Progress in Establishing a Satellite-Derived Climate Data Record for Sea-Surface Temperature

Peter J Minnett, Malgorzata Szczodrak, Miguel Angel Izaguirre, Katherine Kilpatrick
Rosenstiel School of Marine and Atmospheric Science, University of Miami

&

R. Michael Reynolds
Remote Measurements and Research Inc. Seattle.
The successful application of all satellite-derived fields depends on confident knowledge of their accuracies.

Several sources of error and uncertainties impact the satellite measurements and the geophysical variables derived from them.

Determine the accuracies by comparing the satellite-derived temperatures with independent surface based measurements of equal or better accuracy.

This approach integrates the errors and uncertainties from all sources.

Satellite SST requirements for climate research:

- Accuracy = 0.1K
- Stability = 0.04 K/decade

Ocean heat content is increasing

Time series of ocean heat content \((10^{22} \text{ J})\) for the 0-2000 m (red) and 700-2000 m (black) layers based on running pentadal (five-year) analyses. Reference period is 1955-2006.

Red bars and grey-shading represent ±2 standard errors.

The blue bar chart represents the percentage of one-degree squares (globally) that have at least four pentadal one-degree square anomaly values used in their computation at 700 m depth. Blue line is the same as for the bar chart but for 2000 m depth. (Levitus et al., 2012).


The heat content of the World Ocean for the 0–2000 m layer increased by \(24.0 \pm 1.9 \times 10^{22} \text{ J (± 2 S.E.)}\) corresponding to a rate of \(0.39 \text{ Wm}^{-2}\).

A mean increase of temperature of \(0.09^\circ\text{C}\).
On-orbit calibration – MODIS & VIIRS

• Two-point linear calibration using space view and measurement of black body emission.
• Non-linearities determine prior to launch, and monitored using warm-up cool-down of black bodies.
• MODIS and VIIRS use same black body design.

http://dx.doi.org/10.1117/12.977560.
Preliminary Uncertainties for TEB Band 31 (Ch5) @Nominal Plateau
(Estimated variable uncertainties shown in parentheses)
($\lambda_{cir}$= 11.014 $\mu$m, L$_{typ}$= 9.55)
Validation by Comparison with Surface Measurements

**Buoys**
- Numerous, but not uniformly distributed in space or time.
- Long time series, starting in early 1980s.
- Subsurface measurement.
- Calibration issues.
- Not a comparison of like-with-like.

**Radiometers**
- Fewer, and not uniformly distributed in space or time.
- Began in mid-1990’s.
- Skin SST measurement.
- Very good calibration, repeatable and traceable to SI-standards.
- Is a comparison of like-with-like.

**Best approach to use both**
Schematic Temperature Profiles

(a) Night time situation, light wind

(b) Day time situation, strong solar radiation and light winds

Drifting buoys

Before & After

Barnacle-Encrusted Drifting Buoy Recovered after 521 Days at Sea

FRM4STS International Workshop
16-18 October 2017. NPL, UK
Drifting Buoy Calibration Experiment

Objective: to assess any calibration drift in drifter thermometers by long-term monitoring in realistic conditions.

An array of drifters is moored off RSMAS. Data sent to SIO via Iridium, and to NOAA/AOML so data flow is the same as deployed drifters.

Data are not distributed beyond SIO, AOML and RSMAS.

Drifter types:
- Pacific Gyre
- Data Buoy Instrumentation
- SIO

In collaboration with Luca Centurioni (SIO) and Rick Lumpkin (NOAA/AOML).
An SIO drifter has been rebuilt to have a reference thermistor and internal data logger. This is brought into the lab periodically for the data to be downloaded and recalibrated.
VIIRS SST Accuracies wrt Drifters

Median -0.175 K
RStDev 0.271 K
N 18,828

January, 2015
M-AERI
• M-AERI is a very well-calibrated and stable sea-going Fourier Transform Infrared Interferometer.
• At sea calibration by two internal blackbody cavities with thermometers with NIST-traceable calibration.
• Calibration sequence before and after each cycle of measurements.
• Calibration before and after deployments using NIST-designed water-bath blackbody calibration target at RSMAS. Uses SI-traceable thermometers at mK accuracy.
• Periodic radiometric characterization of RSMAS water-bath blackbody calibration target by NIST TXR and NPL AMBER.

