→ 4th ESA ADVANCED TRAINING ON OCEAN REMOTE SENSING

Measuring SST from space

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With acknowledgements to (amongst others):
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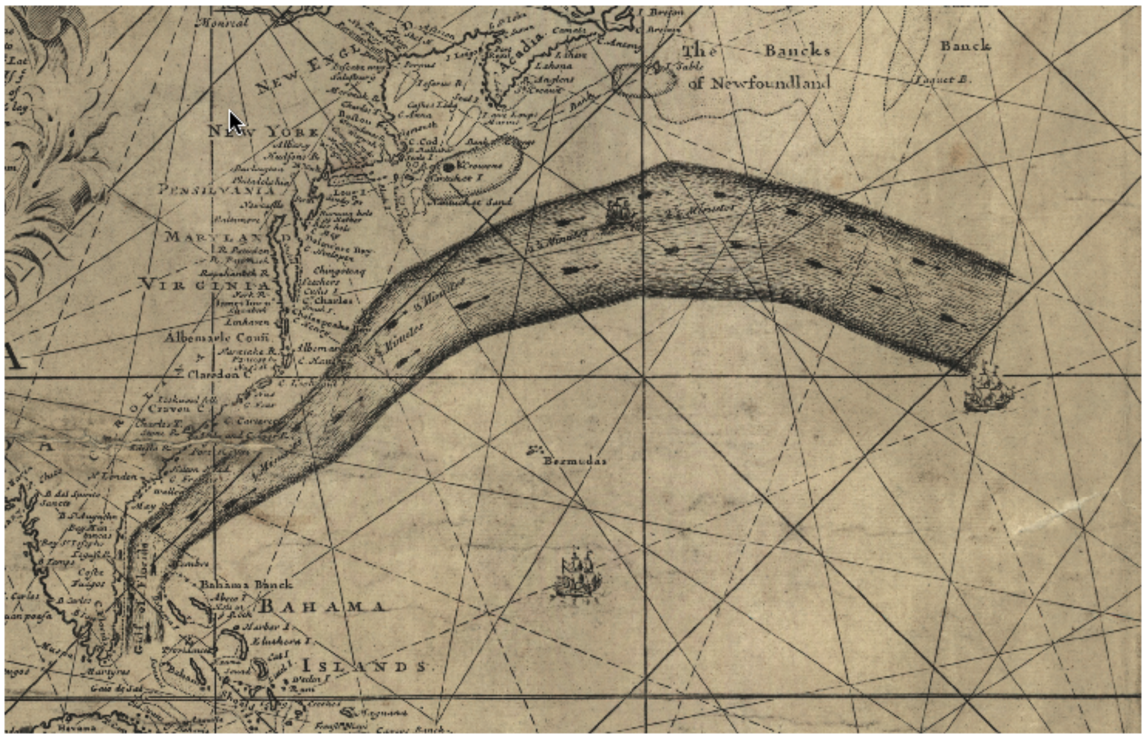
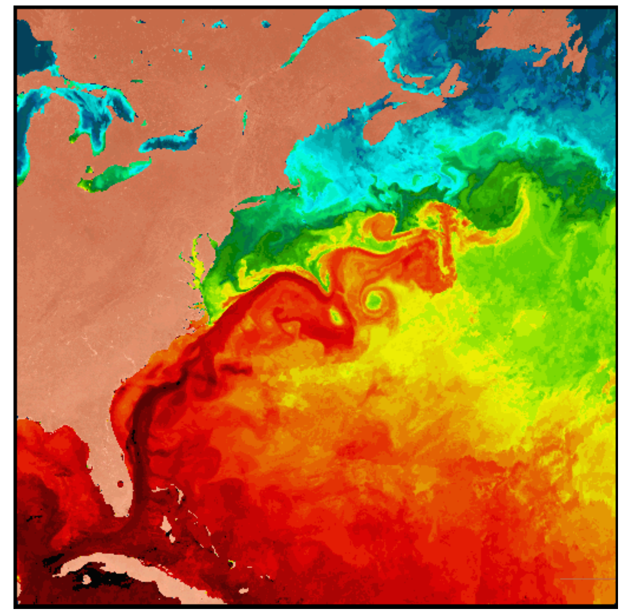
Lecture Outline

- Why Measure SST from Space?
- How do we measure SST from Space?
- What can we see by measuring SST from Space?

WHY MEASURE SST FROM SPACE?

We need to measure ocean surface temperature





- Benjamin Franklin and Timothy Folger - chart of North Atlantic Currents - 1770

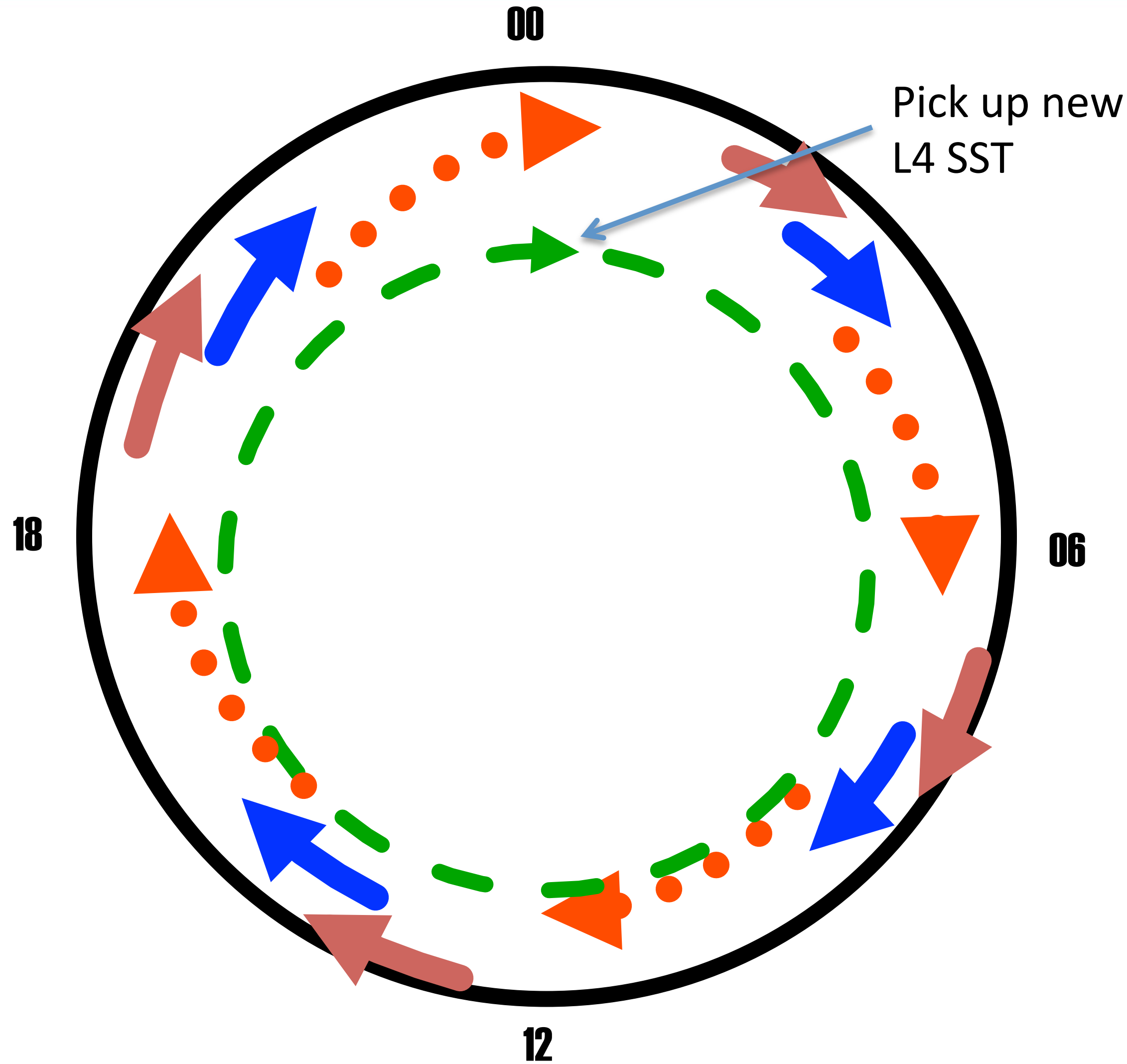
We need to measure ocean surface temperature

Use prescribed SST

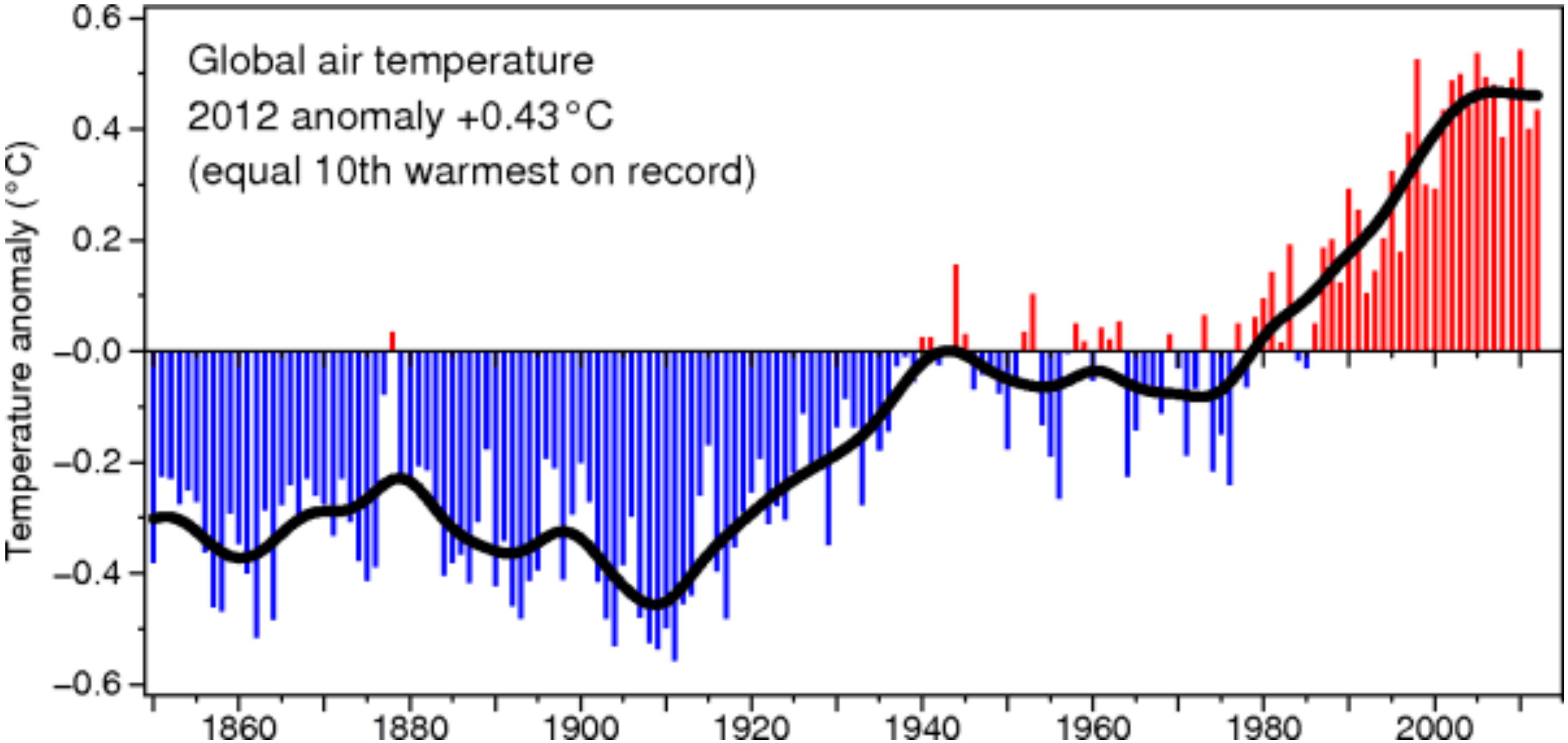
Quality control

Assimilation

Forecast



We need to measure ocean surface temperature



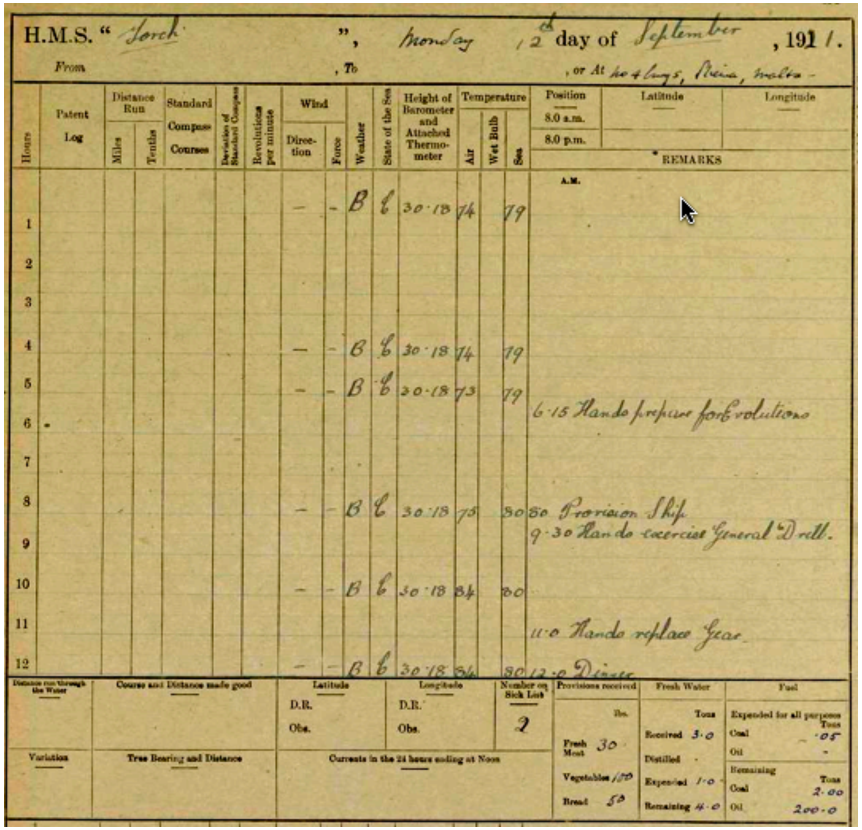
Climatic Research Unit
UEA

Why measure SST?

- SST controls ocean atmosphere heat transfer
- More heat reaches the atmosphere from Earth's surface than from direct Solar Heating
- Ocean-atmosphere heat transfer drives our weather and climate
- Also an important indicator of Climate Change
- Designated ECV by GCOS
  - ECV = Essential Climate Variable

How accurately do we Need to Measure SST?

- Ocean-atmosphere heat transfer - very strong T-dependence of in Tropics – change of 0.3 °C can affect rate by ~ 10% or more
- Process monitoring – e.g. el Niño is typically a 2 °C to 4°C anomaly
  - To monitor progress need to detect 10% of anomaly signal or less.
  - Thus there is a need for accuracy of 0.2 – 0.4 °C
- Climate monitoring requirements are more stringent, with trends of around 0.1 °C per decade
  - Various analyses require accuracies better than 0.2°C with stability of better than 0.1 °C per decade



H.M.S. "Torch", Monday 12d day of September, 1911.

From , To , or At No 4 buoys, Bieia, Malta -

Hours	Patent Log	Distance Run: Miles	Distance Run: Tenths	Standard Compass Courses	Deviation of Standard Compass	Revolutions per minute	Wind: Direction	Wind: Force	Weather	State of the Sea	Height of Barometer and Attached Thermometer	Temperature: Air	Temperature: Wet Bulb	Temperature: Sea	Remarks
							–	–	B	C	30·18	74		79	A.M.
1															
2															
3															
4							–	–	B	C	30·18	74		79	
5							–	–	B	C	30·18	73		79	
6															6·15 Hands prepare for Evolutions
7															
8							–	–	B	C	30·18	75		80	8·0 Provision Ship
9															9·30 Hands exercise General Drill.
10							–	–	B	C	30·18	84		80	
11															11·0 Hands replace Gear
12							–	–	B	C	30·18	84		80	12·0 Dinner

Position: 8.0 a.m. / 8.0 p.m. — Latitude — Longitude

Distance run through the Water

Course and Distance made good

Latitude D.R. Obs.

Longitude D.R. Obs.

