THE MIAMI-2001 RADIOMETER INTERCOMPARISON

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ABSTRACT

The Second International Infrared Radiometer Calibration and Inter-comparison was held in Miami during the period 27 May to 2 June, 2001. Six different makes of radiometers were calibrated against the NIST Standard Black Body in the laboratory and seven radiometers were mounted on the RV *Walton Smith* for an inter-comparison under sea-going conditions. The results confirm that all radiometers are suitable for the validation of land surface temperature, and the majority are able to provide high quality data for the more difficult validation of satellite-derived sea surface temperature, contributing less than 0.1 K to the error budget of the validation. The new NIST EOS Transfer Radiometer was used in the laboratory to characterize several black body calibrators.

1. BACKGROUND

The origin of the infrared signal detected by spacecraft radiometers, such as the Advanced Along-Track Scanning Radiometer (AATSR) measuring the sea-surface temperature (SST) is the skin layer of the ocean. This is generally a few tenths of a degree cooler than the bulk temperature below, as a result of heat flow from the ocean to the atmosphere [1]. During the day, when wind speed over the ocean is low and the insolation high, diurnal temperature gradients can form which further decouple the skin temperature from the temperature measured at depth (e.g. [2]). These gradients, which can be very variable both in space and time [3] [4], make a significant contribution to the error budget of the satellite-derived SSTs when this is determined using sub-surface temperature measurements. Using radiometric measurements of the oceanic skin temperature removes this component from the error budget, leaving an accurate determination of the true uncertainties in the satellite retrievals [5]. The objective of the Second International Infrared Radiometer Calibration and Inter-comparison Workshop was to bring as many types of ship-board radiometers used by different researchers to validate satellite SSTs together to ensure compatibility of their measurements and to determine their individual contributions to the error budgets of the satellite-derived SST fields. It was hoped at the outset that these contributions would not be dominant, and this was indeed found to be the case. The workshop was held from May 27 to June 2, 2001, and had two components: one in the laboratory and the other in the filed on board the R/V *Walton Smith*. Twenty participants from several international institutes participated in the program.

The first inter-comparison of infrared radiometers was held at Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami, during March 1998 (http://www.rsmas.miami.edu/ir/ [6]). This involved several high quality radiometers and some off-the-shelf devices. NIST (US National Institute of Standards and Technology) provided their standard black body target [7] for calibration of each radiometer. Other black bodies available for calibration included a NIST water-bath blackbody calibration target provided by the University of Washington, a smaller unit from JPL, the CASOTS (Combined Action to Study the Ocean's Thermal Skin, a European Commission Framework IV Program on Environment and Climate) black body [8] and a portable unit designed by CSIRO, Australia. In the period since the first inter-comparison several new radiometers have been constructed (e.g. CIRIMS, ISAR-5; see Tables 1 and 2) for the validation of satellite-derived SSTs. It was important that these radiometers be calibrated against NIST standards as well as compared with the other radiometers. It was also a further objective of the workshop to compare the skin SST measurements of the radiometers in a true deployment situation, during a short cruise aboard a research vessel.

2. LABORATORY MEASUREMENTS

The laboratory part of the Workshop involved most radiometers viewing the available calibration blackbodies at a range of temperatures between 10 and 50^{o}C. As well as the NIST standard blackbody, the equivalent RSMAS water-bath blackbody [7] was used for the calibration of the radiometers allowing the measurements of each radiometer to be traced to the NIST standard. The black body calibrators participating in the workshop are given in Table 3. All except the M-AERI use filters to define the spectral band-pass of the measurements, and several radiometers are designed to match the relative spectral response characteristics of spacecraft radiometers. The M-AERI (Marine Atmospheric Emitted Radiance Interferometer [9])[9] is a well calibrated Fourier-Transform spectroradiometer that operates in the range of wavelengths from ~3 to ~18µm, from which accurate skin temperatures can be derived [9] [10]. Shown in Figure 1, the new NIST EOS transfer radiometer (TXR, [11]) is a purpose-built cryogenic infrared radiometer that operates at two wavelengths, 5 and 10 µm [11]; it was used to characterize other black body calibrators used for field and laboratory calibrations. The RSMAS water-bath blackbody calibrator is shown in Figure 2, and that of the CASOTS design in Figure 3.

