Validation of satellite-derived ocean skin temperatures using the M-AERI

Peter J. Minnett and the M-AERI team*
University of Miami, Rosenstiel School of Marine and Atmospheric Science,
Division of Meteorology and Physical Oceanography,
4600 Rickenbacker Causeway,
Miami, Florida, 33149. U.S.A.

Abstract: As with any geophysical measurement, a careful assessment of the accuracy of the ATSR sea-surface temperature retrievals is a pre-requisite of the application of ATSR data. Using the Marine-Atmosphere Emitted Radiance Interferometer (M-AERI), ocean skin temperature measurements can now be made in a routine fashion from ships with an absolute uncertainty of less than 0.1K. This level of accuracy permits the validation for the atmospheric correction algorithms applied to AVHRR and ATSR data to retrieve sea surface temperature.

Introduction

The main objective of the Along Track Scanning Radiometers (ATSRs) is the accurate measurement of sea-surface temperature (SST). To achieve this goal requires several conditions to be met: the on-board calibration has to be accurate and reliable, and the temperature and radiometric references used have to be traceable to national standards; and the atmospheric correction algorithm has to be effective. The result, the sea-surface temperature fields, must then be validated to demonstrate their accuracy. Failure to determine the accuracy limits could lead to erroneous conclusions being drawn, and a convincing validation can persuade the skeptic of the value of the data. Conventional approaches using *in situ* sensors introduce uncertainties caused by near surface temperature gradients caused by the thermal skin effect and diurnal temperature cycles, and these uncertainties are attributed to satellite retrieval errors. The use of infrared radiometers for SST validation has often been hampered by the difficulty of maintaining, and demonstrating, absolute accuracy in the field to the necessary levels <0.1K. The M-AERI is a well-calibrated spectroradiometer that is being used to validate satellite SST retrieval and to study the near-surface skin gradients.

The M-AERI

The Marine-Atmosphere Emitted Radiance Interferometer (M-AERI) is a development of the AERI (Atmosphere Emitted Radiance Interferometer), an instrument developed at the Space Science and Engineering Center at the University of Wisconsin-Madison for the Department of Energy Atmospheric Radiation Measurement Program (Stokes and Schwartz, 1994; Mather *et al*., 1998), and of the High-Resolution Interferometric Spectroradiometer (HIS) which has been flown on the NASA ER-2 research aircraft (Revercomb *et al*., 1988).

Figure 1. The M-AERI mounted on the NOAA Ship *Ronald H Brown*.

The M-AERI, a Fourier-Transform Interferometric Radiometer, operates in the range of infrared wavelengths from ~3 to ~18μm and measures spectra with a resolution of ~0.5 cm^{-1} (Figures 1 and 2). It uses a sandwich of two infrared detectors (Indium Antimonide and Mercury Cadmium Telluride) to achieve the wide spectral range, and these are cooled to ~78°K by a Stirling cycle mechanical cooler to

* Members are listed in the Acknowledgements

reduce the noise equivalent temperature difference to levels well below 0.1K. The M-AERI includes two internal blackbody targets for accurate real-time calibration. A scan mirror directs the field of view from the interferometer to either of the blackbody cavity calibration targets or to the environment from nadir to zenith. The mirror is programmed to step through a pre-selected range of angles. When the mirror is angled below the horizon the instrument measures the spectra of radiation emitted by the sea-surface, and when it is directed above the horizon it measures the radiation emitted by the atmosphere. The sea-surface measurement also includes a small component of reflected sky radiance. The interferometer integrates measurements over 45 to 90 seconds per view to obtain a satisfactory signal to noise ratio and a typical cycle of measurements including those of the calibration targets, takes <10 minutes. The M-AERI is equipped with pitch and roll sensors so that the influence of the ship's motion on the measurements can be determined.