Number on Sick List: 2

Provisions received (lbs.): Fresh Meat 30, Vegetables 100, Bread 50

Fresh Water (Tons): Received 3·0, Distilled -, Expended 1·0, Remaining 4·0

Fuel: Expended for all purposes (Tons): Coal ·05, Oil -; Remaining (Tons): Coal 2·00, Oil 200·0

Variation

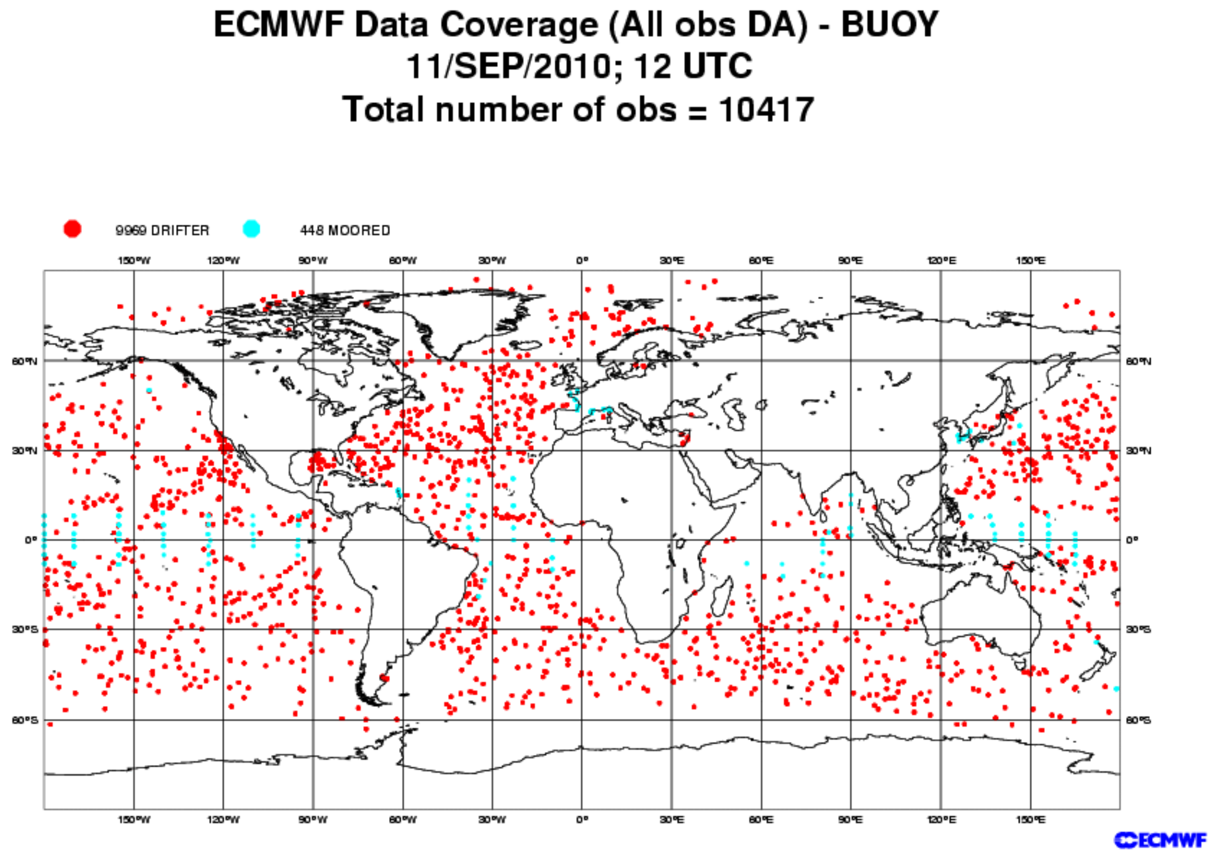
True Bearing and Distance

Currents in the 24 hours ending at Noon

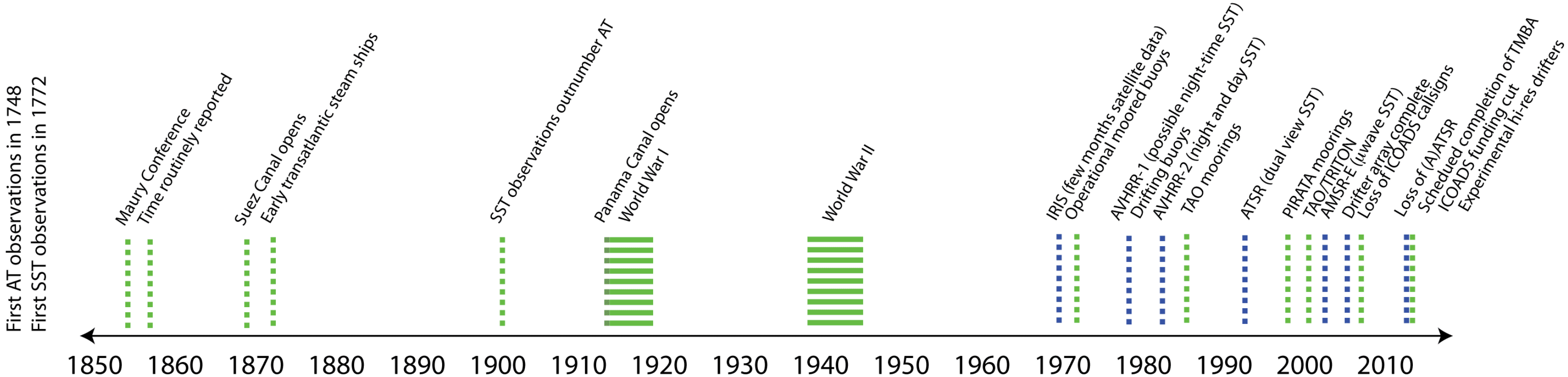
- HMS Torch (Alert class sloop)

www.oldweather.org

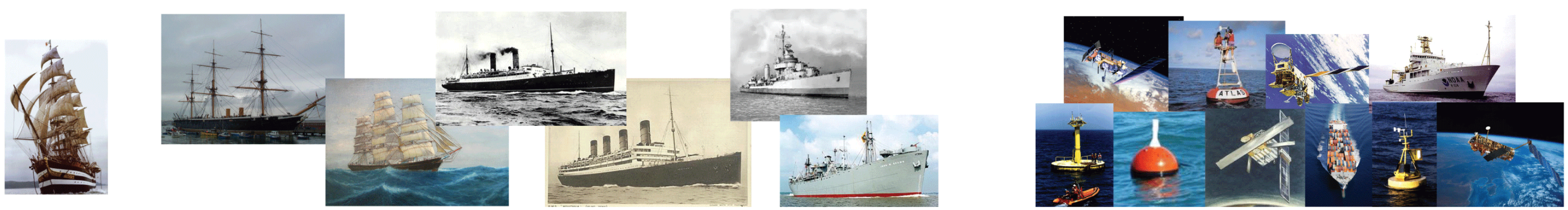
Modern in situ: drifting buoys



The evolving marine surface temperature observing system



Platforms



- The quantity, quality and location of observations over time depends on:
  - Technology
  - Platforms – from sailing ships to drifting buoys and satellites
  - Civil engineering – the Suez and Panama Canals
  - Conflict and economics – Wars, available platforms, budgets and priorities
  - Psychology – high quality observations require committed observers/analysts

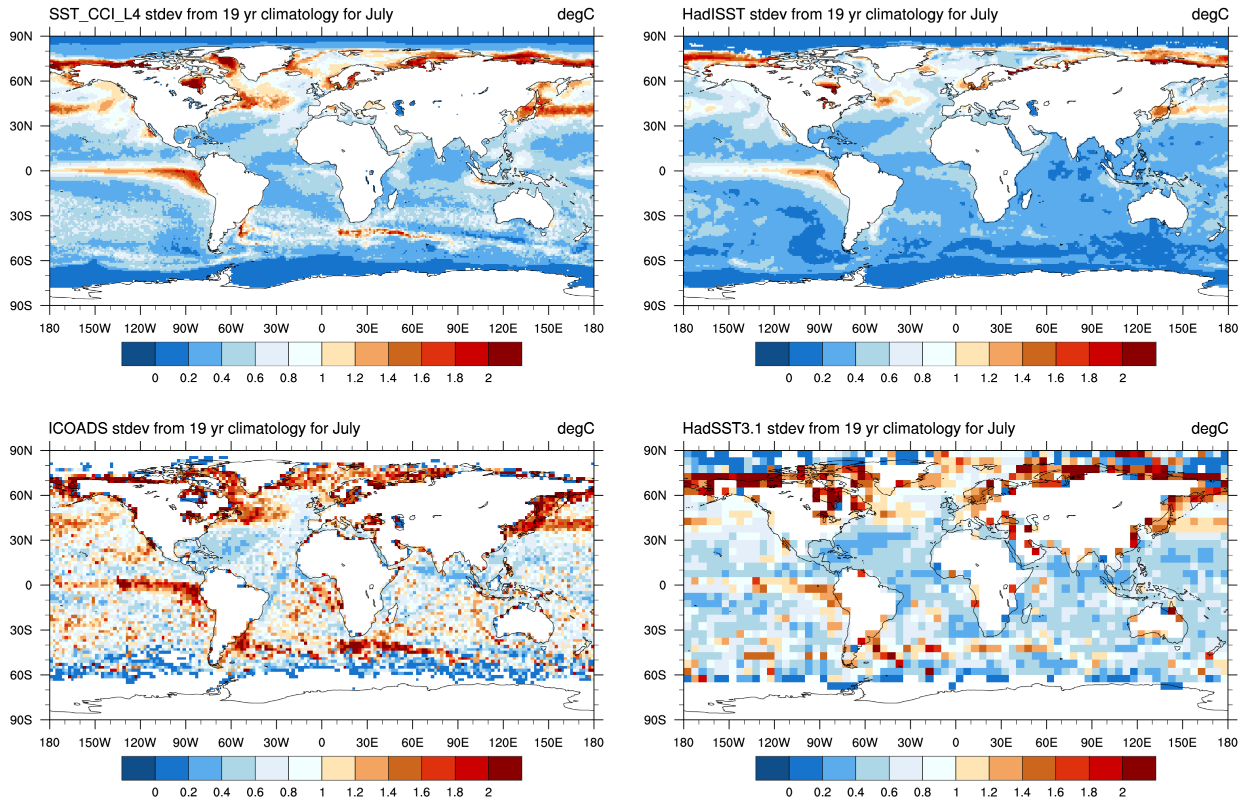
Reasons for using space

- *The three C's ->*

- **Coverage**

- **Continuity**

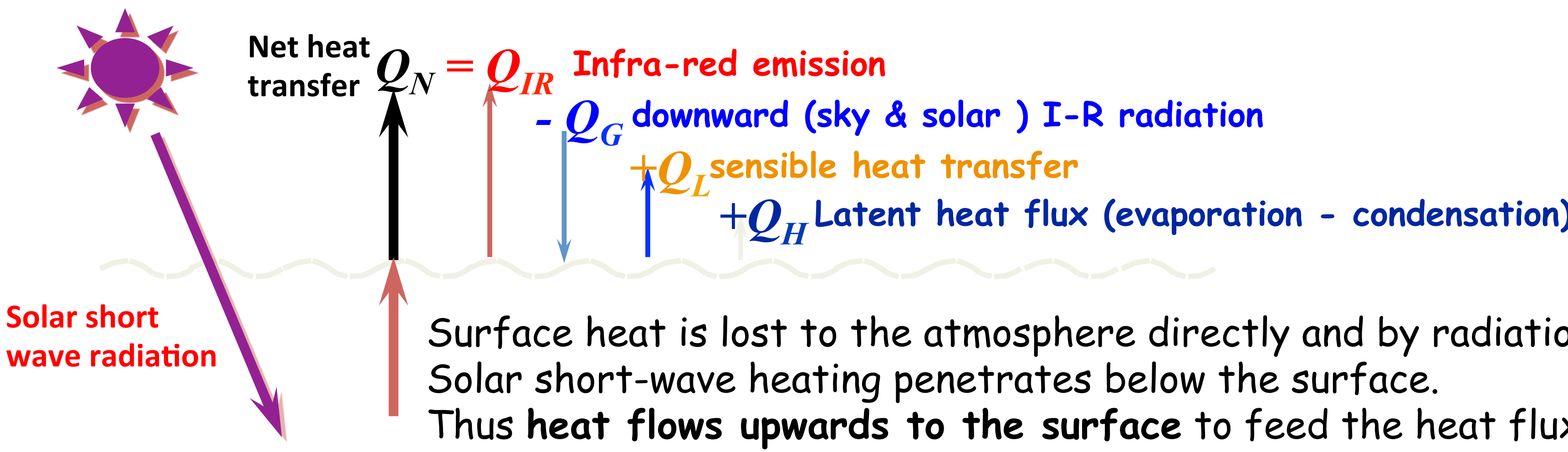
- **Consistency**



What is SST?

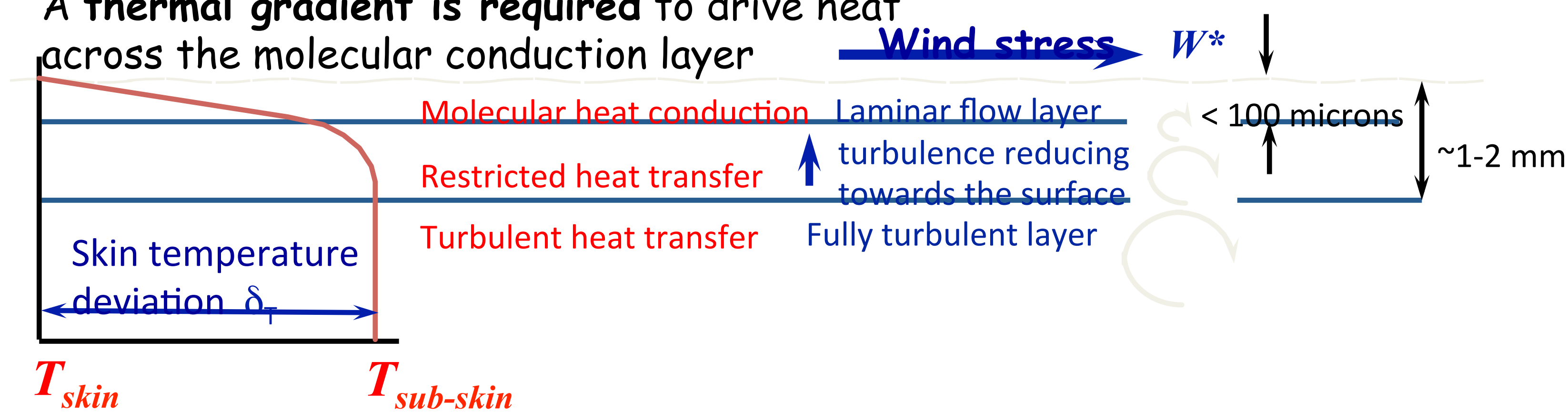
- SST is a variable function of time and space, determined by integrated fluxes (including insolation), turbulent mixing, and advection (including upwelling).
- "SST" depends on how and where measured:
  - Heat flux between ocean and atmosphere leads to a skin layer at the ocean surface
  - Absorption of insolation can lead to surface gradients, especially in low winds.

Atmosphere/ocean interface: the skin effect

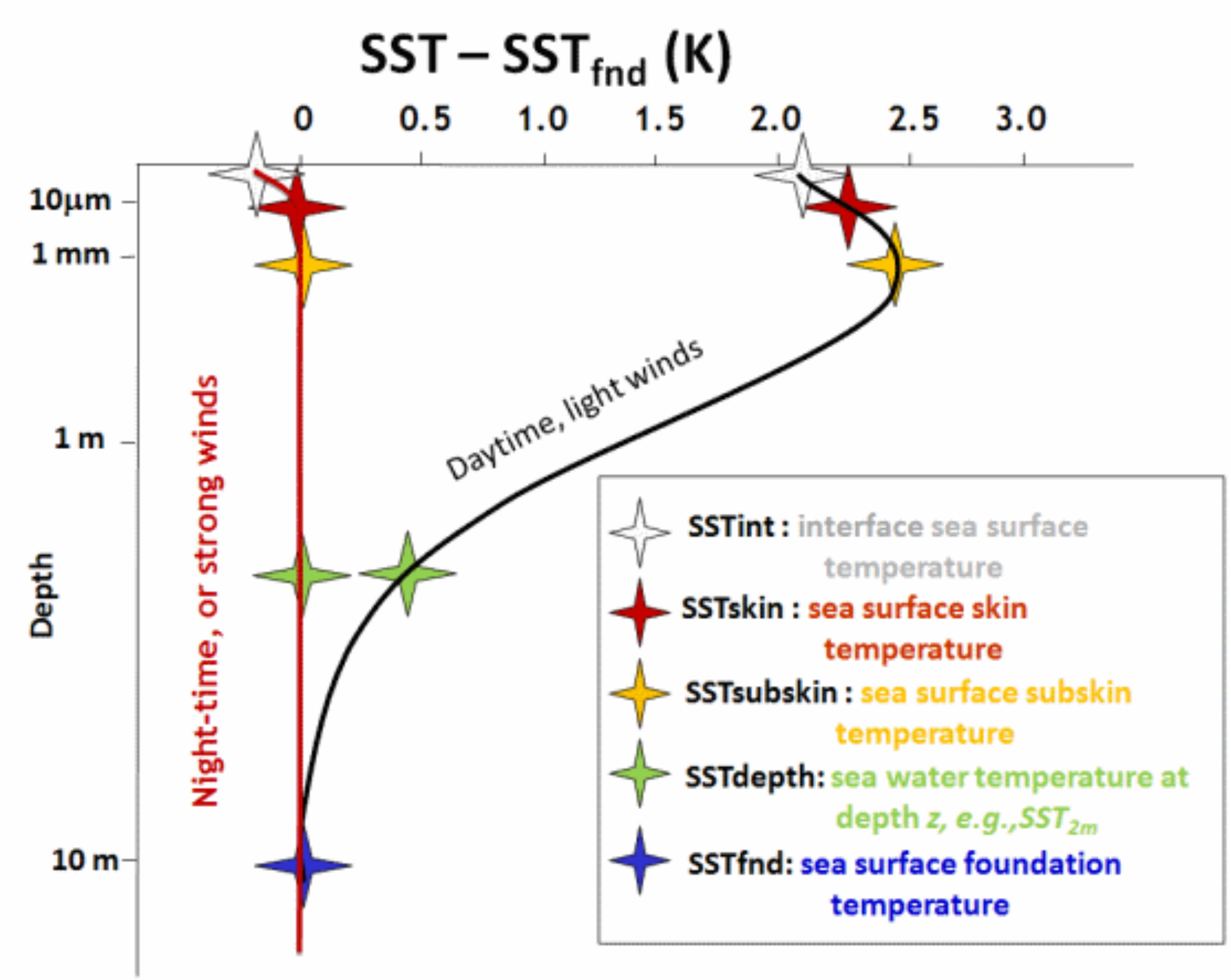


Surface heat is lost to the atmosphere directly and by radiation.
Solar short-wave heating penetrates below the surface.
Thus **heat flows upwards to the surface** to feed the heat flux Q_N.