ISAR
• ISAR is a very well-calibrated and stable sea-going filter radiometer.
• At sea calibration by two internal blackbody cavities with thermometers with SI-traceable calibration.
• Calibration sequence before and after each cycle of measurements.
• Calibration before and after deployments using NIST-designed water-bath blackbody calibration target at RSMAS or UW-APL. Use SI-traceable thermometers at mK accuracy.
• Periodic radiometric characterization of RSMAS water-bath blackbody calibration target by NIST TXR and NPL AMBER.
Research Ship Radiometer Deployments
M-AERI Cruises

M-AERI Skin SSTs

Current Cruise Ship Deployments

Collaboration with Royal Caribbean Cruise Lines

*Celebrity Equinox*

*Royal Caribbean Cruise Lines*

*Allure of the Seas*

*Adventure of the Seas* installation in January 2018.

FRM4STS International Workshop
16-18 October 2017. NPL, UK
### Error Budget of Miami Water-bath Blackbody Target

<table>
<thead>
<tr>
<th>Uncertainty Contribution</th>
<th>Set point temperature</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All values in mK</strong></td>
<td>288 293 298 303 308 313 318</td>
<td></td>
</tr>
<tr>
<td><strong>Thermometer calibration</strong></td>
<td>4.24 4.24 4.24 4.24 4.24 4.24 4.24</td>
<td>Average of two thermometers, each with uncertainty (k=2) of 6.0 mK (Fluke calibration reports, 5 April, 2016)</td>
</tr>
<tr>
<td><strong>Blackstack thermometer resistance measurement</strong></td>
<td>0.54 0.12 0.35 0.42 0.13 0.35 0.19</td>
<td>k=2. Fluke calibration report.</td>
</tr>
<tr>
<td><strong>Conversion of resistance to temperature</strong></td>
<td>0.35 0.23 0.08 0.07 0.19 0.27 0.30</td>
<td>k=2. Fluke calibration report.</td>
</tr>
<tr>
<td><strong>Stability of the water bath</strong></td>
<td>0.16 0.16 0.17 0.17 0.18 0.19 0.17</td>
<td>k=2. 2x standard error of temperature measurements at set points.</td>
</tr>
<tr>
<td><strong>Emissivity uncertainty</strong></td>
<td>50.0 50.0 50.0 50.0 50.0 50.0 50.0</td>
<td>Fowler, 1995; Rice et al, 2004. Upper bound. (k=2)</td>
</tr>
<tr>
<td><strong>Temperature drop across copper cone</strong></td>
<td>0.5 0.0 0.5 1.0 2.0 2.2 2.0</td>
<td>Fowler, 1995, Table 4. (k=2)</td>
</tr>
<tr>
<td><strong>Spatial temperature gradients in cavity</strong></td>
<td>5.0 5.0 5.0 5.0 5.0 5.0 5.0</td>
<td>Thermal imager – no gradients detectable with FLIR SC3000 with sensitivity of 20mK</td>
</tr>
<tr>
<td><strong>Radiative heat exchange with environment</strong></td>
<td>15.0 15.0 15.0 15.0 15.0 15.0 15.0</td>
<td>Assumes uncertainty in knowledge of ambient temperature of 0.5K and uncertainty in cone reflectivity of 0.0003; Fowler, 1995.</td>
</tr>
<tr>
<td><strong>Convective heat exchange with environment</strong></td>
<td>1.0 1.0 1.0 1.0 1.0 1.0 1.0</td>
<td>From uncertainty budget of NPL Gallium reference BB</td>
</tr>
</tbody>
</table>
RSMAS Water-bath Blackbody vs AMBER
RSMAS Water-bath Blackbody vs AMBER

Note: discrepancies are within uncertainties of AMBER reference radiometer.
## Error Budget of M-AERI measurements