The results of the characterization of the blackbody calibrators again the NIST EOS TXR are summarized in Table 4, and given in more detail elsewhere [12].

Table 1. Infrared radiometers that participated in the campaign.

Instrument	Institution	Lab.	Sea	P.I.
TXR (Transfer radiometer)	NIST, USA	Yes	No	J. Rice
M-AERI (Marine-Atmospheric Emitted Radiance Interferometer)	RSMAS, U. Miami.	No	Yes	P. Minnett
SISTeR (Scanning Infrared Sea Surface Temperature Radiometer)	RAL,UK.	Yes	Yes	T. Nightingale
DAR011	CSIRO, Australia.	Yes	Yes	I. Barton
CIRIMS (Calibrated InfraRed In situ Measurement System)	APL, U. Washington.	No	Yes	A. Jessup
ISAR-5 (Infrared SST Autonomous Radiometer -5)	JRC, EEC.	Yes	Yes	C. Donlon
Near-Nulling Radiometers	NASA JPL	Yes	Yes	S. Hook
Tasco (off-the-shelf)	CSIRO, Australia	Yes	Yes	I. Barton

Table 2. Radiometer characteristics.

Radiometer	Pass-band µm	Detectors	Blackbodies	Sky correction	Notes
M-AERI	3-18	HgCdTe – In Sb Cooled to 78K	Two large cavities – SSEC design	Scan mirror	SST derived at 7.7µm
CIRIMS	9.6 - 11.5	Heitronics KT-11.85*	Hart Scientific mini-water bath black body	Dedicated radiometer, Heitronics KT-11.85	Mismatch of pass-bands of two radiometers during the workshop.
SISTeR	10.8	Pyroelectric	Two small cavities.	Scan mirror	
ISAR	9.6-11.5	Heitronics KT-11.85D*[#]	Two small cavities	Scan mirror	
DAR011	10.5-11.5	Pyroelectric	Two small cavities	Scan mirror	Sky view in opposite quadrant
JPL-NNR	7.8 -13.6	Thermopile	One cavity, actively controlled	Modelled	Uses 'nulling' of signal to internal black body
Tasco	??	??	External	None	Hand-held

*The Heitronics uses a chopped pyroelectric detector.
[#]The ISAR Heitronics is modified to allow the measurement of temperatures down to –100°C.

Table 3. Black bodies used for laboratory calibration.

Instrument	Institution	P.I.
NIST-Certified & Designed Black Body Target	RSMAS, U. Miami	P. Minnett
NIST Standard Black Body Target	NIST, USA	C. Johnston
CASOTS black body	JRC, EEC	C. Donlon
Hart Scientific Portable Black Body Target	APL, U. Washington	A. Jessup
JPL Black Body Calibrator	NASA-JPL	S. Hook

Figure 1. The NIST EOS TXR

Figure 2. The RSMAS water-bath blackbody calibrator, following the design of Fowler.

Figure 3. The CASOST-style blackbody calibrator.

Table 4. Characterization of the blackbody calibrators (from [12]).

Quantity	RSMAS BB	JPL BB	CASOTS U. Leicester BB
Spacing (mm)	64	128	114
$1-\varepsilon_{BBX}$	1×10^{-5}	8.379×10^{-3}	9.457×10^{-3}
$1-\varepsilon_{BBX}$ fitting uncertainty	7×10^{-4}	8.43×10^{-4}	6.44×10^{-4}
ε_{BBX}	1.0000	0.9916	0.9905
ε_{BBX} fitting uncertainty	0.0007	0.0008	0.0006
Intercept (W cm^{-2} sr^{-1})	-1.9×10^{-7}	-8.96×10^{-6}	-1.047×10^{-5}
Intercept fitting uncertainty (W cm^{-2} sr^{-1})	8×10^{-7}	9.4×10^{-7}	7.2×10^{-7}
T_s (°C)	N/A	31.57	33.82
T_s fitting uncertainty (°C)	N/A	0.28	0.05