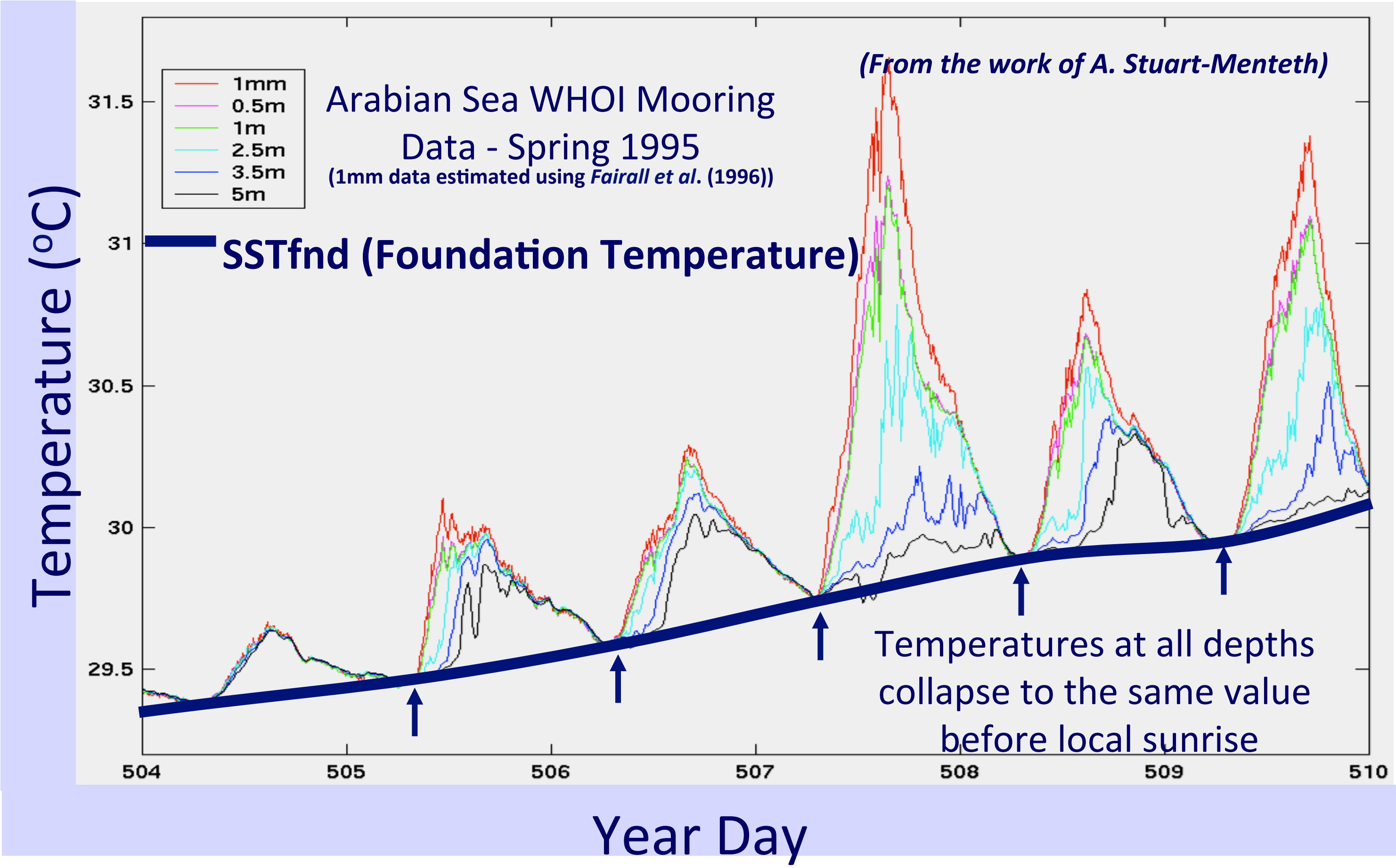
A **thermal gradient is required** to drive heat across the molecular conduction layer



Schematic Temperature Profiles



Diurnal variability



HOW DO WE MEASURE SST FROM SPACE?

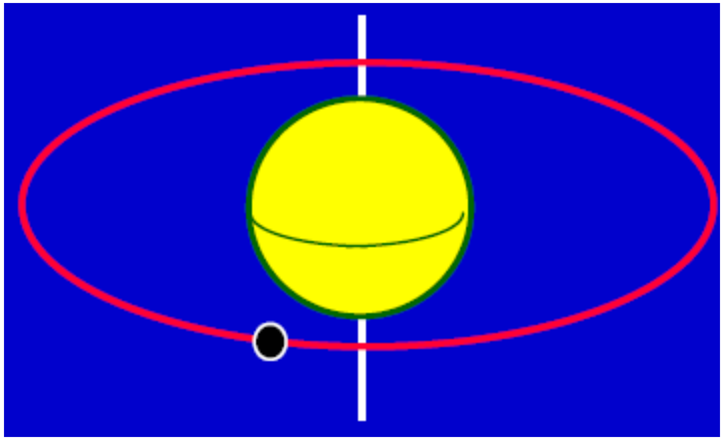
How do we measure SST from Space?

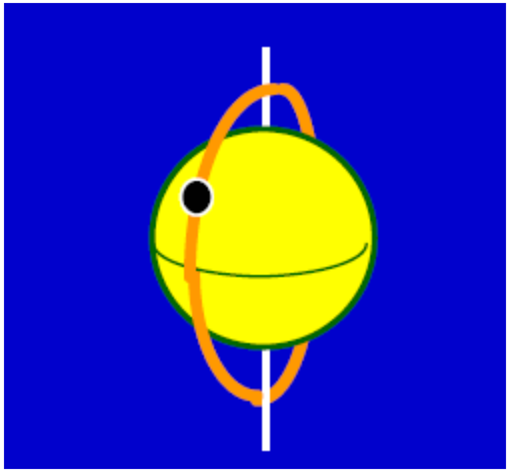
- We need two things:
  - A high-performance radiometer in Space
  - An effective Atmospheric Correction

- Orbits
- Radiometry
- Atmospheric Corrections
- Microwave or Infrared wavelengths
- Example SST sensors

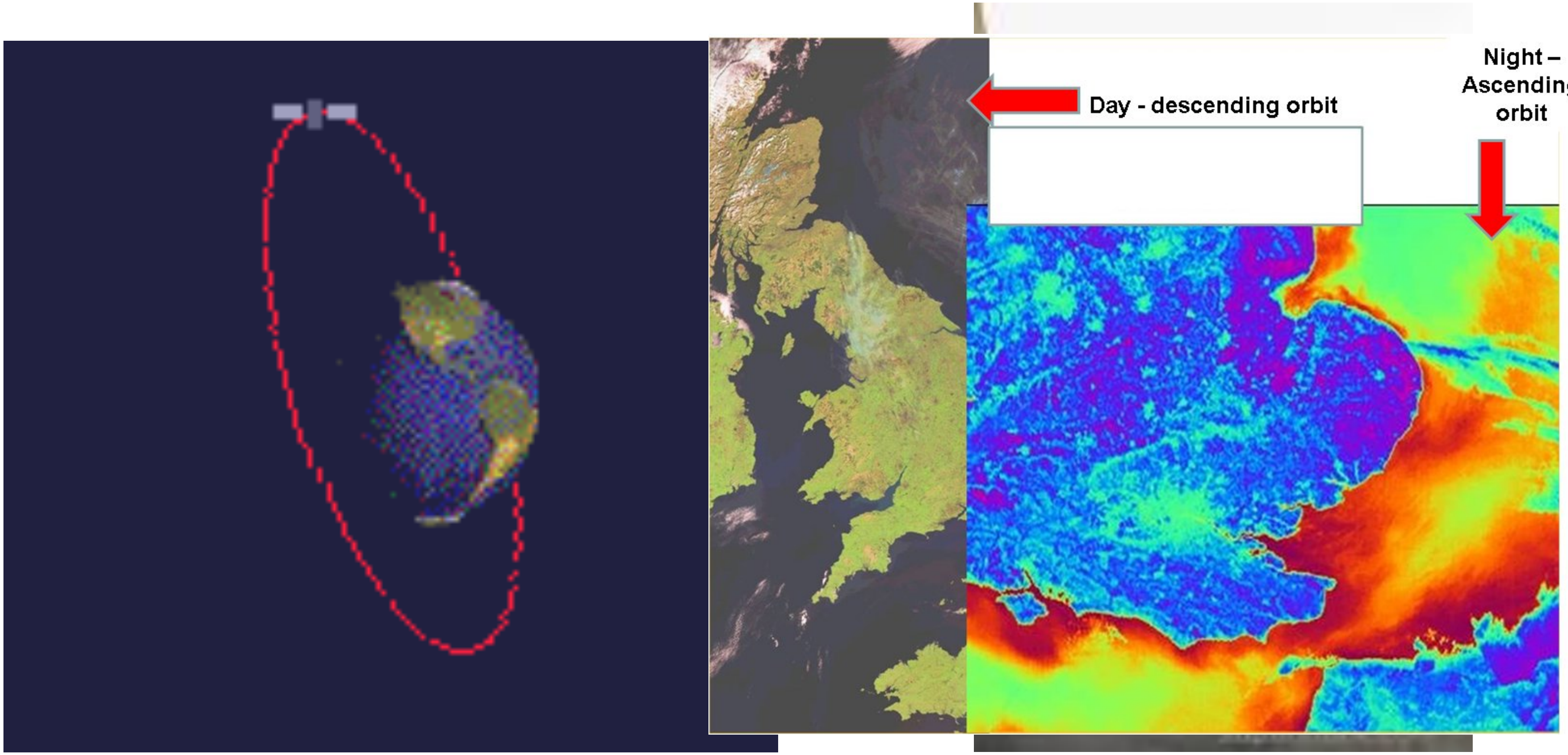
Two main types of orbit for remote sensing

- Geostationary orbits
  - For an orbital period of one sidereal day (*T*= 23.93 hours), the satellite travels with the earth.
  - This requires *r* = 42290 km,
    h = 35910 km.
  - The satellite remains over the equator.
- Near-polar orbits
  - *T* is approximately 100 min.
  - *H* is 700 to 1000 km.



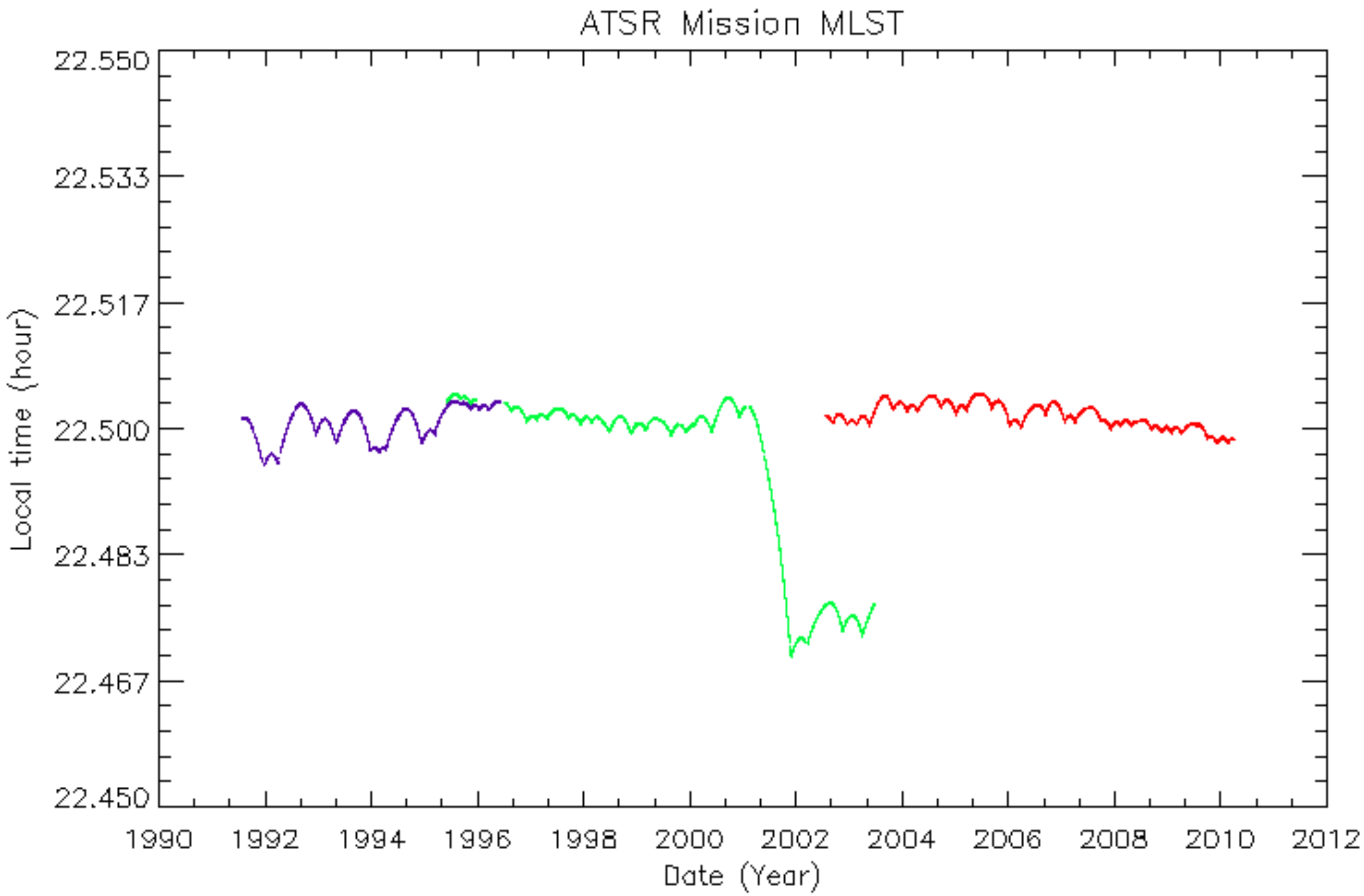


The Sun-Synchronous Orbit



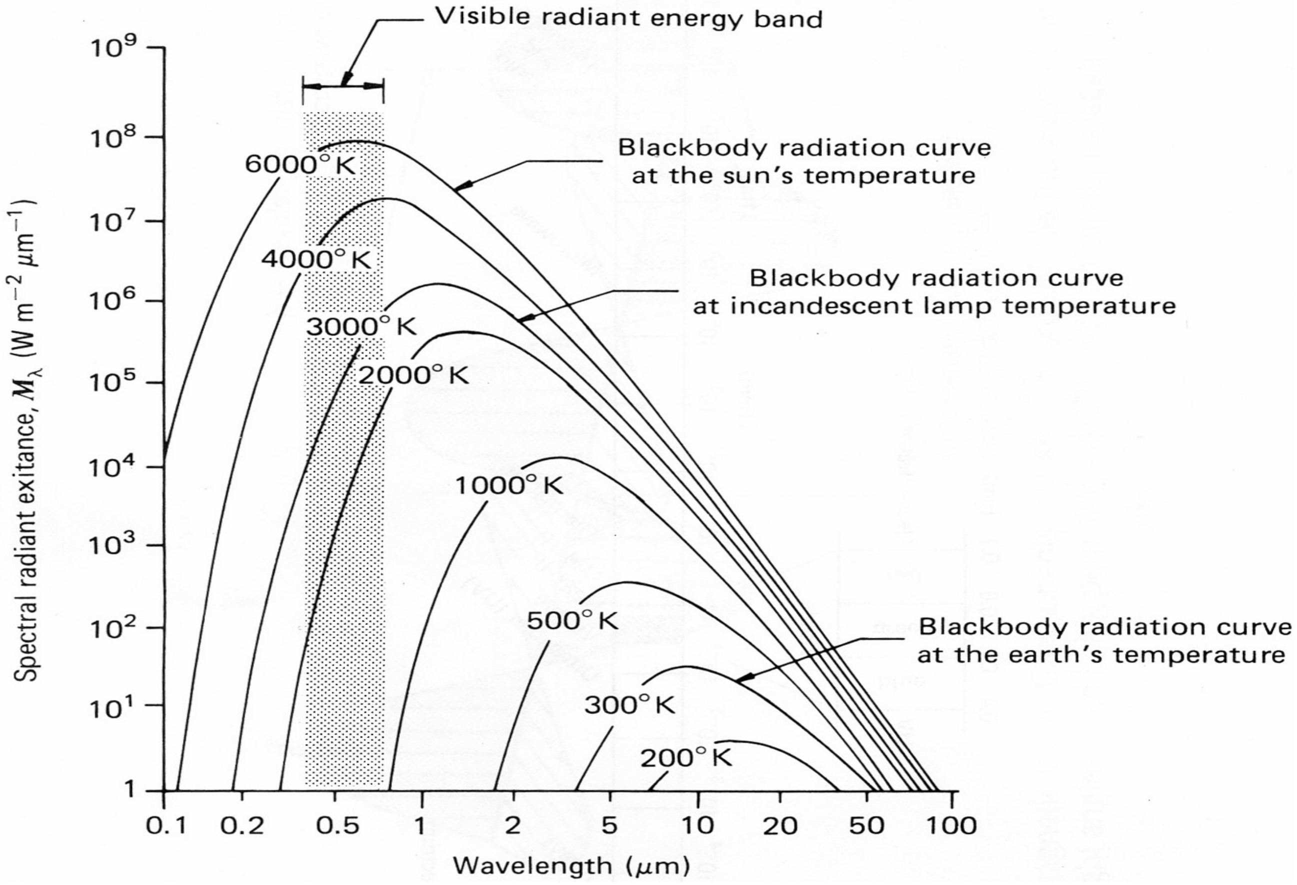
Challenge: Find the mistake!

Orbit stability



Note: AATSR has had 30 minutes added to each time

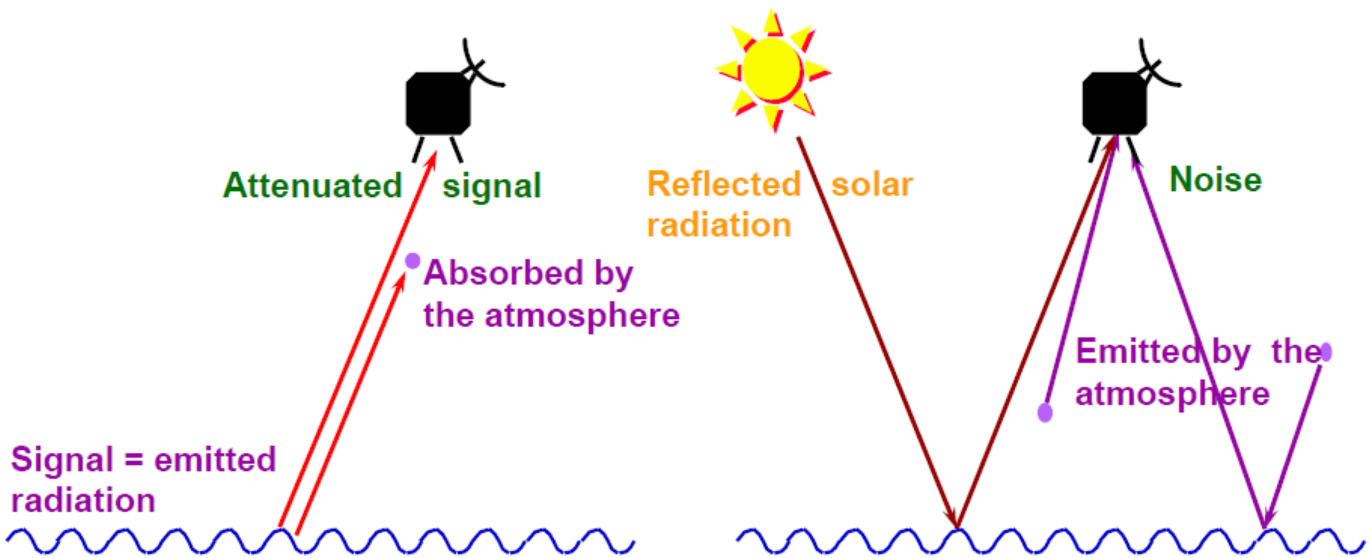
Spectral Distribution of Energy Radiated from Blackbodies at Various Temperatures



Ifremer

Atmospheric interactions with radiation

esa



ε for sea water is about 0.99 so the water-leaving signal is almost the black body radiation.

