Measuring Sea-Surface Temperature from Space

David Llewellyn-Jones
Space Research Centre
University of Leicester, UK
SST from Space
Thursday, 27th September, 2006

Outline Teaching Programme

0800 – 0900 Lecture: Measuring SST from Space (DLJ)
0900-1000 Lecture: Large-scale SST features (ISR)

Coffee

10.30-12.30 AATSR Practical 1: IDL viewer of global SST (DLJ)

Lunch

1400-1500 Lecture: SST Mesoscale ocean phenomena (ISR)
1500-1600 AATSR Practical 2: Bilko analysis of individual images

Coffee

1630-1830 AATSR Practical 2: (continued)
SST from Space

Course Content

Learning Objectives

1) The importance of measuring SST from Space
2) How SST is measured from Space
3) How the Large-Scale and Mesoscale Behaviour of the Oceans is Investigated Quantitatively from Space
SST from Space

What you Should Learn To-day

1) The principles of radiometry from Space
2) Characteristics of Major European and Other Space Missions to Measure Global SST
3) Some of the large-scale and Mesoscale Thermal Properties of the Global Ocean Surface
4) How to use a simple ready-made IDL Tool for the ‘Quick Look’ analysis of a long-term (4 years) Global Data-set – SST from AATSR on ENVISAT
5) How to use a PC-based image analysis tool (Bilko) to carry out detailed analyses of high-resolution thermal images covering Mesoscale Areas of the Ocean Surface using thermal radiometric data.
Lecture 1 Outline

• Why Measure SST from Space?
• How do we measure SST from Space?
• Who measures SST from Space?
• What can we see by measuring SST from Space?
Why measure SST from Space?

- 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
  
  \( ECV = Essential \, Climate \, Variable \)
Reasons for Using Space to Summarise:

Coverage

Continuity

Consistency
How Do We Use SST Data?

For process monitoring:

• Tracer for major current systems (Gulf Stream, Aghulas, Malvinas, KuroShio etc)

• Detection of major anomalies or periodic events (el Niño, Somali upwelling etc)

• Detection and monitoring of long-term changes
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
How do we measure SST from Space?

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

- Radiometry
- Atmospheric Corrections
- Microwave or Infrared?
- Coverage and Spatial Resolution
- Modern SST sensors
Essentials of Radiometry

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)
Example of Space-borne Radiometer AVHRR

- Designed in 1960’s
- 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

Position of BB ref target
The Problem of Atmospheric Correction

• Generally use thermal infrared or microwave regions for SST radiometry
• In the infrared, molecular absorption from atmosphere is significant
• Water vapour is the variable component
• Also, Cloids are opaque and aerosols partially absorb and emit
("Classic" SST thermal channels are indicated in red)

\[ \lambda = 3.7 \text{ micron} \quad \lambda = 11, 12 \text{ micron} \]
Thermal Channels for SST used by AATSR & other sensors

Figure 2.1: Atmospheric transmission for three different amounts of precipitable water (7mm — polar; 29mm — temperate; 54 mm — tropical), and the ATSR spectral channels matched to atmospheric “window” regions.
Multi-channel Atmospheric correction - how is it done?

\[ \text{SST} = f(T_1, T_2, \ldots) , \] where \( T \) is the measured Top-of-the-Atmosphere Brightness Temperature (ToABT)

\[ \text{and where } f \text{ is generally a really complicated function} \]

\[ \text{then linearise it (take first term of a binomial expansion)} \]

\[ \text{SST} \approx a_0 + a_1 T_1 + a_2 T_2 + \ldots \]
Optimal Estimation – the future for SST?

Ø Computing a terrestrial geophysical parameter from satellite-measured quantities is called a “retrieval” of the desired parameter and can be done simply and systematically from the satellite data.

Ø If the problem is too complex for the linear approximation it is necessary to use a forward method and the ‘answer’ obtained by iteration from a ‘first guess’ – this is called “Optimal m Estimation (OI)” and is the basis of direct assimilation e.g. into weather-forecasting models.
Spatial Resolution and Radiometry

- We MUST know what we are looking at
- In the infrared we need to constrain our view to cloud-free areas
- In the microwave we need to avoid coastlines
- Angular spread of telescopes view is limited to $\lambda/\theta_D$ radians (1 radian $\approx 60^\circ$)
- What does that imply for FoV footprints?
Radiometric Sensitivity
Planck’s Radiation Law says it all!
The Planck Function and radiometric Sensitivity
## Radiometry – Microwave and Infrared

