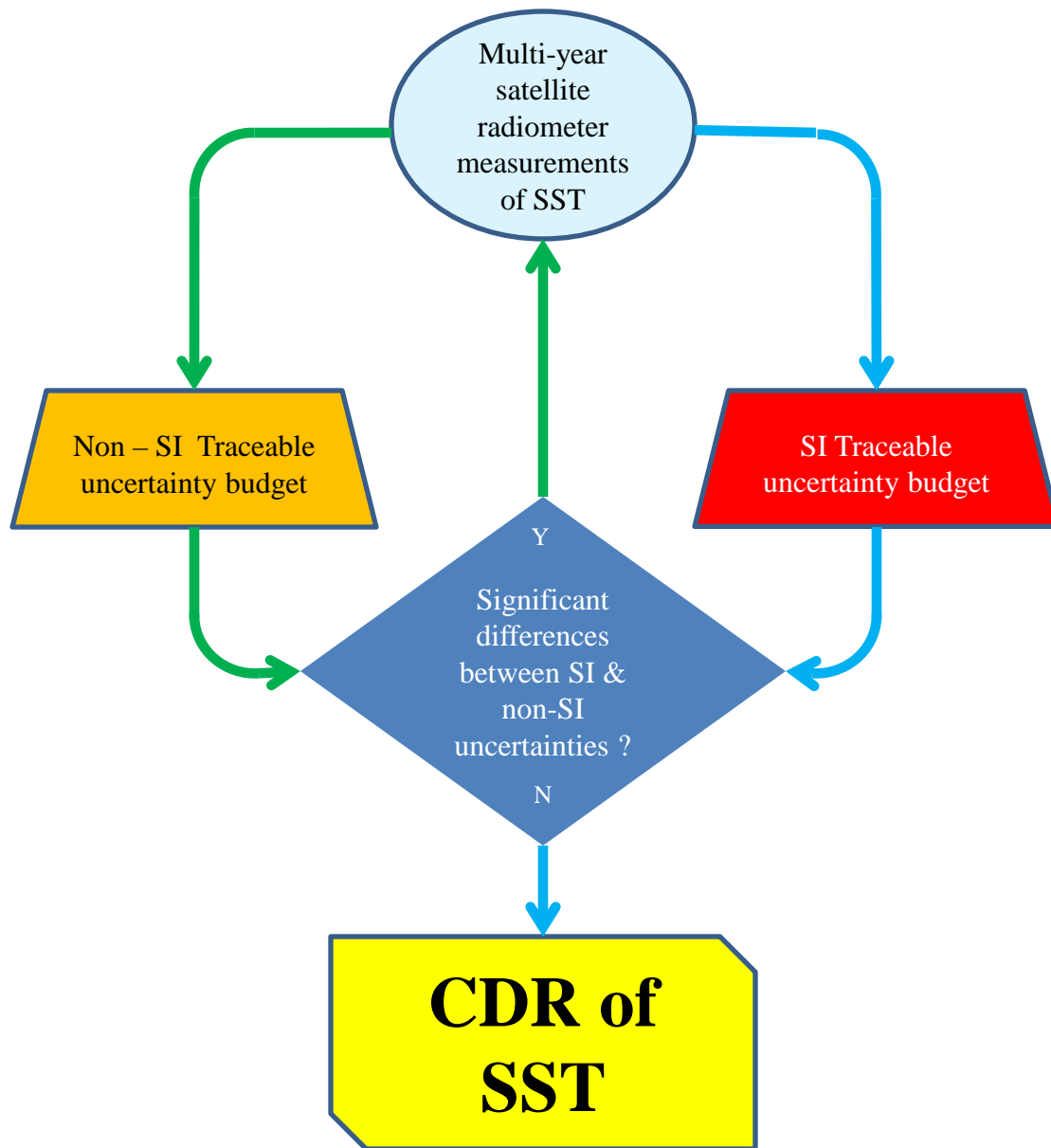## 3rd Miami IR Radiometry Workshop

Traceability to SI references is achieved.

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CDR Summary

- Generation of SST CDRs requires validation with NIST-traceable radiometers.

- NIST TXR is the transfer reference standard for infrared radiometry

- The Miami Infrared Workshops have provided a mechanism for traceability to NIST standards of satellite-derived SSTs.

- SST CDRs are a reality.

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Questions ?

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