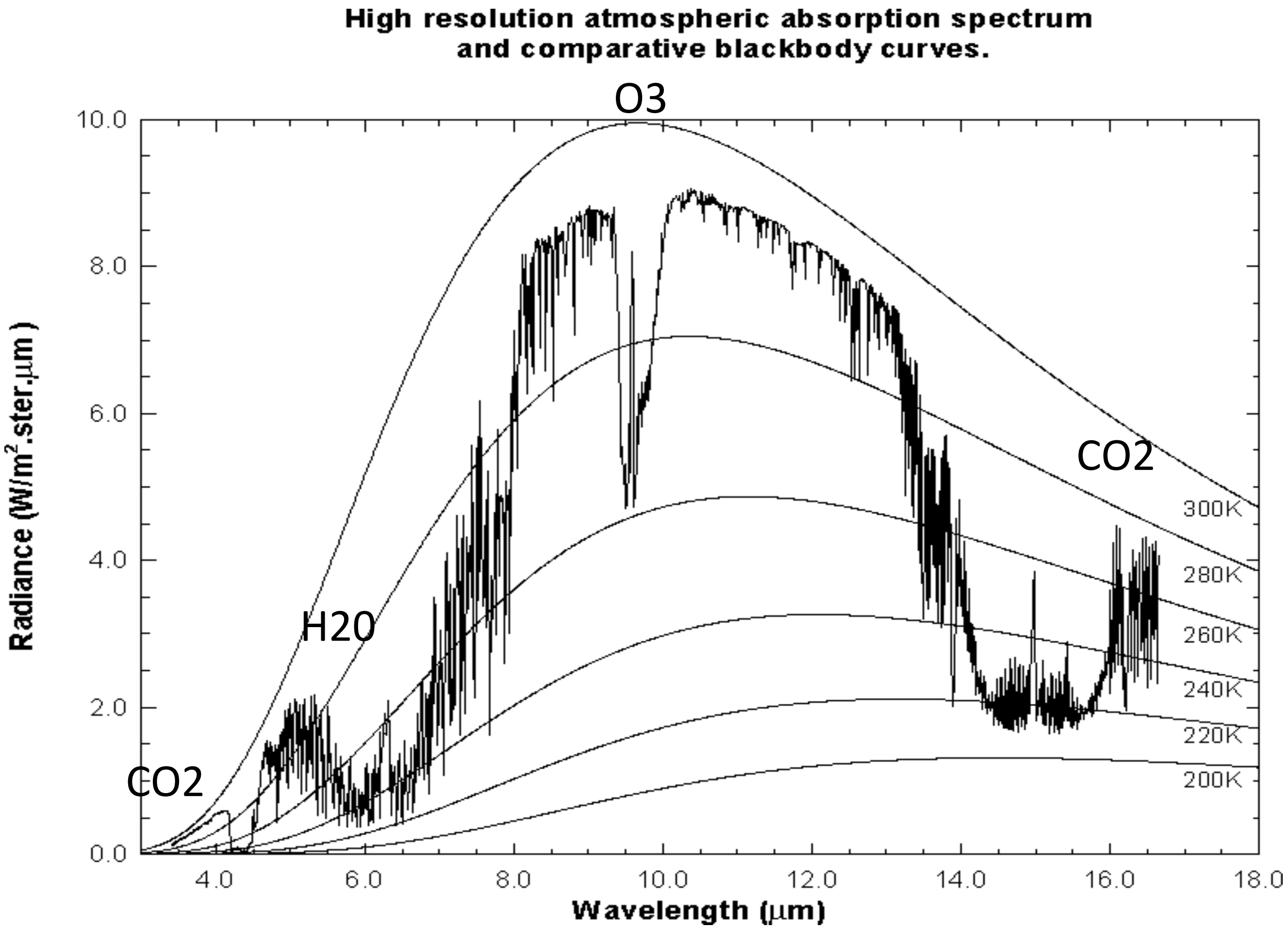
Reflectance is (1 -ε) which is very small, so solar reflection is negligible at 11 microns.

Thermal emission is approximately Lambertian, but it may be affected by surface foam and films.

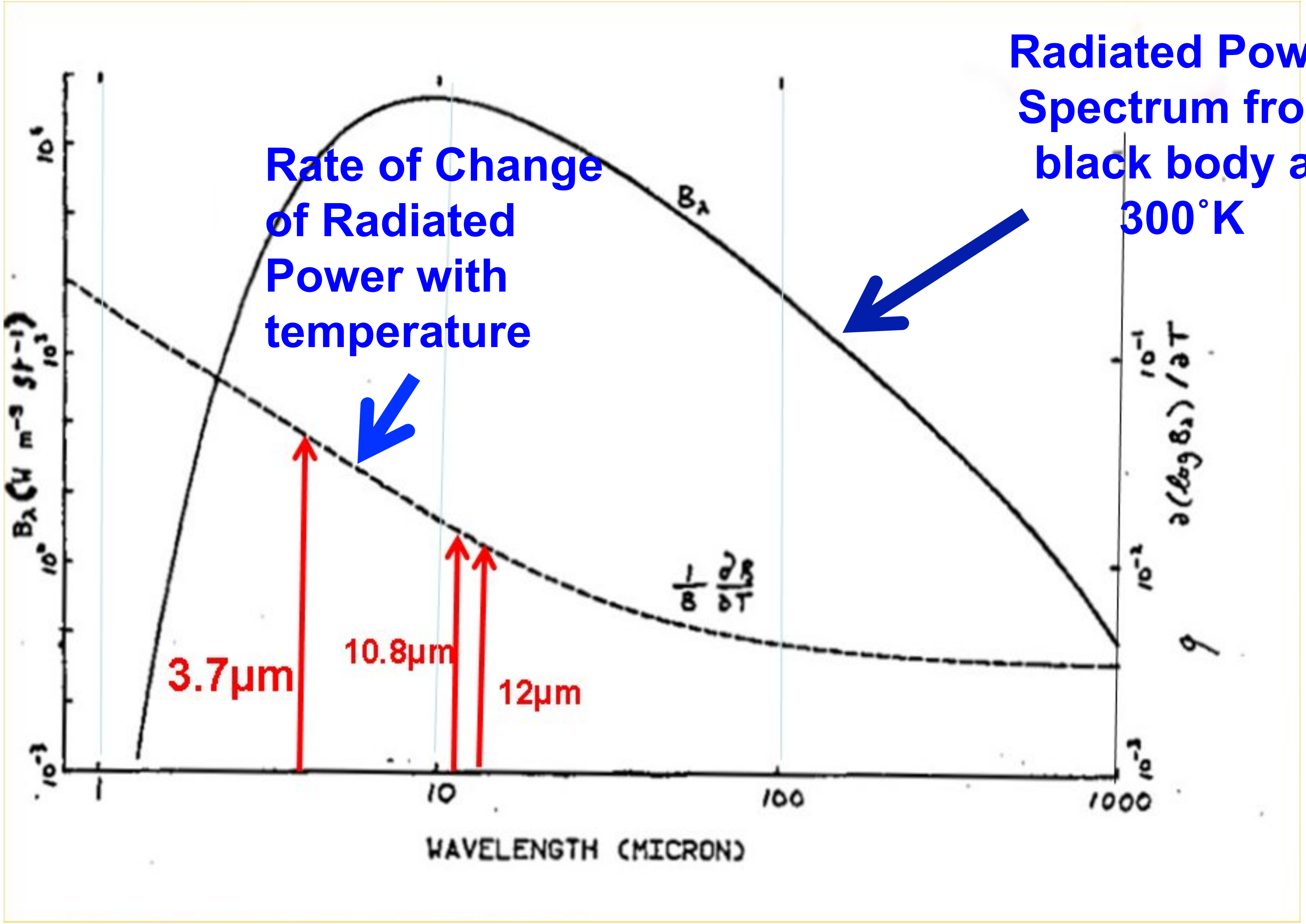
Thermal emission by the atmosphere is the greatest source of atmospheric noise.

Atmospheric effects

Earth emitted spectra overlaid on Planck function envelopes



Planck Function – Temperature Dependence



Satellite SSTs at a glance

Infra-red observations

- Spatial resolution: 1 to 10 km
- Single pixel precision: 0.15 to 0.5 K
- Accuracy (bias): <0.1 K to few tenths
- Limitations: cloud cover
- Temporal resolution per sensor (not accounting for clouds): sub-hourly (geo), ~ twice-daily (polar)
- Linear Radiometric Sensitivity
- Since 1981

Passive microwave observations

- Spatial resolution: 50 to 100 km
- Single pixel precision: 0.5 K
- Accuracy (bias): few tenths
- Limitations: rain, 50 km margin around land and ice, radio frequency interference
- Temporal resolution per sensor (not accounting for contaminants): ~ twice daily
- High Radiometric Sensitivity (T^5 – T^{15})
- Since 1997

- We need to know:
- What we are looking at (field of view)
- At what wavelengths we are looking (spectral response)
- How much radiant power are we receiving (radiometric calibration)

IR Radiometric Calibration Model

- Scene radiance at T(K) is a linear function of the measured signal

  $L_{scene} = Gain C_{scene} + Offset$

- Using Signals from Hot and Cold Blackbodies we can obtain *Gain* and *Offset*

  $Gain = (L_{hot}-L_{cold})/(C_{hot}-C_{cold})$ and

  $Offset = (L_{hot}C_{cold} - L_{cold}C_{hot})/(L_{hot}-L_{cold})$

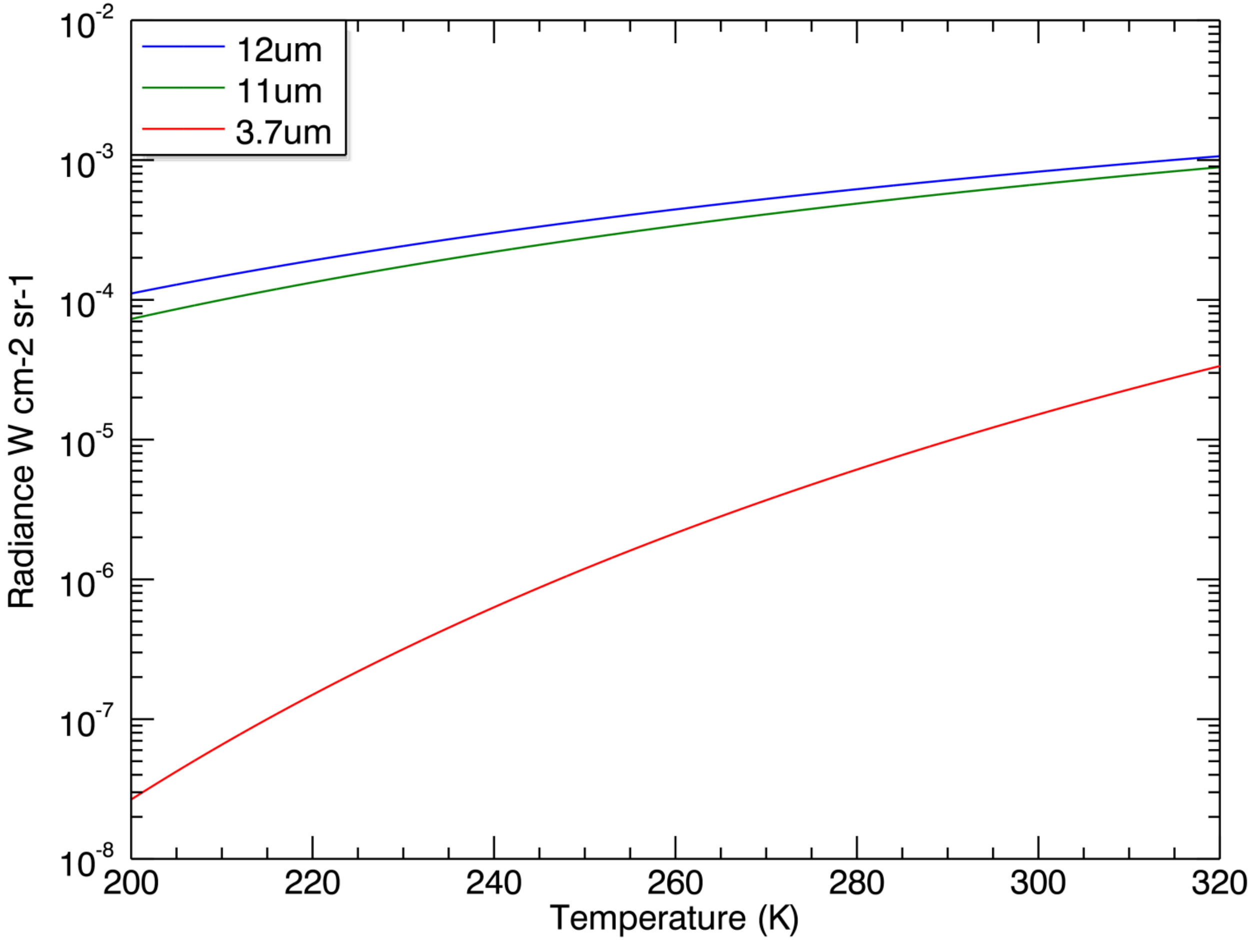
- L_{hot} and L_{cold} are the blackbody radiances derived using the Planck function from the measured blackbody temperatures and emissivities.

  $L=\varepsilon P(T_{BB}) + (1-\varepsilon)P(T_{inst})$ and

  $P(T) = \int R(l) 2hc^2/(\lambda^5 exp(hc/lkT)-1)dl$

- In practice we use look-up tables to convert from temperature to radiance and vice versa.

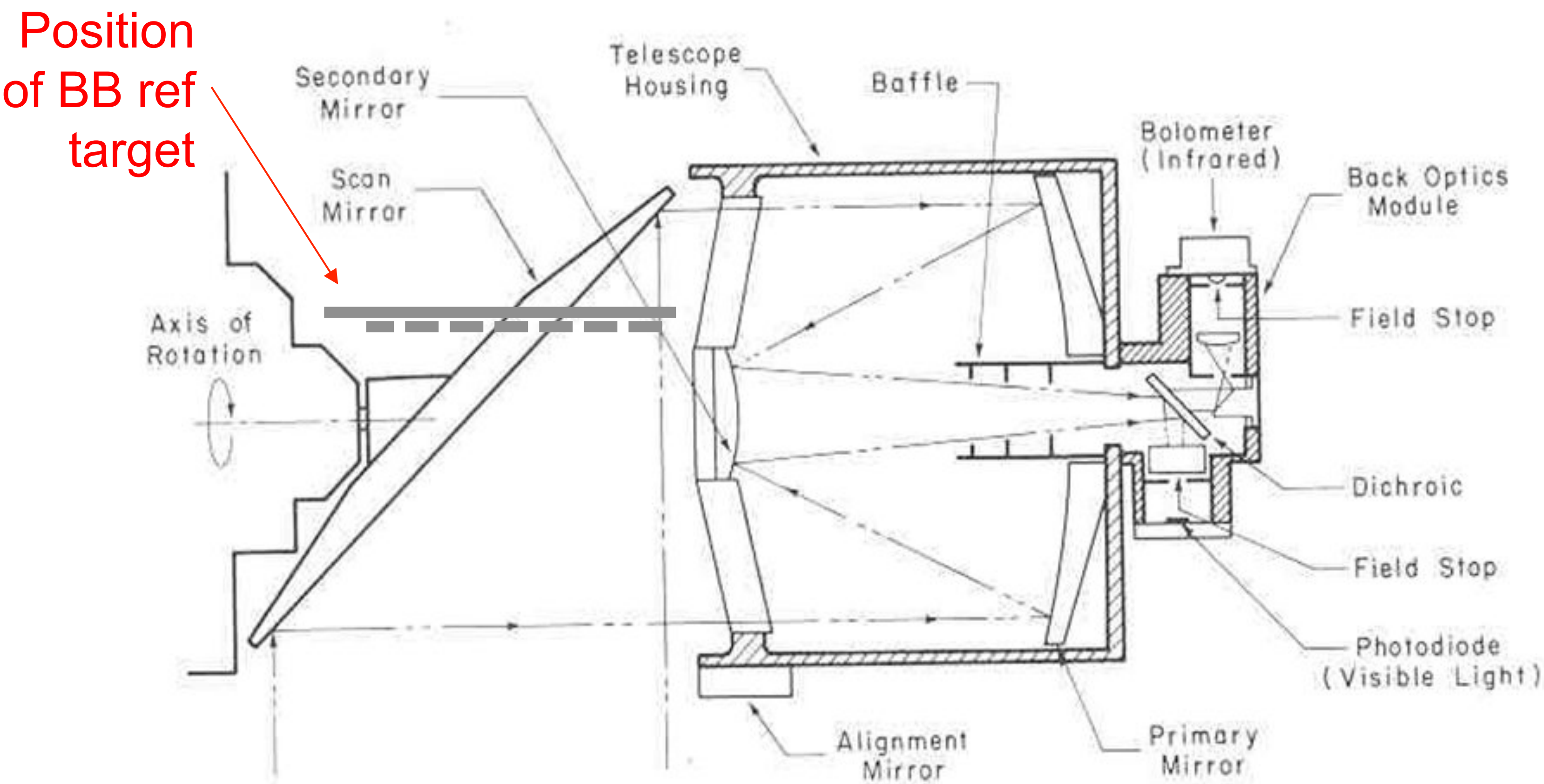
Radiance vs. Temperature



Example of space-borne radiometer: AVHRR

- Designed in 1960’s to see the motion of clouds
- World’s first general-access Earth imager
- Telescope to define FoV
- Filters to define spectral response of detectors
- Single temperature reference target plus a space view to define radiometric standards

Layout of AVHRR - Simple and Effective!