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very little affected by Cloud</td>
<td></td>
</tr>
<tr>
<td>Low Atmospheric Correction</td>
<td></td>
</tr>
<tr>
<td>Low spatial resolution [ \lambda / D ]</td>
<td>20-100Km</td>
</tr>
<tr>
<td>Linear Radiometric Sensitivity</td>
<td></td>
</tr>
<tr>
<td>Only usable in cloud-free areas</td>
<td></td>
</tr>
<tr>
<td>Atmospheric Correction needed, up to 15-20°C in tropics</td>
<td></td>
</tr>
<tr>
<td>1Km resolution readily achievable</td>
<td></td>
</tr>
<tr>
<td>High Radiometric Sensitivity ( T^5 - T^{15} )</td>
<td></td>
</tr>
</tbody>
</table>
Other issues

- Aerosols (*problem for IR*)
- Rain (*problem for MW*)
- Surface Emissivities (*problem for MW – and IR?*)
- Radio interference (*problem for MW*)
- Others
On-board Calibration

- Essential for quantitative remote sensing
- Need stable, black target(s)
- Stable thermal environment
- Good optical design – no stray light!
- Need to know precise temperature and uniformity of black body target
- Need to know linearity of detector response
(A)ATSR Principles of Operation

- 7 spectral channels (like AVHRR, or MODIS)
  - 3 thermal IR: at 3.7 μm, 11 μm, 12 μm (similar to AVHRR)
  - 4 Vis/NIR: at 0.55 μm, 0.67 μm, 0.87 μm, 1.6 μm
    - provides basic SST information

- Dual view
  - nadir and 55° to nadir
  - Gives a direct measurement of atmospheric effects
  - Very effective for dealing with aerosol contamination

- On board calibration
  - 2 on-board black bodies for IR calibration
  - VISCAL unit for visible channel calibration
ATSR Principles of Operation - 2

- **Swath-width** - 500 km
  - Dual view ineffective at wide swath-widths

- **Field-of-view** - 1 km at nadir
  - Same as AVHRR

- **Stirling Cycle Coolers**, cooling low noise detectors to 80K
  - Gives optimum detector performance and exceptional image clarity
The power of AATSR’s Dual View - Atmospheric dust and Aerosol
AATSR – Scan Geometry
AATSR Scan sequence - showing on-board Calibration System

Blackbodies viewed every scan.
AATSR Black-body Temperature records showing variations over one day with near-sinusoidal orbital variations superimposed.
A single orbit record of AVHRR Black-body temperature passing the terminator
AATSR Black-body ‘crossover’ test

This plot identifies the time at which both sets of black-body temp sensors indicate the same temperature. At this time both BB’s give same signal to within <30mkK.

Results show discrepancies of less than 30mK
AATSR - Earth-viewing face
EENVISAT
Europe’s largest satellite

AATSR

, launched March 2002

Sun-synchronous orbit, 1030 local time
daylight descending
ENVISAT, People and the AATSR
Sea Surface Temperature gradients near the Balearics, from AATSR
Classic Images from ATSR

The Gulf Stream

ATSR-2 Image

Image courtesy of RALNERC/ESA
AATSR - General Approach to SST Validation

*Three levels:*

1) Continuous checks of global fields by inter-comparison with drifting-buoy data and analysis fields, or data from other satellite sensors

2) Continuous Autonomous radiometric measurements of SST from ship-borne platforms

3) High-precision radiometric measurements at selected sites
AATSR Validation Results

3½ years, over 26000 match-ups
Summary and Conclusions of SST validation results for AATSR

- AATSR Global validation, using buoy match-ups, autonomous ship-borne radiometers and precision ship-borne radiometers indicates that AATSR is achieving SST accuracy of \( \pm 0.1^\circ K \) in many regions.

- Residual problems concern aerosol and cloud-identification.

- In multi-satellite systems AATSR provides a standard of accuracy.

- The AATSR is an independent measuring system.
AVHRR (solid): 0.09°K/decade
ATSR (dashed): 0.13°K/decade

Residual Trends in ATSR and AVHRR SST records

Note: AVHRR is tied to buoy SSTs, ATSR is independent
Summary and Conclusions

- SST from space can be measured to accuracies ~ 0.1 - 0.2°C
- Still some issues relating to clouds and aerosols – and coverage
- AATSR sets a new standard for accuracy and stability
- Synergistic processing is key to coverage problem
Four years of SST from ENVISAT
Main Take-home Messages

• Observations are the starting-point and the finishing point of all scientific discovery

• You must LOOK at your object of study

• If your object of study is the Global Ocean System, space provides an essential vantage points

You must LOOK!!
Simply the Best!