3. AT-SEA MEASUREMENTS

Following the laboratory measurements, the radiometers were mounted on the RSMAS research catamaran, the R/V *F.G. Walton Smith* for a short cruise between Miami and the Bahamas. The radiometers, along with the M-AERI, were mounted on the port railing at the level of the bridge (Figure 4) where they could measure the surface emission ahead of the bow wave and out of the influence of the ship. An exception to this was the JPL NNR which was mounted on the forward railing, looking ahead between the two hulls of the ship, again measuring the surface emission ahead of the ship's bow waves. Each sensor was controlled by a computer which also logged the measurements. The hand-held 'lunchbox' TASCO radiometer was used intermittently from a point adjacent to the main group of radiometers and the measurements recorded in a notebook. The track of the ship crossed the Gulf Stream (Figure 5), proving a range of skin SSTs from about 26.5 to 29^{o}C. The sky was partially cloudy throughout, including some high cirrus. The skin temperature measurements were augmented by a sub-surface bulk measurement by a pumped thermosalinograph at a depth of about 1m (Figure 6). The results show that the skin SST is cooler than the bulk temperatures, and that the skin SSTs measured by the radiometers agree in the mean to much better than 0.1K. The scatter, as represented by the standard deviations of the differences is generally at the level of 0.1K or below. Some of this scatter is environmental in origin as the radiometers were not bore-sighted did not have synchronized measurements schemes [13]. The exception is the JPL NNR which tended to show more scatter, which can be traced to the absence of a direct sky radiance measurement for compensation of the reflected sky emission, which was variable given the conditions of broken cloud. The results are summarized in Table 5 and discussed in much more detail elsewhere [13].

The TASCO measurements taken during the cruise suggest that, if great care is taken with the measurement, then a reasonable skin SST estimate can be made with these off-the-shelf instruments. For useful SST validation an accurate system that includes frequent calibration will be required. The results suggest that an accuracy of better than 0.2 K is possible which is an order of magnitude better than the absolute accuracy figures quoted by the manufacturer.

Table 5. Means and standard deviations of the differences in skin SST differences measured by pairs of radiometers for the entire cruise period.

Radiometer Pair	Mean (K)	Std.Dev (K)	N
M-AERI - ISAR	0.002	0.135	80
M-AERI - SISTeR	0.046	0.066	144
M-AERI - JPL NNR	0.007	0.114	148
M-AERI - DAR011	-0.008	0.076	149
ISAR - SISTeR	0.038	0.101	79
ISAR - JPL NNR	0.026	0.142	81
ISAR - DAR011	0.007	0.114	80
SISTeR - JPL NNR	-0.048	0.099	144
SISTeR - DAR011	-0.053	0.074	144
JPL NNR - DAR011	-0.014	0.103	148