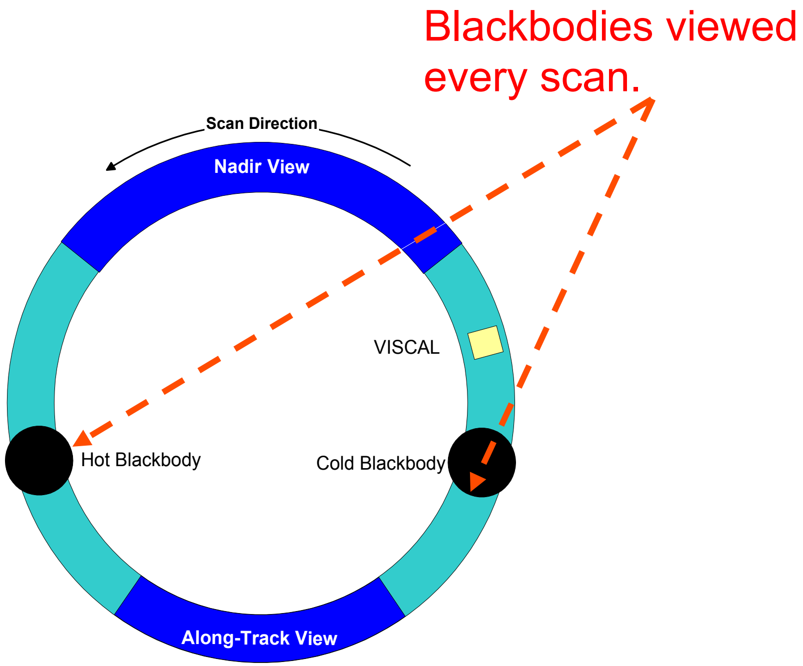
Scan Mirror **Telescope** **Detector**

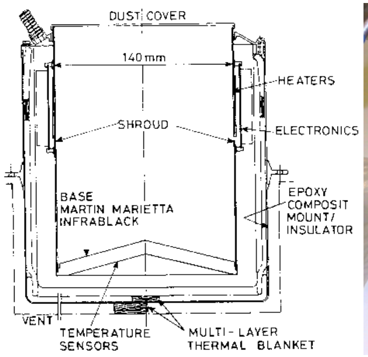
Example of space-borne radiometer: ATSR

- ATSR – Along-Track Scanning Radiometer
  - ASTR on ERS-1
  - ATSR-2 on ERS-2
  - AATSR (Advanced ATSR) on Envisat
- Only spacecraft radiometer optimised for SST measurements

ATSR IR Calibration

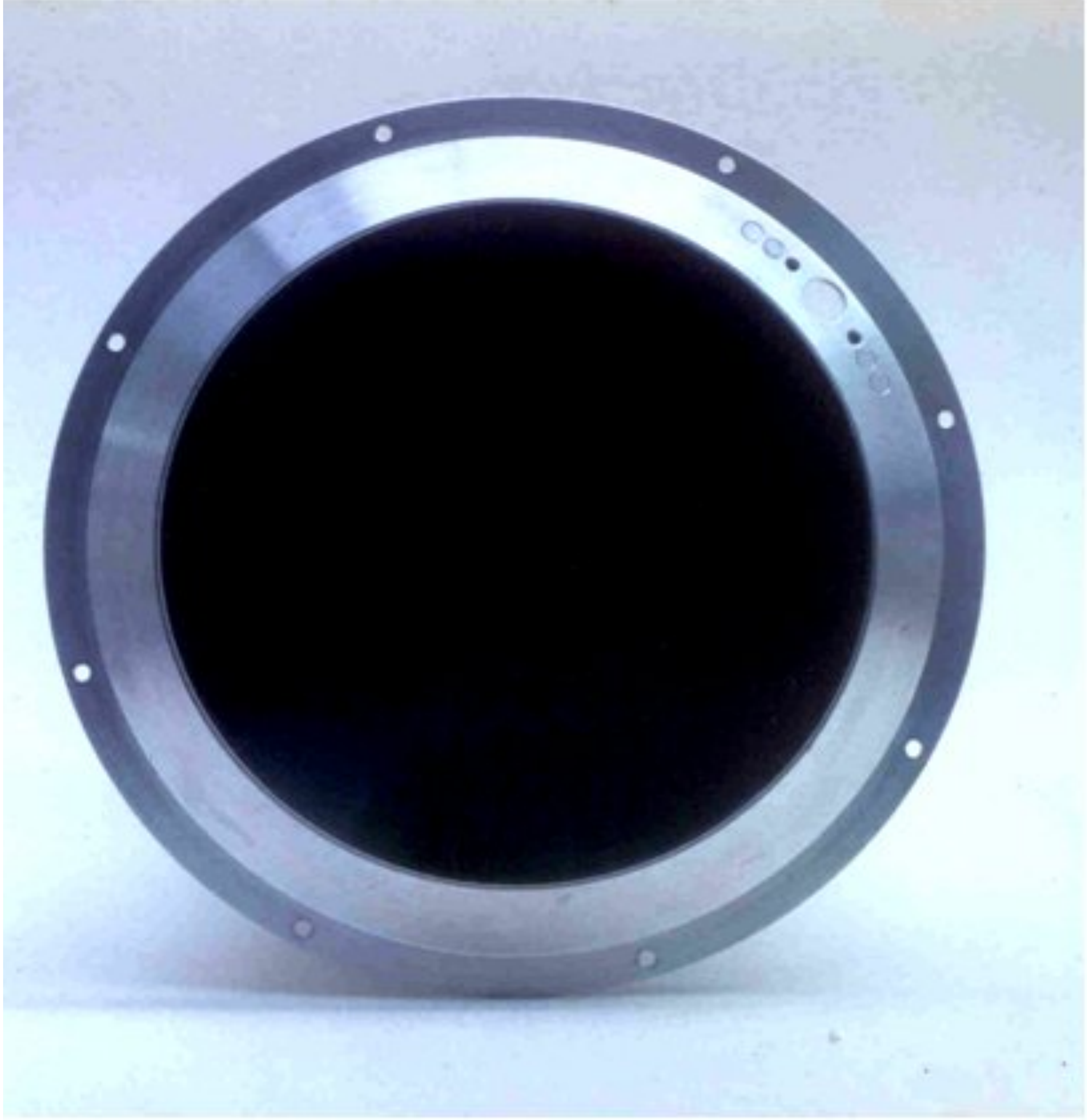
- 2-point scheme covering the range of expected SST
  - Cold bb ~300K
  - Hot bb ~256K (floating at optics temperature)
- High Emissivity >0.999
- Precision Thermometry
  - 5 baseplate sensors
  - Calibration traceable to ITS-90
- Illuminates the full optical chain.
- Calibration system does not involve the use of ‘special’ modes, mechanisms or additional optics.





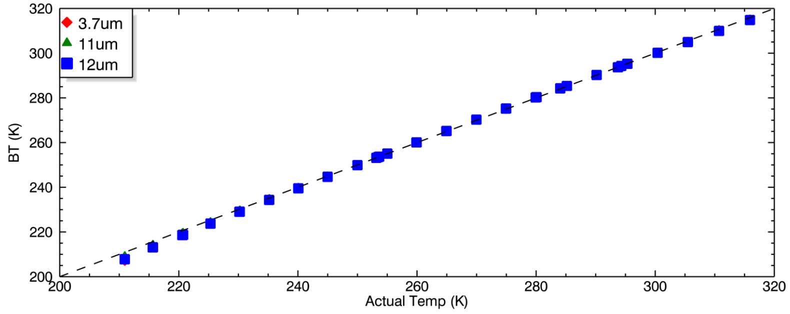
An ATSR on-board Black Body

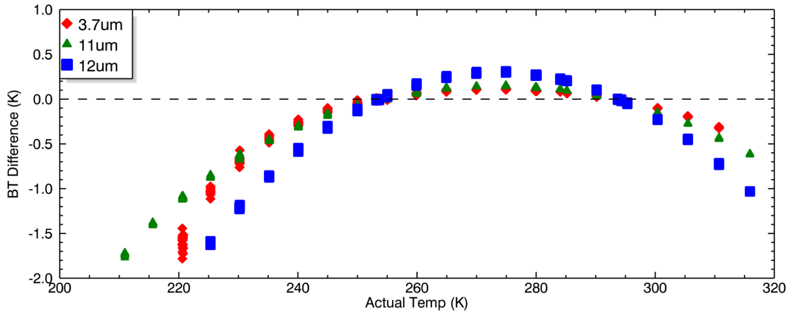
Peering into the Void - How Black is Black?



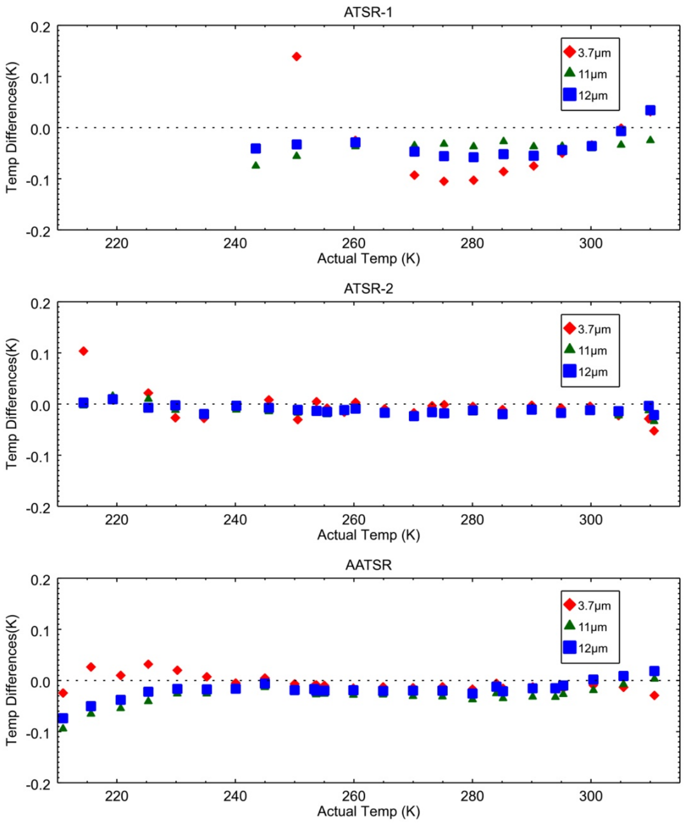
Calibration vs. Target Temperature

Before correction





After correction



A single orbit record of AVHRR Black-body temperature passing the terminator

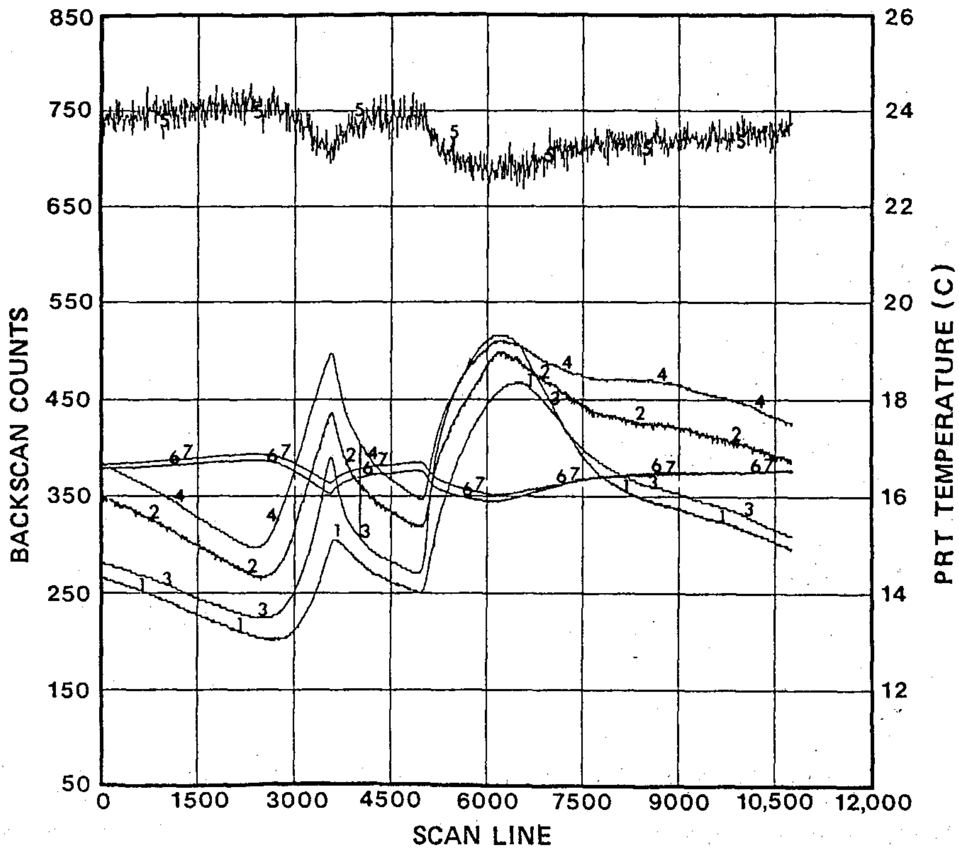
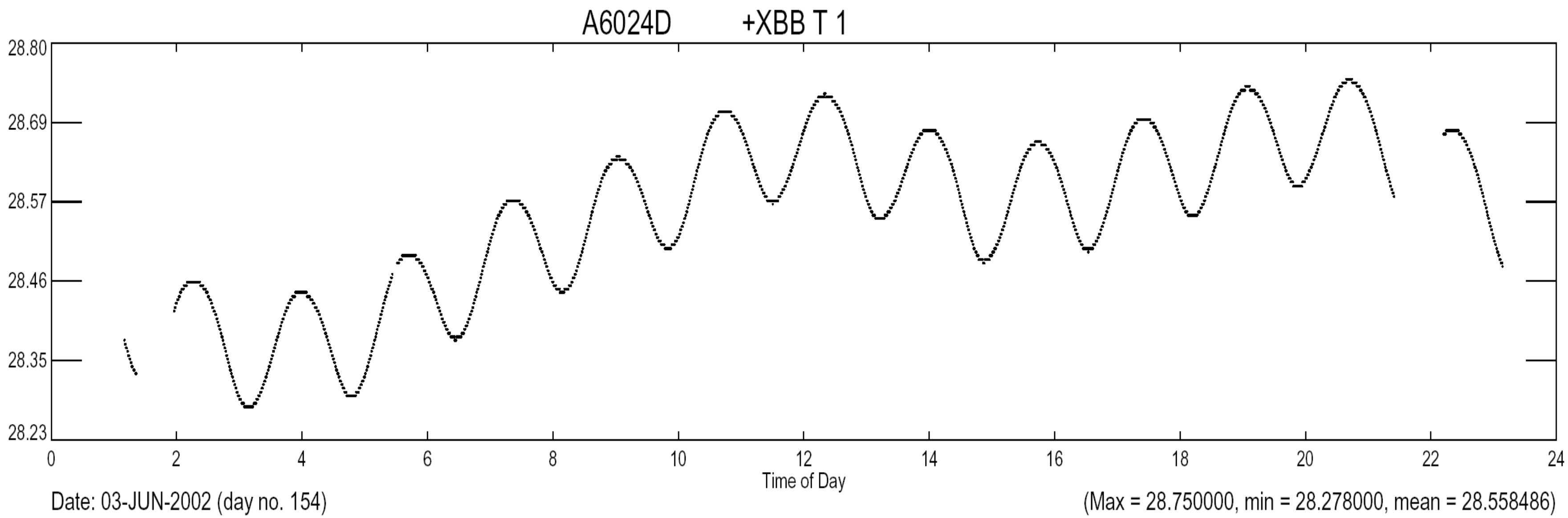


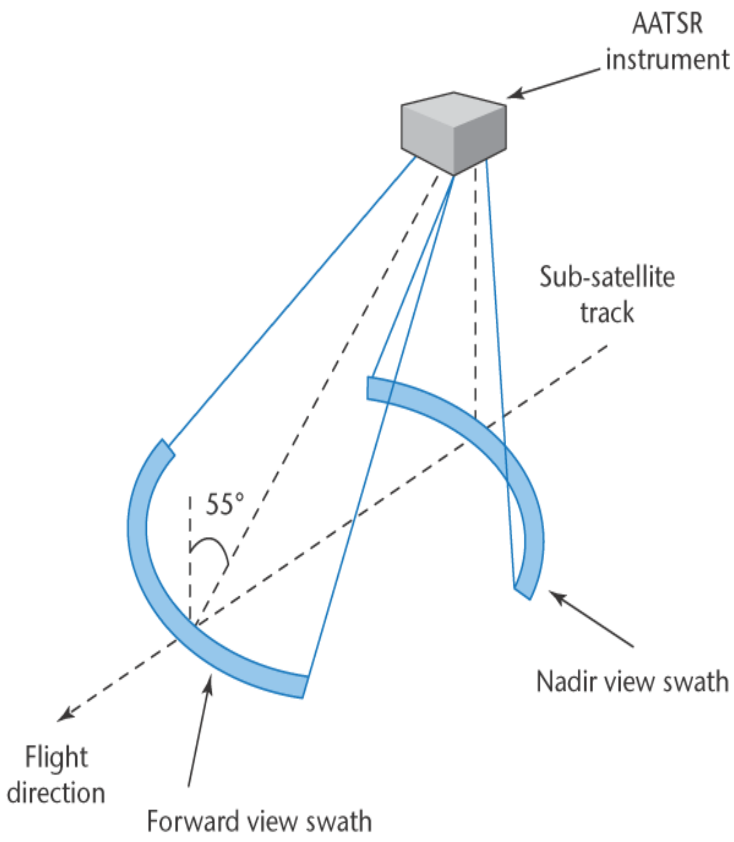
Fig. 6. Time series plot of observed PRT temperature for one orbit on NOAA 7. These data were taken on October 2, 1984, starting at 1732 UT. Numbers 1–4 identify temperatures for PRT's 1–4; temperature values are indicated on the right ordinate. Numbers 5, 6, 7 identify backscan counts for channels 3, 4, 5, respectively; count values are indicated on the left ordinate.