### At $\lambda = 10.0 \mu m$ (1000 cm$^{-1}$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type A Uncertainty in Value [ K ]</th>
<th>Type B Uncertainty in K</th>
<th>Uncertainty in Brightness temp K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of Measurement</td>
<td>0.014</td>
<td></td>
<td>0.014</td>
</tr>
<tr>
<td>Reproducibility of Measurement</td>
<td>0.0058 (0.0035)</td>
<td>0.0058 (0.0035)</td>
<td>0.0003</td>
</tr>
<tr>
<td>Linearity of radiometer</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0097</td>
</tr>
<tr>
<td>Primary calibration</td>
<td>0.0097</td>
<td>0.0097</td>
<td>0.0003</td>
</tr>
<tr>
<td>Drift since calibration</td>
<td>0.0152 (0.0144)</td>
<td>0.0102</td>
<td>0.0182 (0.0176)</td>
</tr>
<tr>
<td>RMS total</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### At $\lambda = 7.7 \mu m$ (1302 cm$^{-1}$)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type A Uncertainty in Value [ K ]</th>
<th>Type B Uncertainty in K</th>
<th>Uncertainty in Brightness temp K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repeatability of Measurement</td>
<td>0.0349</td>
<td></td>
<td>0.0349</td>
</tr>
<tr>
<td>Reproducibility of Measurement</td>
<td>0.0178 (0.0089)</td>
<td>0.0003</td>
<td>0.0003</td>
</tr>
<tr>
<td>Linearity of radiometer</td>
<td>0.0003</td>
<td>0.0003</td>
<td>0.0086</td>
</tr>
<tr>
<td>Primary calibration</td>
<td>0.0086</td>
<td>0.0086</td>
<td>0.0003</td>
</tr>
<tr>
<td>Drift since calibration</td>
<td>0.0392 (0.0360)</td>
<td>0.0091</td>
<td>0.0402 (0.0372)</td>
</tr>
<tr>
<td>RMS total</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
M-AERI vs NPL Reference Blackbody

M-AERI vs NPL Reference Blackbody

![Graph showing temperature error in mK as a function of reference temperature in °C. The graph includes two lines, one for 1000 cm\(^{-1}\) and another for 1302 cm\(^{-1}\).]
M-AERI vs RSMAS Blackbody

$R_m$ is measured radiance from the RSMAS WB BB cone, which is:

$$R_C = [R(T_{BB}) \times \varepsilon_{BB} + (1 - \varepsilon_{BB}) \times R(T_{amb})].$$

Error is $R_m - R_C$.

Wavelength dependence treated explicitly.

Measurements taken at a range of set point temperatures.

Measurements include a third M-AERI BB mounted on the zenith view port of the M-AERI.

$\varepsilon_{BB}$ is adjusted to minimize dependence of the error on the target temperature.
## Estimates of Cone Emissivity

Four M-AERIs show very similar results for the cone emissivity.

These results are for new or recently cleaned mirrors.

Is this a reasonable approach?

<table>
<thead>
<tr>
<th>Date</th>
<th>Unit</th>
<th>1300 cm$^{-1}$</th>
<th>1000 cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015/03</td>
<td>A</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>2015/05</td>
<td>A</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>2016/02</td>
<td>A</td>
<td>0.9982</td>
<td>0.9989</td>
</tr>
<tr>
<td>2016/02</td>
<td>A</td>
<td>0.9997</td>
<td>0.9993</td>
</tr>
<tr>
<td>2017/04</td>
<td>A</td>
<td>0.9982</td>
<td>0.9981</td>
</tr>
<tr>
<td>2017/04</td>
<td>A</td>
<td>0.9997</td>
<td>0.9993</td>
</tr>
<tr>
<td>2016/03</td>
<td>B</td>
<td>0.9985</td>
<td>0.9984</td>
</tr>
<tr>
<td>2016/03</td>
<td>B</td>
<td>0.9958</td>
<td>0.9959</td>
</tr>
<tr>
<td>2014/02</td>
<td>C</td>
<td>0.9967</td>
<td>0.9969</td>
</tr>
<tr>
<td>2014/02</td>
<td>C</td>
<td>0.9957</td>
<td>0.9955</td>
</tr>
<tr>
<td>2015/10</td>
<td>D</td>
<td>0.9963</td>
<td>0.9964</td>
</tr>
<tr>
<td>2016/02</td>
<td>D</td>
<td>0.9962</td>
<td>0.9961</td>
</tr>
<tr>
<td>2016/02</td>
<td>D</td>
<td>0.9966</td>
<td>0.9964</td>
</tr>
<tr>
<td>2016/06</td>
<td>D</td>
<td>0.9961</td>
<td>0.9961</td>
</tr>
<tr>
<td>2016/06</td>
<td>D</td>
<td>0.9960</td>
<td>0.9960</td>
</tr>
<tr>
<td>2017/06</td>
<td>D</td>
<td>0.9939</td>
<td>0.9937</td>
</tr>
<tr>
<td>2017/09</td>
<td>D</td>
<td>0.9946</td>
<td>0.9947</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>0.9972</strong></td>
<td><strong>0.9971</strong></td>
</tr>
</tbody>
</table>
RSMAS ISAR Deployments
## MODIS SSTs & Ship Radiometers