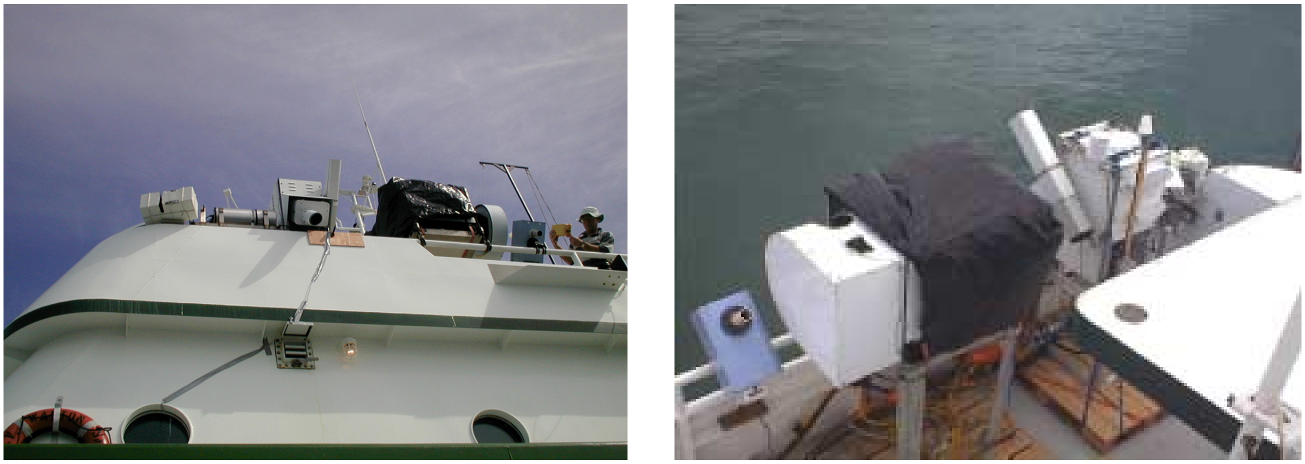

Figure 4. Left – the infrared radiometers mounted on the upper deck. From the left these are SISTeR, ISAR, CIRIMS, M-AERI, DAR011, and the hand-held TASCO. Right – the view from above. The JPL radiometer was mounted on the fore-deck, viewed the sea between the two hulls of the *Walton Smith*, and is not visible in these photographs.

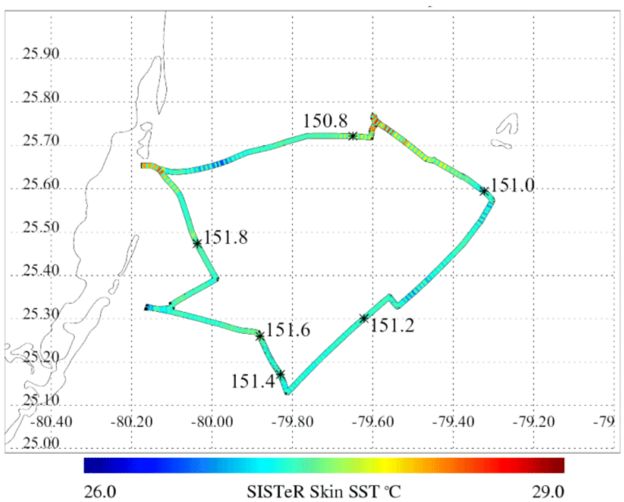

Figure 5. The track of the RV *Walton Smith* during the 2-day cruise. The times are day-of-year plus decimal days (UTC). Day 151.0 is 8:00 pm local time on May 30. The track is colored by the measurements of the SISTeR.

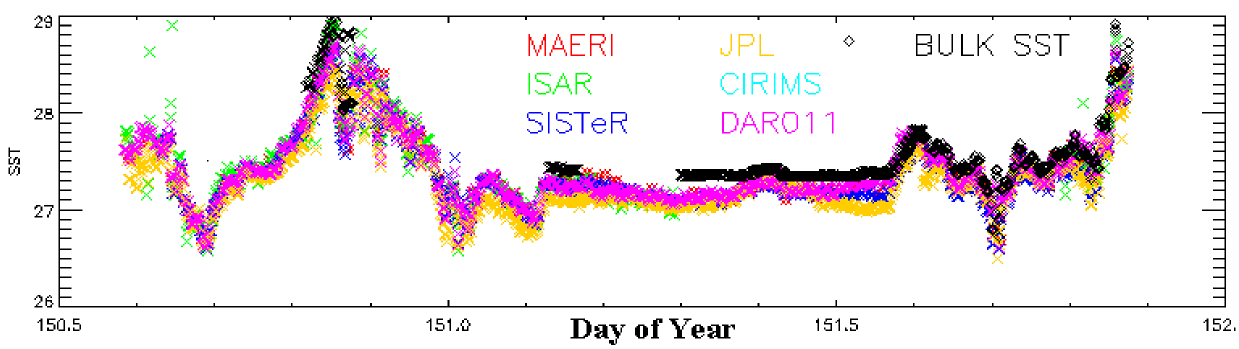

Figure 6. Skin SSTs derived form the radiometers during the R/V *Walton Smith* cruise. The bulk SSTs (black) are from a depth of about 1m.

4. CONCLUSIONS

The Miami2001 Infrared Radiometer Calibration and Intercomparison Workshop has demonstrated consistency between the measurements from the various designs of radiometers, listed in Table 5, that are used to validate satellite-derived skin SSTs. Discrepancies are below the 0.1K level. Furthermore, traceability to NIST standards had been achieved for the blackbody calibration targets used to check the calibration of these radiometers, and the small, temperature-dependent corrections to compensate for the non-unity emissivity of these targets have been established. As a result the scientific and operational communities should have confidence of in the uncertainties in satellite-derived skin SSTs obtained by comparison with these radiometers, individually and collectively.

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