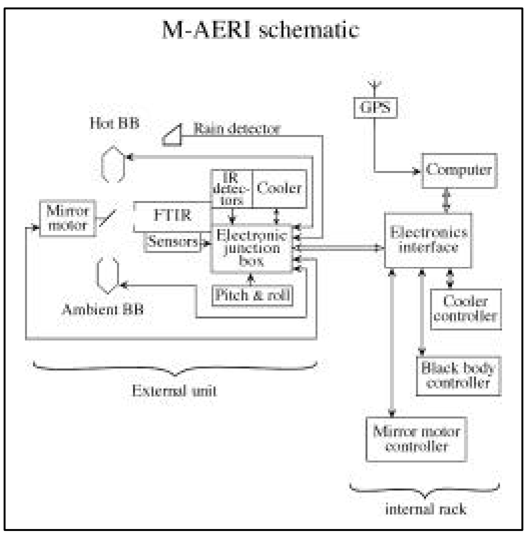

Figure 2. Schematic drawing of the M-AERI components.

Sea surface skin temperature measurements

The sea surface skin temperatures are retrieved from the 55^o sea and sky view data using measurements in a narrow spectral interval at 7.7µm (1302.0 to 1307.0 cm^{-1}), where the atmosphere is only moderately transparent (Smith et al., 1996). The emissivity used in the retrievals is 0.962627 (Wu and Smith, 1997). This is somewhat smaller than the value in the 10-12µm interval where SST is conventionally measured by infrared radiometry. However, at the longer wavelength interval, where the atmosphere is relatively transparent, the reflected component has its origin higher in the atmosphere, and so is much colder that the radiation originating at the interface. It is also

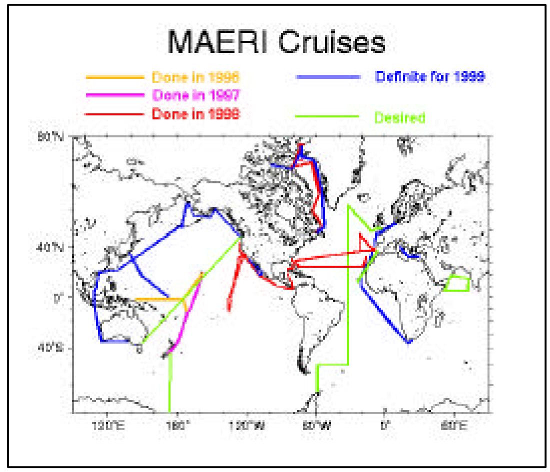

Figure 3. M-AERI cruise tracks.

sensitive to the presence of low clouds, which insert a warm radiation source in the reflected sky radiation. Thus, even if the reflected component is larger at 7.7µm than at 10-12 µm, the correction for sky radiation is less dependent on the cloud conditions, as nearly all of the reflected sky radiation has its origin in the lower troposphere. Uncertainties in the correction for the reflected component are dependent on the temperature difference between the surface and the source of the atmospheric component, which is much smaller at 7.7µm than 10-12 µm. A small correction is made for the effects of the atmosphere between the sea surface and the height of the instrument.

At-sea deployments

The M-AERI has been deployed at sea on a number of cruises that span the oceans and a very wide range of climactic regimes (Figure 3). During one of these, form Hawaii to New Zealand on the R/V *Roger Revelle*, two M-AERIs were operated side by side to determine the accuracies of the SST measurements. Before mounting on the ship the calibrations of both M–AERIs were tested by measuring the temperature of a third black body target at a known temperature. Both M–AERIs measured the temperature of this target with an uncertainty of <0.03K.

Daily averages of the differences in skin SST's from both instruments are given in Table 1 together with their standard deviations. It can be seen that the correspondence is remarkably good. These measurements are independent in the sense that each instrument has its own internal calibration. This agreement is better than anticipated given the design goals (<0.1K) and what were believed to be the inherent uncertainties in key components of the instrument (e.g., emissivity of black body calibration targets; accuracy of thermistors in the black body targets).