<table>
<thead>
<tr>
<th>Satellite and Algorithm</th>
<th>Mean</th>
<th>Median</th>
<th>Standard Deviation</th>
<th>Robust St. Deviation</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terra SST Day</td>
<td>0.082</td>
<td>0.080</td>
<td>0.567</td>
<td>0.409</td>
<td>1025</td>
</tr>
<tr>
<td>Terra SST Night</td>
<td>0.048</td>
<td>0.034</td>
<td>0.467</td>
<td>0.337</td>
<td>2454</td>
</tr>
<tr>
<td>Terra SST4 Night</td>
<td>0.016</td>
<td>0.023</td>
<td>0.339</td>
<td>0.244</td>
<td>2467</td>
</tr>
<tr>
<td>Aqua SST Day</td>
<td>0.105</td>
<td>0.107</td>
<td>0.666</td>
<td>0.480</td>
<td>910</td>
</tr>
<tr>
<td>Aqua SST Night</td>
<td>0.020</td>
<td>0.027</td>
<td>0.489</td>
<td>0.353</td>
<td>1752</td>
</tr>
<tr>
<td>Aqua SST4 Night</td>
<td>-0.010</td>
<td>0.016</td>
<td>0.396</td>
<td>0.285</td>
<td>1858</td>
</tr>
</tbody>
</table>
Generating an SST CDR

- Ship Radiometers Measure skin SST and are SI-traceable.
- But are few in number.
- Buoys measure sub-surface SST, and are not SI-traceable.
- But are numerous, even if not uniformly distributed.
Outstanding issues

• Better cloud screening and atmospheric correction algorithms.
• Developing full error and uncertainty budgets for satellite-derived SSTs.
• Assess sampling errors in drifting buoy data and ship radiometer measurements.
• The SSES (Sensor Specific Error Statistics) for each SST product should be revisited.
• Improved modeling of thermal skin effect is needed.
• And much more…. 
Summary

• Target accuracies and decadal stability requirements for SST are very demanding, and challenging to verify.
• Comparison with ship-board radiometers provides a primary mechanism for ensuring satellite SSTs have an SI-traceable reference.
• SI-traceability permits the generation of SST Climate Data Records.
• Experiment to assess thermometer calibration drift in (moored) drifters has started at RSMAS.
Conclusion

National Science Foundation: Science Hard

INDIANAPOLIS—The National Science Foundation’s annual symposium concluded Monday, with the 1,500 scientists in attendance reaching the consensus that science is hard.

“For centuries, we have embraced the pursuit of scientific knowledge as one of the noblest and worthiest of human endeavors, one leading to the enrichment of mankind both today and for future generations,” said keynote speaker and NSF chairman Louis Farian. “However, a breakthrough discovery is challenging our long-held perceptions about our discipline—the discovery that science is really, really hard.”

“My area of expertise is the totally impossible science of particle physics,” Farian continued, “but, indeed, this newly discovered ‘Law of Difficulty’ holds true for all branches of science, from astronomy to molecular biology and everything in between.”
And bear in mind…. 

“God made the bulk; surfaces were invented by the devil.”

Wolfgang Pauli
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Thank you.