AATSR Black-body Temperature records showing variations over one day with near-sinusoidal orbital variations superimposed

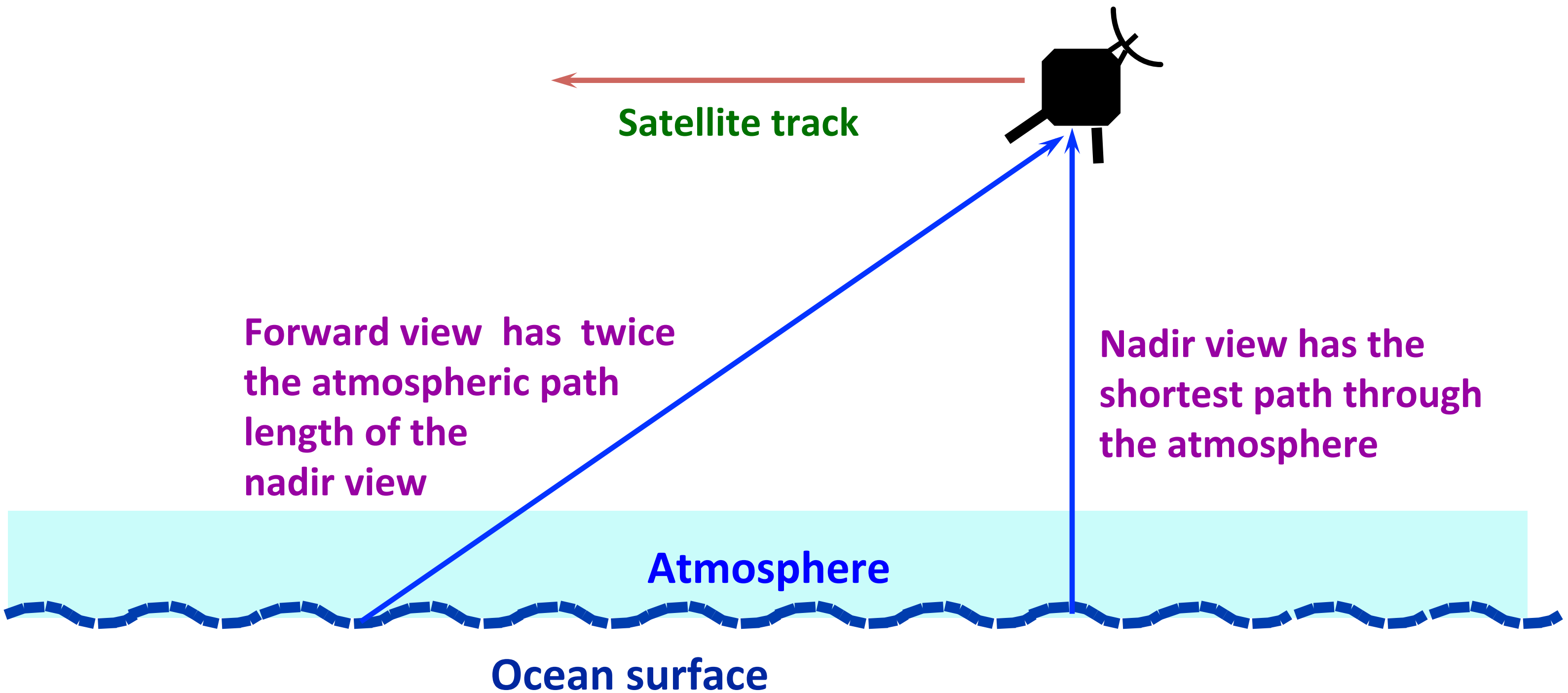


Along Track Scanning Radiometers

- Series of three
- Dual view
- Two-point high-quality black-body calibration
- Low noise detectors
- Accurately characterised spectral responses



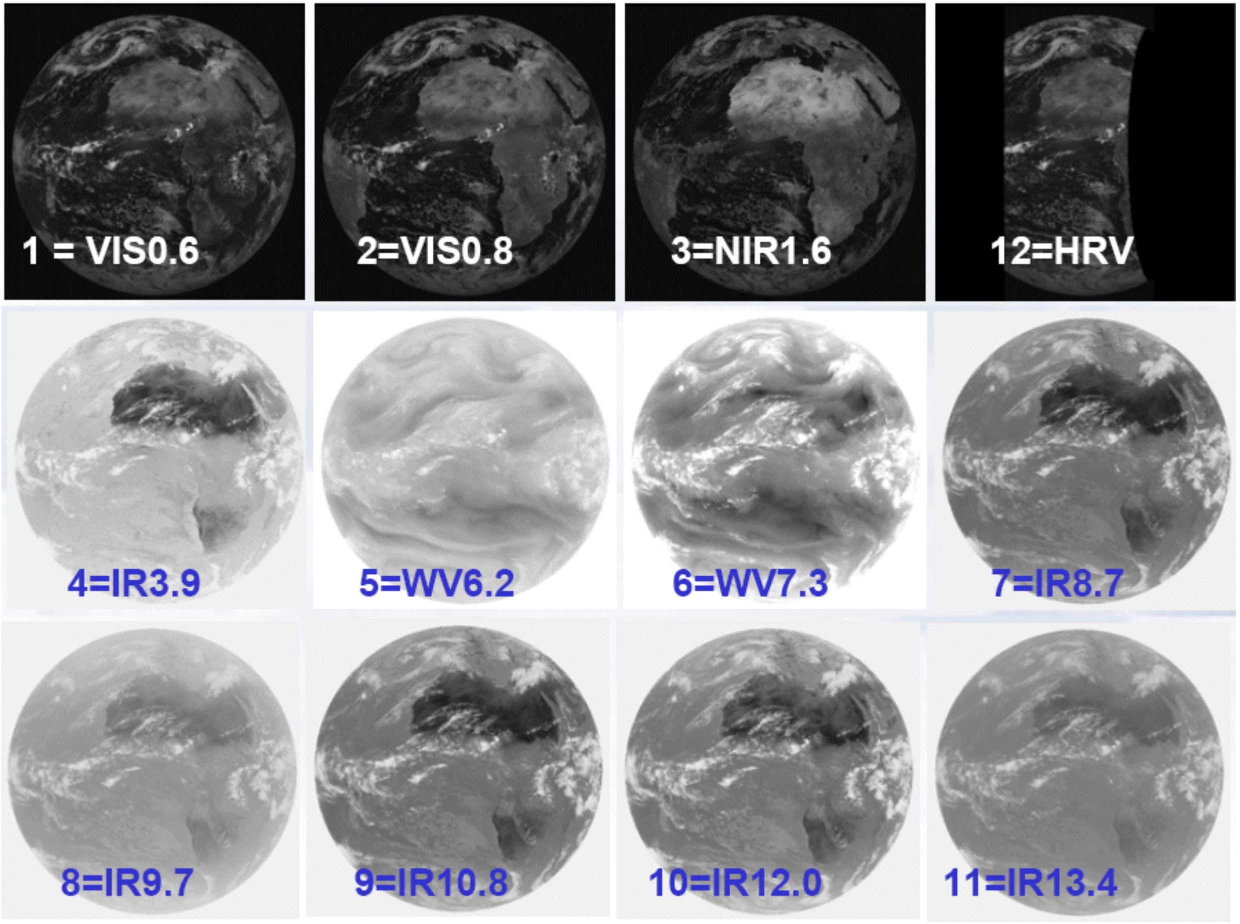
Multi-look atmospheric correction



Different views of the same patch of sea (separated in time by ~3.5 min.) through different thicknesses of atmosphere will differ by an amount which depends upon the total effect of the atmosphere on the radiance reaching the satellite.

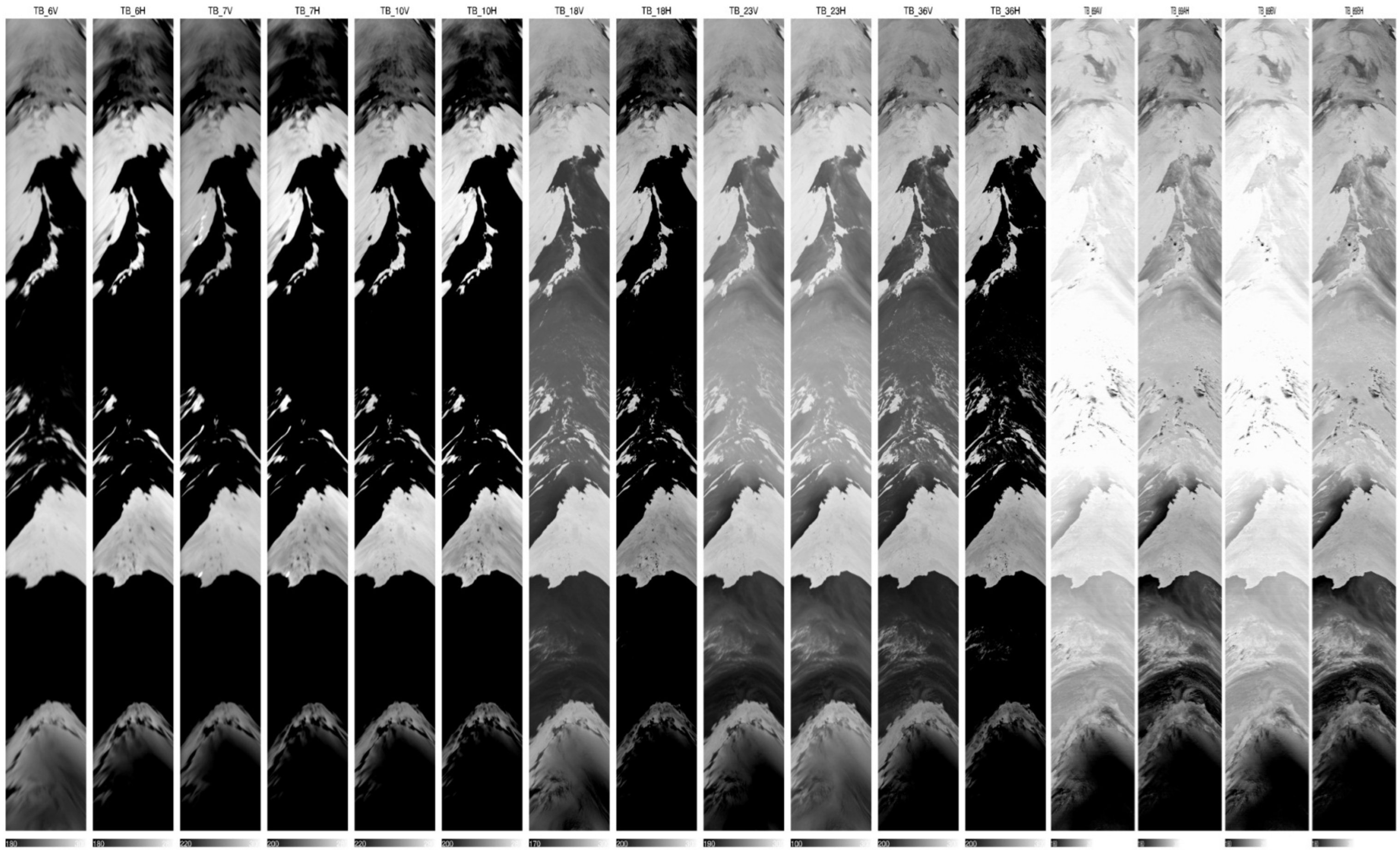
Improved atmospheric correction algorithms use two views (multi-angle) as well as multi-spectral information

SEVIRI spectral images



AMSR2 All Channels

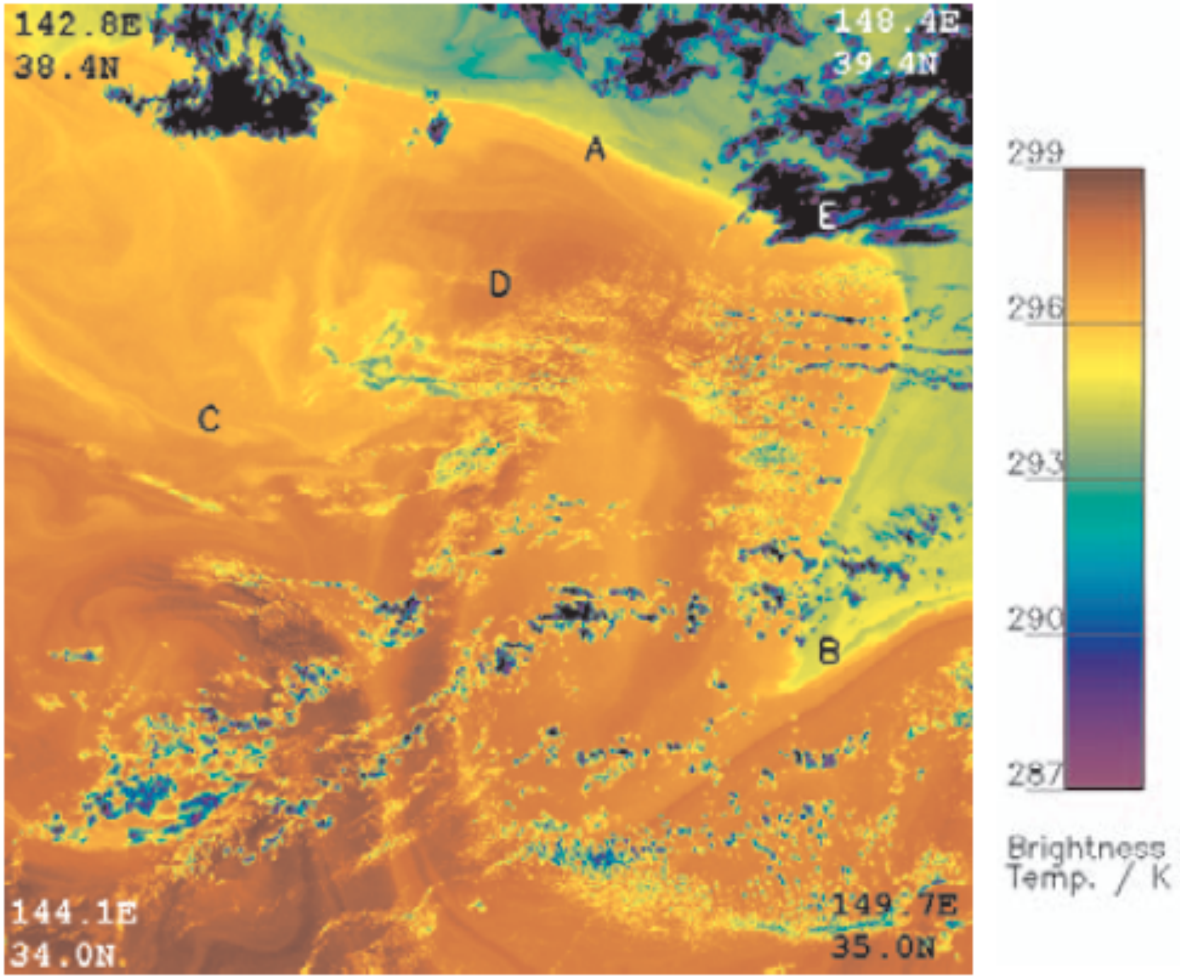
6V 6H 7V H 10V 10H 18V 18H 22V 22H 37V 37H 89AV 89AH 89BV 89BH



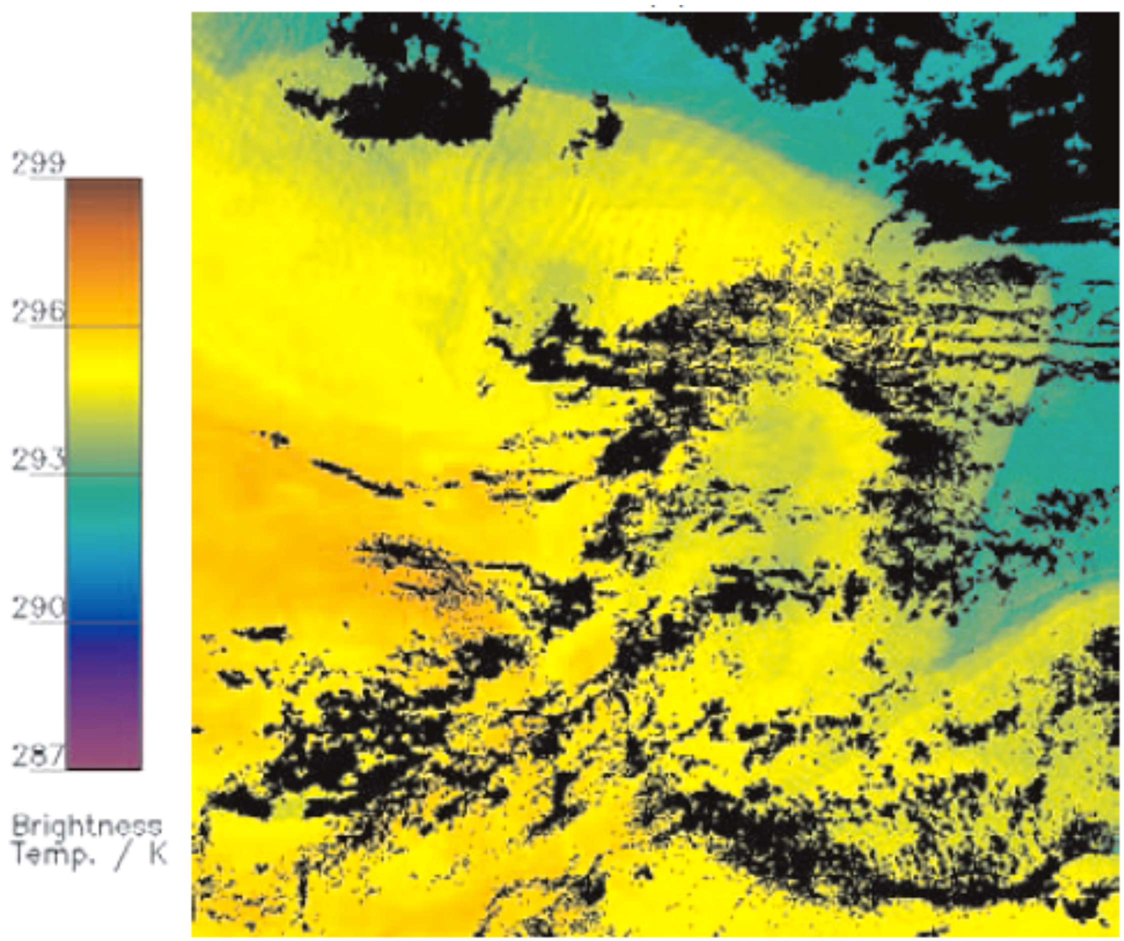
Interpreting imagery (1)