Table 1. Statistics of SST measurements from two independent M-AERIs

Date - UTC	N	Mean ΔT /K	St.dev. ΔT /K
October 1	70	0.005	0.033
October 2	58	0.020	0.084
October 3	56	0.002	0.092
October 4	85	0.005	0.059
October 5	56	0.000	0.091
October 6	79	0.021	0.067
October 7	146	0.000	0.073
October 8	74	-0.003	0.085
October 9	133	0.009	0.062
October 10	133	-0.003	0.099
October 1-10	890	0.005	0.077

ΔT = Skin SST (M-AERI 02 –– M-AERI 01)

Laboratory calibration

An infrared radiometry workshop held at UM-RSMAS in March 1998 (Kannenberg, 1998) provided the means of testing the absolute calibration of the M-AERIs, and other radiometers, against a range of calibration targets. One of these was provided by NIST, which used a water bath to ensure temperature stability of the conical black target, and this was used to check the absolute radiometric accuracy of the M-AERI (model 02). Measurements were taken with the NIST calibration target at 20^{o}C, 30^{o}C and 60^{o}C. The results are summarized in table 2.

The results of the M-AERI 02 – NIST comparison show very small absolute uncertainties, especially at 20 ^{o}C, i.e. close to ambient temperature. The increasing discrepancies with increasing temperature can be explained if the effective emissivity of the NIST target is about 0.998. When used on ships, the M-AERI SST measurement is of a temperature close to ambient, and is taken at the wavenumber interval of 1302.0 to 1307.0 cm^{-1} where the absolute calibration uncertainties are very small indeed.

Table 2. Mean discrepancy in the M-AEI 02 measurements of the NIST water bath blackbody calibration target in two spectral intervals.[1]

Target Temp.	LW (980-985 cm^{-1})	SW (2510-2515 cm^{-1})
20^{o}C	+0.013 K	+0.010 K
30^{o}C	-0.024 K	-0.030 K
60^{o}C	-0.122 K	-0.086 K

Discrepancies are M-AERI minus NIST.

As a result of these measurements taken in the laboratory and in the field, we have confidence in the absolute accuracy of the skin SST measurements being well below the design objective of <0.1K. More details of the M-AERI are available in Minnett *et al.*, 1999 (in preparation).

AVHRR Validation

The skin SSTs derived form the M-AERI measurements have been compared with AVHRR SSTs derived using the Miami AVHRR Pathfinder data set (Kilpatrick *et al*., 1999; in preparation). Both the M-AERI and AVHRR data were subject to quality controls prior to producing a matchup dataset. Ideally the quality control of each data stream (M-AERI and AVHRR Pathfinder SSTs) should be independent and the two data streams only brought together for the comparison itself. However, in this case we know there are issues at play that can introduce errors in to the data that are not attributable to the clear sky atmospheric correction algorithm. For the AVHRR these are sub-pixel cloud and instrumental effects, such as digitizer errors; for the M-AERI these are undetected spray or other contamination of the field of view. Given that extensive comparisons between the AVHRR Pathfinder SST and in situ measurements from drifting buoys indicate the expected uncertainties in the comparison, attributed to the AVHRR Pathfinder algorithm, are about 0.5K rms (1σ) about a mean <0.1K, we feel justified in using tests in the M-AERI quality assurance that include rejection of outliers based on a comparison between M-AERI data and the Reynolds' AVHRR-based OISST (Optimally

[1] Table provided by Dr R. O. Knuteson, University of Wisconsin, Madison

Interpolated SST; Reynolds and Marisco, 1993). The first step in the M-AERI quality control is removing all measurements taken when the aperture was covered. Then M-AERI data were eliminated that were more than ±3K from the Reynolds' OISST. Also, those M-AERI SST values were removed that differed from the ship's thermosalinograph measurements (where available) by more than given thresholds, which were determined from the R/V *Roger Revelle* deployment. The difference, ΔT, between the skin and the bulk temperatures under a range of typical wind and sea conditions were found to be $-1.75K < \Delta T < 0.5K$. Finally, the standard deviation of each M-AERI air temperature (derived by analyzing measurements taken in spectral intervals where the atmosphere is not very transmissive) and SST retrievals (determined from the variability of the individual M-AERI SSTs within the chosen spectral interval) were used to eliminate those measurements where the standard deviation of the air temperature estimate exceeded 0.06K or that of the sea surface temperature estimate exceeded 0.09K. For the AVHRR data, the quality assurance tests developed for the Pathfinder – buoy match ups were applied (Kilpatrick *et al*., 1999; in preparation).

The M-AERI locations and times from the cruises listed in Table 3 were used to identify those AVHRR orbits that would provide data coincident and collocated with the M-AERI. The AVHRR Pathfinder SSTs were mapped at 4km resolution. For each mapped orbital scene pixels within 4 km and 90 minutes to the M-AERI measurement were extracted.

Some ancillary information was also assembled to aid in the interpretation of the comparison. To provide an independent estimate of the atmospheric water vapor content at each AVHRR pixel selected for the match-up, daily Special Sensor Microwave Imager (SSM/I) water vapor values were obtained by spatial bilinear interpolation to its location. The thermo-salinograph (TSG) data, with SST computed every 30 seconds, provide a bulk estimate of the SST for each cruise. For the NOW98 cruise, these TSG data have not yet been released by the Japanese group doing the quality assurance, necessitating that some statistics be given inclusive and exclusive of this cruise. The values of the weekly Reynolds' OISST were also extracted for each target pixel using bilinear interpolation from the 1º fields; these values are compared to M-AERI SST along the whole cruise track.

The sparcity of the M-AERI—Pathfinder matchups, compared to the M-AERI—TSG and M-AERI—OISST data, is apparent. This is because, away from the high latitude regions, each NOAA polar orbiting satellite passes overhead only twice a day, and at those times it is necessary for the M-AERI to be in a location of clear skies to register as a good M-AERI—Pathfinder comparison.

The statistics of the results from the SST, using the M-AERI SST as the reference temperature, from each cruise and as a whole, are presented in Table 16. Note that the mean difference, combining all good records from the mid-latitude cruises, between the Pathfinder and the M-AERI SSTs is 0.06K, with a standard deviation of 0.29K. Inclusion of the noisier NOW data increase these estimates to 0.13 ± 0.37K. The results are biased towards those from the GASEX98 and NOW98 cruises, as the data collected during these are more numerous than those from other shorter cruises.

These results compare very favorably with those from the climatological study of Casey and Cornillon [1999] and with the estimates from a similar, much more extensive, comparison of NOAA-14 MPFSST to buoy data which provides a mean difference of 0.02 K and a standard deviation of 0.53K. The ships' TSGs are closest to the M-AERI SST; those times where there are substantial differences are related to skin—bulk SST differences at times of high insolation and small wind mixing. Next best is the Pathfinder 4 km resolution estimate, generally >10% worse than the TSG with an additional bias of approximately 0.5K. The Reynolds' OISSTs have the largest errors, which is not surprising given the weekly averaging and smoothing inherent in those fields. The OISST outliers are the result of poor OISST boundary conditions in the Arctic (NOW) and along the west coast of North America (FPO).

The results of the comparisons from the Arctic NOW98 cruise have enhanced error for a number of reasons. The lack of the TSG data and a meaningful Reynolds' OISST field hindered the M-AERI quality control, as outliers are more difficult to identify. More importantly, the Pathfinder algorithm may not perform well in the Arctic due to a lack of in situ buoy data with

Table 3. M-AERI –AVHRR Match-up cruise times and locations. (From Kearns *et al.*, 1999, in preparation)

Cruise Name	**Ship**	**Year**	**Begin Day**	**End Day**	**Area of Study**
Combined Sensor Program (CSP)	NOAA S *Discoverer*	1996	78	103	Equatorial Western Pacific
Hawaii-New Zealand transect (HNZ)	R/V *Roger Revelle*	1997	272	286	Central Pacific Meridional Section
Section 24^{o}N Section (24N)	NOAA S *Ronald H. Brown*	1998	8	55	Zonal Section along 24 ^{o}N in North Atlantic
GASEX (GSX)	NOAA S *Ronald H. Brown*	1998	127	188	Mid-latitude North Atlantic
Florida- Panama-Oregon Transit (FPO)	NOAA S *Ronald H. Brown*	1998	196	210	Florida to Panama to Oregon
North Water Polynya study (NOW)	CCGS *Pierre Radisson*	1998	150	203	Baffin Bay, Arctic Polynya