Example of the appearance of 1 km imagery, with SST thermal features and intervening scattered and major cloud

3.7 µm



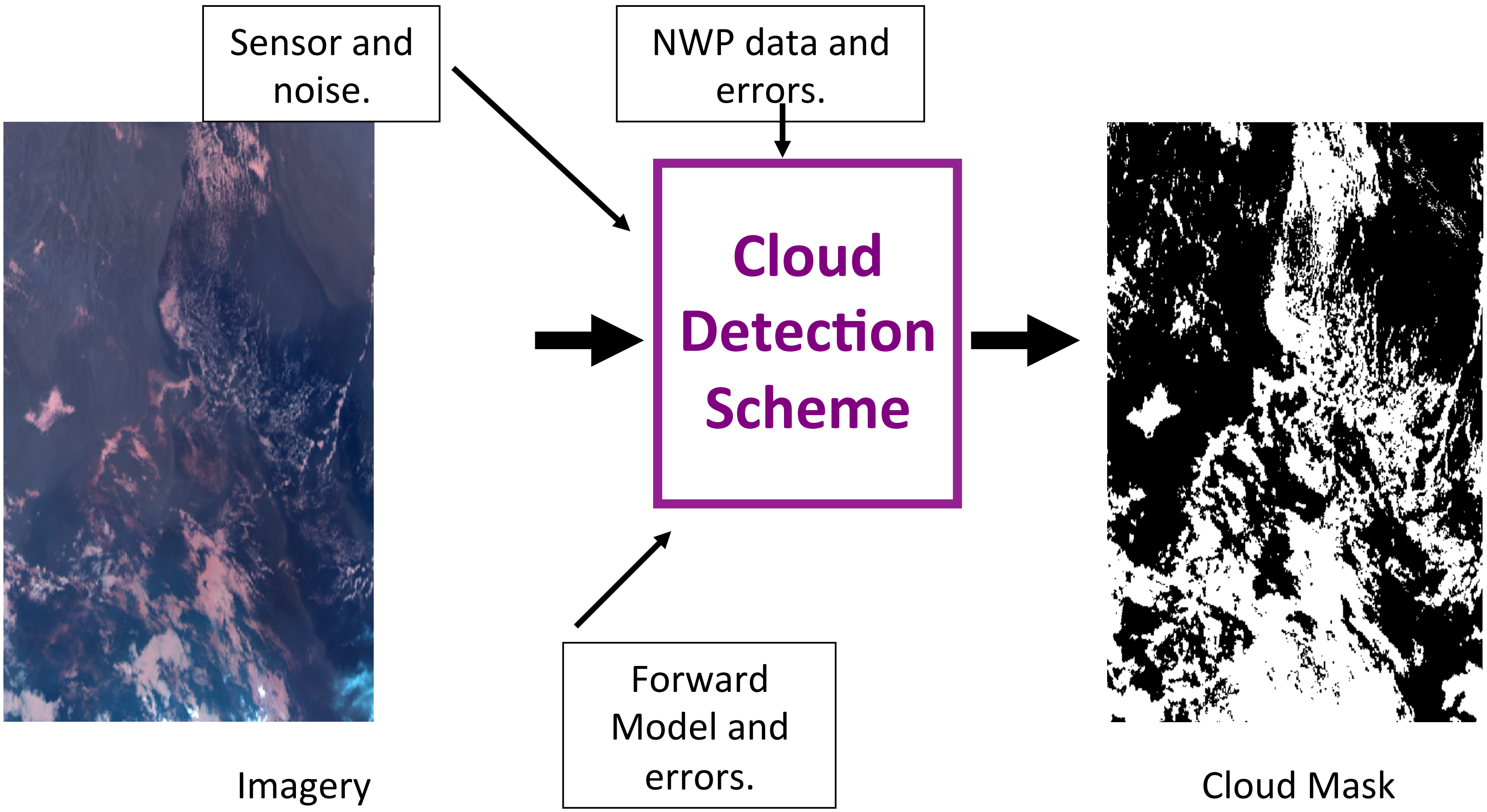
Interpreting imagery (2)



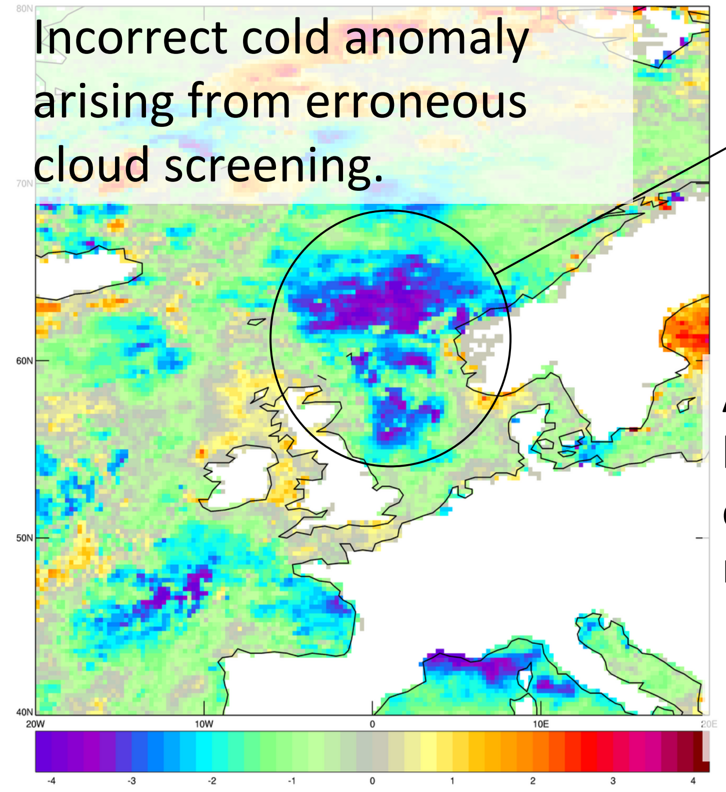
Successfully cloud masked image (same scene, different wavelength)

11 µm

Cloud Detection – very important

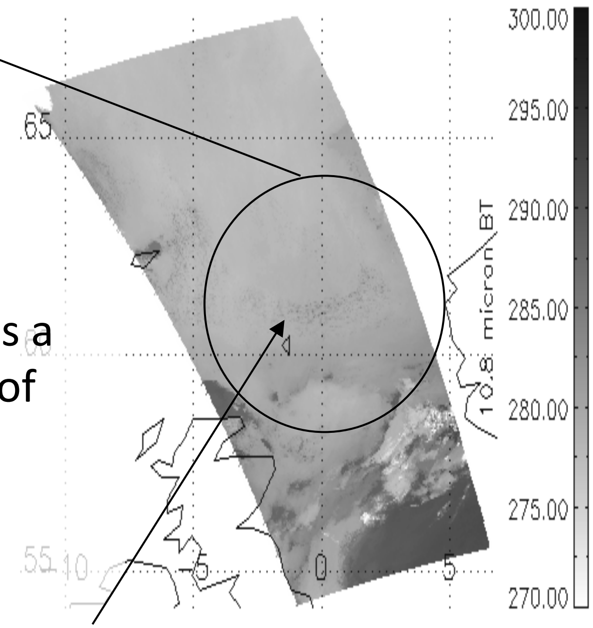


Forecast error due to cloud contamination



OSTIA

AATSR shows a large swath of cloud in this region.



AATSR 10.8 µm BT

ECMWF Forecast - 26/07/11: Northerly winds blowing over the anomaly affected weather in the UK.

*Cloud detection is fundamental to weather and climate applications.

Split window SST equation

$$(SST - T_{11}) = m\left(T_{11} - T_{12}\right) + c$$

$$SST = T_{11} + m(T_{11} - T_{12}) + c$$

Anding and Kauth, 1970 (83 citations)

A procedure is derived for obtaining improved estimates of water surface temperature by … simultaneous radiometric measurements in two wavelength intervals … to approximately ±0.15°C.

SST retrieval approach (1)

BTs, **y**

SSTs, *x*

Least squares regression

Coefficients, **a**

Empirical approach:
regression to in situ

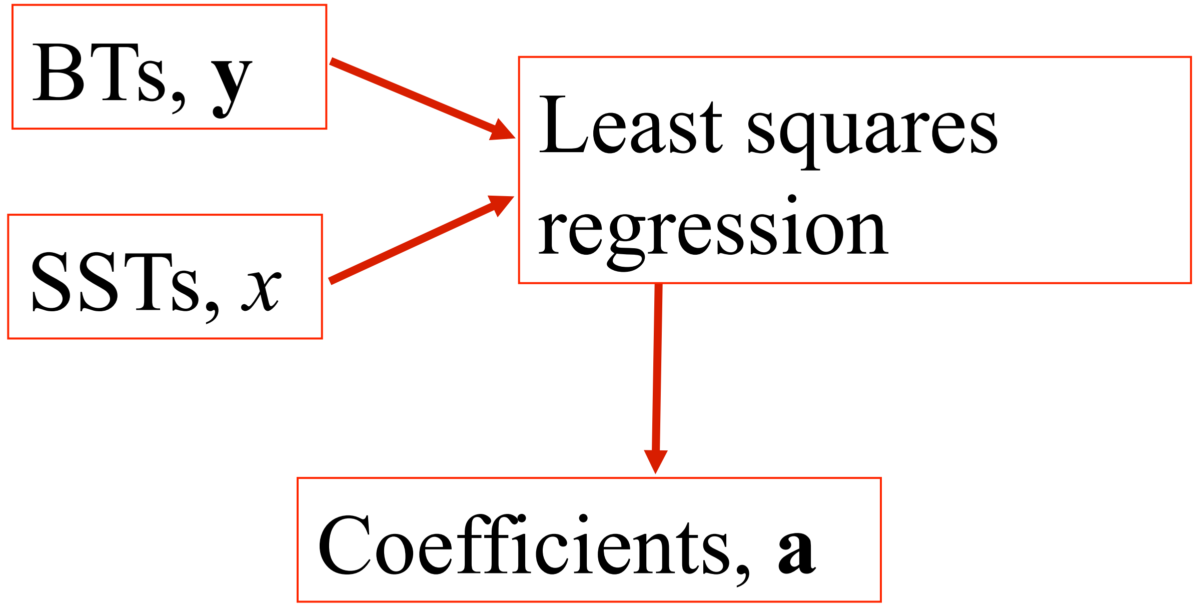
$$\hat{x} = a_0 + \sum_{\text{channels}, c} a_c y_c$$

SST retrieval approach (2)

ECMWF

\+

Radiative Transfer



Physics based approach gives independent SST: feasible since ~2000

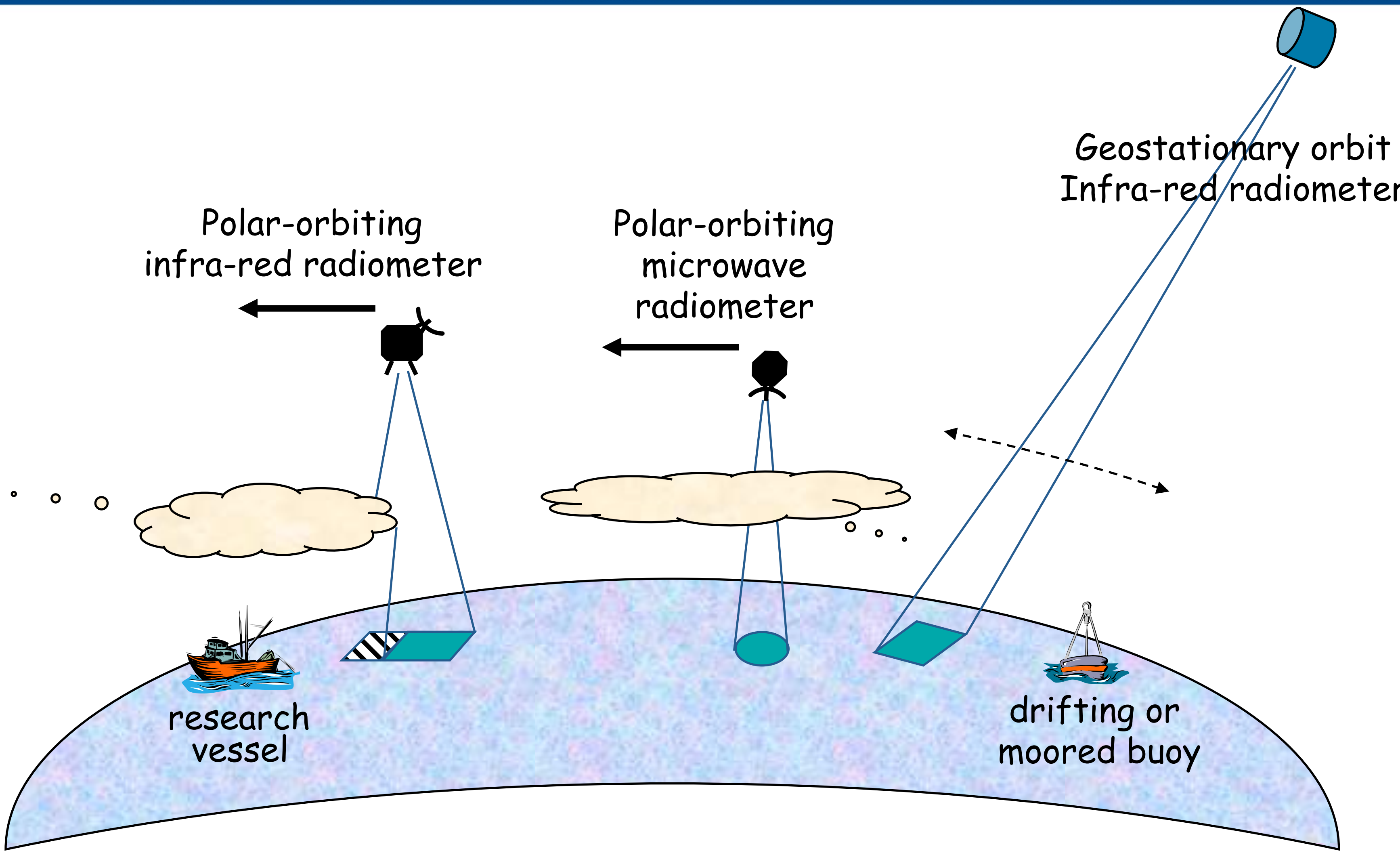
$$\hat{x} = a_0 + \sum_{\text{channels}, c} a_c y_c$$

Progress in SST retrievals

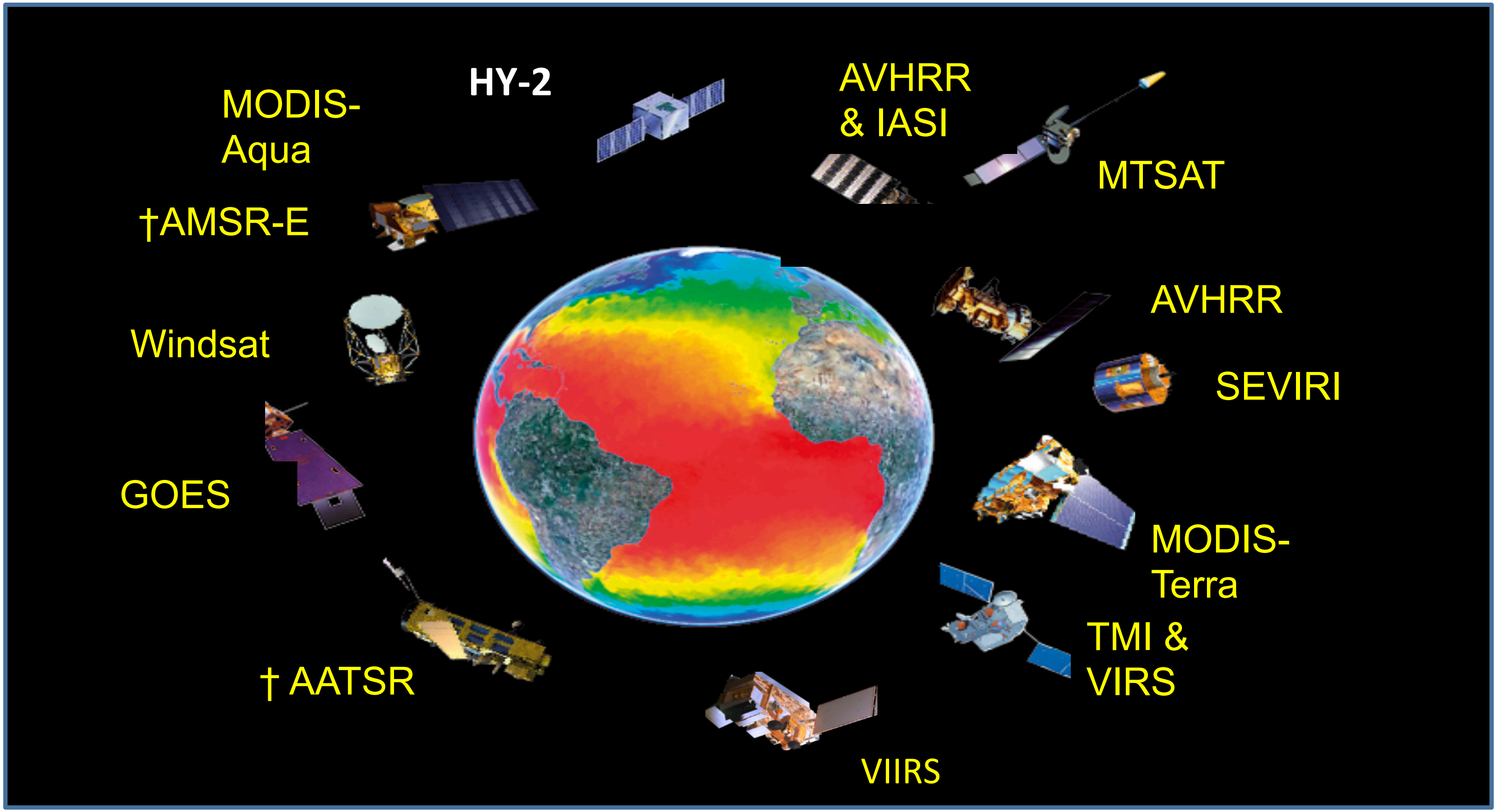
	Retrieval	Cloud detection	Uncertainty model
1st	Empirical regression to buoys	Empirical screening thresholds	Empirical (SSES)
2nd	Regression to RT modelling	Fixed RT screening thresholds	
3rd	Optimal estimation of SST & TCWV	Probabilistic / dynamic RT	Uncertainty model

WHAT CAN WE SEE BY MEASURING SST FROM SPACE?

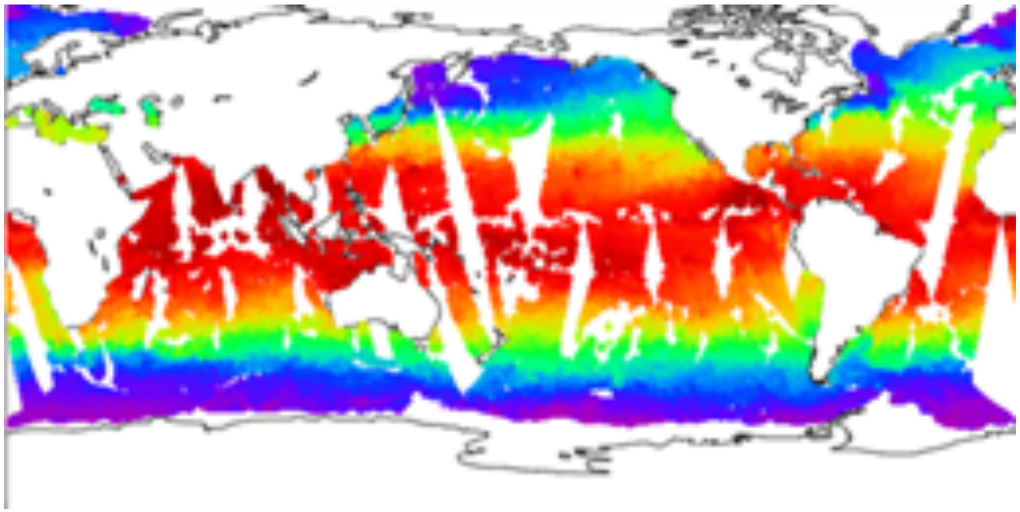
Platforms for measuring SST

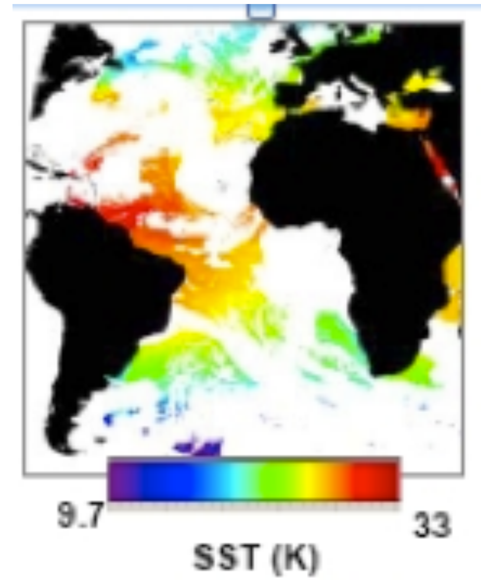


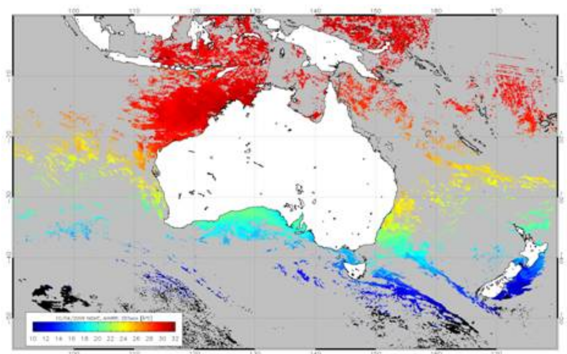
The SST constellation



Level 2 (SSTs as obtained from satellite)



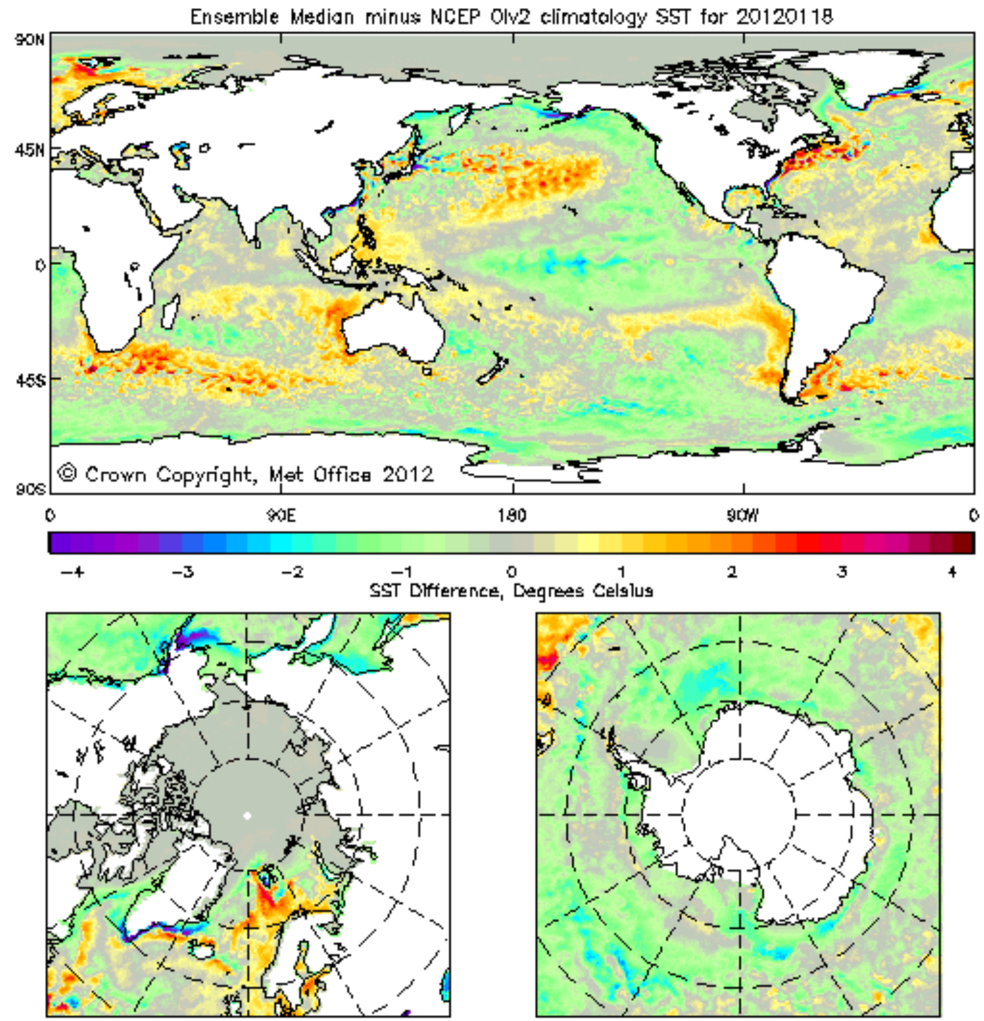




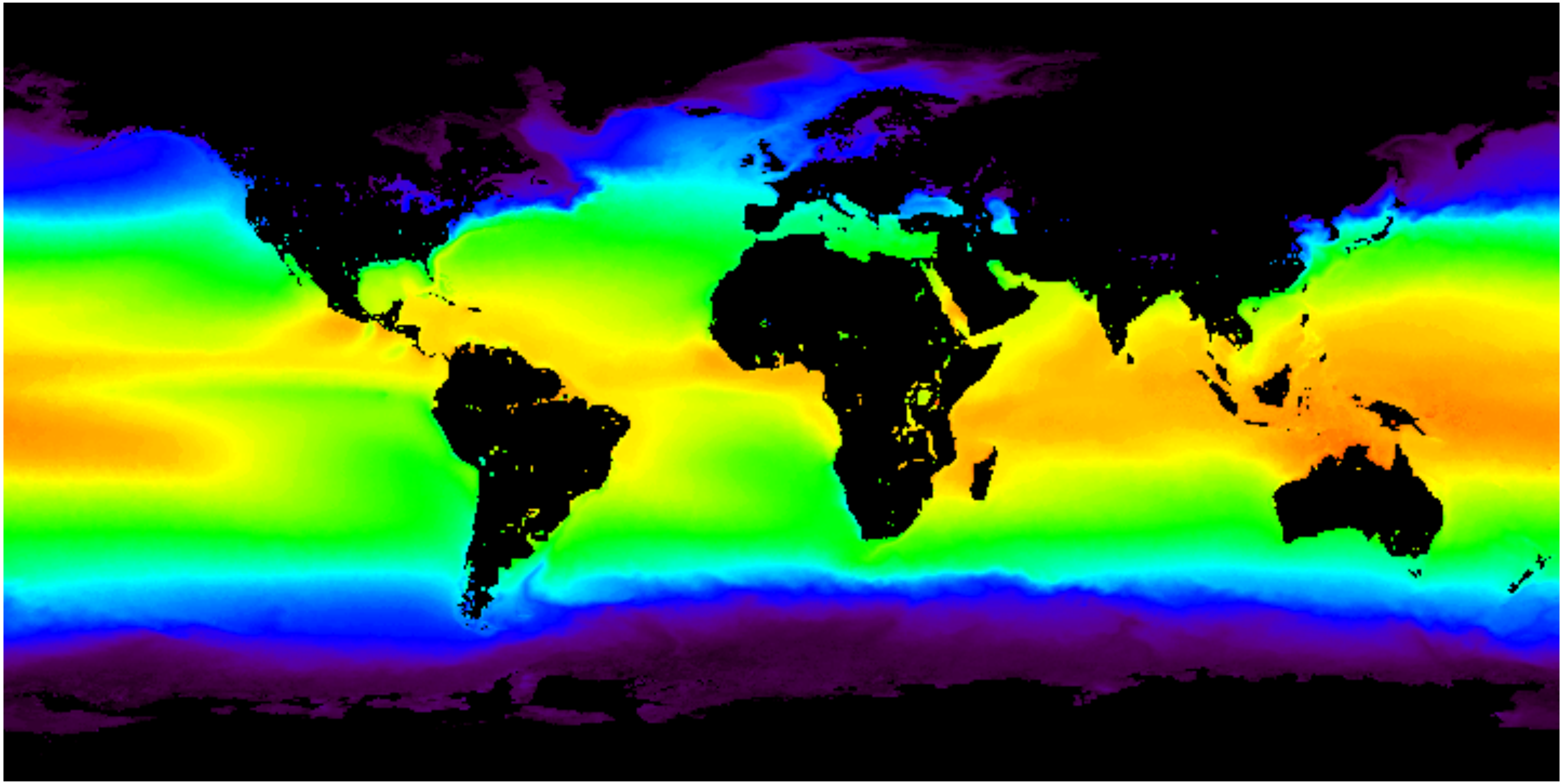
“Level 3” – regularly gridded, perhaps averaged, single sensor

Level 4 or SST analysis

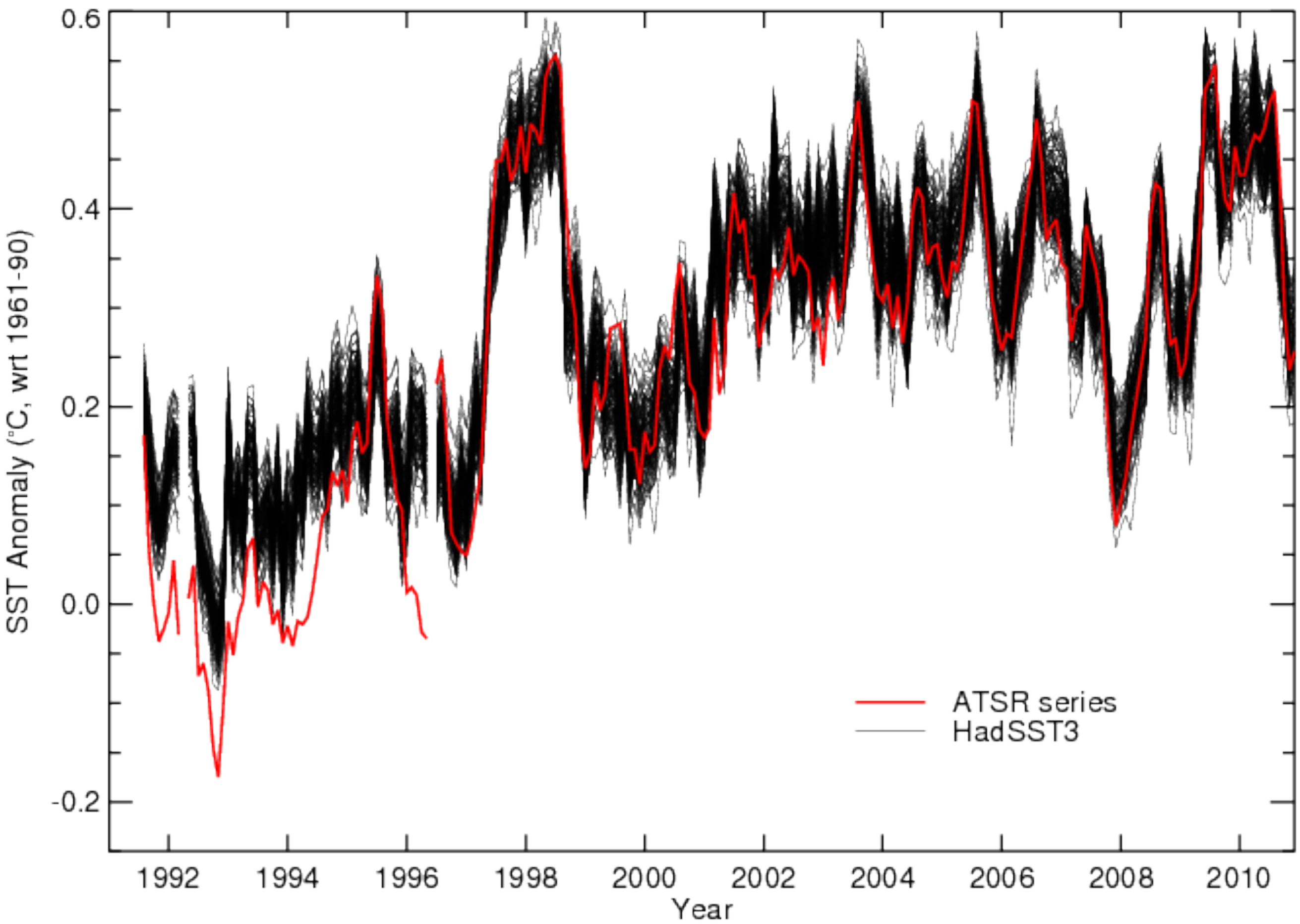
- Gap free (interpolated) and probably derived from multiple sensors
  - I.e., from several L2 and/or L3 data streams



ATSR ARC SST Climatology



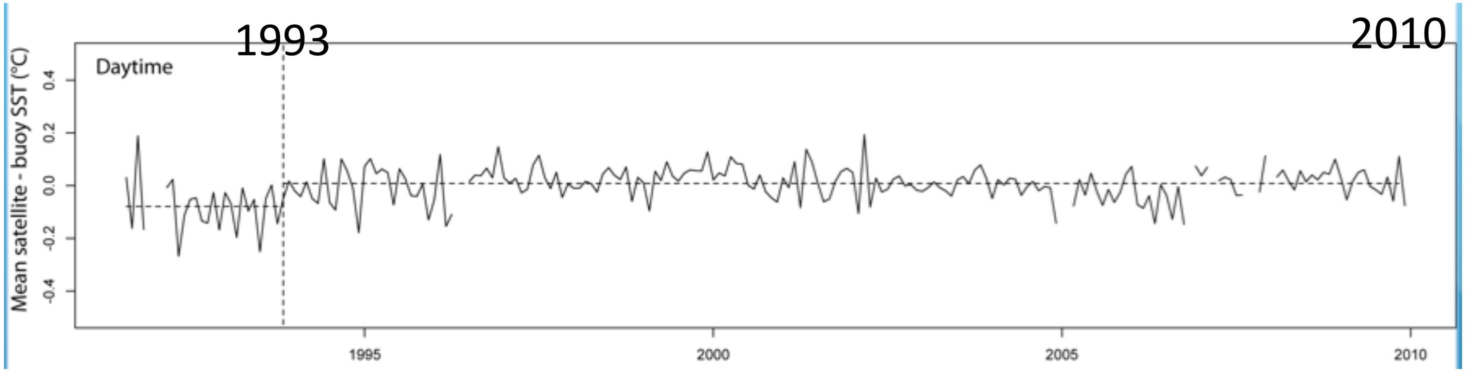
Independent comparison of ARC with HadSST3



Stability assessment of ARC SSTs

- Assessed de-seasonalised discrepancy between ARC SST_{1m} and Global Tropical Moored Buoy Array (GTMBA) for trends (Dave Berry, NOCS)

Region	Period	Time of day	Trend / mK yr^{-1}	95% conf. int. / mK yr^{-1}
Tropics	1993 - end	Day	-0.6	-2.6 < trend < 1.5
Tropics	1993 - end	Night	1.0	-1.4 < trend < 3.4



SUMMARY

What have you learned (1)

- Measuring SST is important
  - Small-term changes for NWP
  - Long-term changes for climate
- Space offers a unique vantage
  - The three C's
  - Using multiple orbits and wavelengths is beneficial
- The basics of radiometry
  - The importance of instrument characterisation
  - Calibration (ideally two on-board two black bodies)

What have you learned (2)

- Retrieving SST from radiances
  - Accounting for clouds and other atmospheric effects
- Merging all complementary SST measurements provides an optimal solution
  - L4 daily analyses
- SST is not a single parameter
  - Accounting for differences in measurement types is critical

Contact details

- Thank you for your attention
- For further information please contact
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