Table 4. Summary Statistics for M-AERI Matchups. . (From Kearns *et al.*, 1999, in preparation)

Cruise Description	**SST Difference**	**Mean**	**Standard Deviation**
CSP 1996, N = 23 (1112 total)	TSG - M-AERI	0.07 (0.04)	0.10 (0.20)
	OISST - M-AERI	0.20 (0.09)	0.32 (0.45)
	MPFSST- M-AERI	0.16	0.20
HNZ 1997, N = 6 (726 total)	TSG - M-AERI	0.10 (0.14)	0.05 (0.19)
	OISST - M-AERI	0.04 (-0.13)	0.08 (0.49)
	MPFSST- M-AERI	-0.03	0.25
24N 1998, N = 16 (1833 total)	TSG - M-AERI	0.22 (0.17)	0.07 (0.13)
	OISST - M-AERI	0.05 (0.08)	0.42 (0.41)
	MPFSST- M-AERI	0.03	0.18
GASEX 1998, N = 168 (5104 total)	TSG - M-AERI	0.02 (0.02)	0.30 (0.32)
	OISST - M-AERI	0.32 (0.30)	0.47 (0.56)
	MPFSST- M-AERI	-0.01	0.25
FPO 1998, N = 47 (1244 total)	TSG - M-AERI	0.14 (0.06)	0.19 (0.29)
	OISST - M-AERI	0.85 (0.37)	0.86 (0.71)
	MPFSST- M-AERI	0.27	0.40
NOW 1998 (Arctic), N = 176 (4251 total)	TSG - M-AERI	NA (NA)	NA (NA)
	OISST - M-AERI	-0.79 (-1.11)	0.57 (0.82)
	MPFSST- M-AERI	0.24	0.44
Total, all data, N = 436 (total 14277)	OISST - M-AERI	-0.08 (-0.18)	0.82 (0.89)
	MPFSST - M-AERI	0.13	0.37
Total, excluding NOW data, N = 260 (total 10015)	TSG - M-AERI	0.06 (0.06)	0.26 (0.28)
	OISST - M-AERI	0.38 (0.21)	0.58 (0.56)
	MPFSST- M-AERI	0.06	0.29

The numbers in brackets refer to statistics derived from all appropriate data and not just restricted to the times of match-ups with the AVHRR.

which to calculate the appropriate Pathfinder coefficients, a poor first guess field provided by the Reynolds' OISST average, and the nearby presence of sea ice may adversely affect the AVHRR retrievals.

Conclusions

The M-AERI has proven itself to be capable of providing consistent data sets of oceanic skin temperatures in the full range of environmental conditions necessary to validate global, satellite-derived SST fields. In a comparison with AVHRR SSTs, the removal of the errors introduced in conventional validations by the skin-bulk temperature differences, results in appreciably lower uncertainties in the satellite retrievals.

Although the number of M-AERI—Pathfinder points is relatively small, these results suggest that the Miami Pathfinder algorithm is much more accurate than has been estimated by previous studies - at least for those atmospheric and oceanic conditions sampled by these six cruises. The fact that Pathfinder SSTs are nearly as good as the thermosalinographs of these research vessels, when compared to the M-AERI data, is very encouraging for global SST studies using AVHRR data. The similarity of the Pathfinder and TSG statistics confirms that the Pathfinder algorithm derives an estimate of a bulk temperature in which a mean thermal skin effect is embedded, as a direct result of the method of deriving the coefficients.

The M-AERI—Pathfinder comparisons have clearly demonstrated the feasibility of using M-AERI measurements to validate the ATSR SST retrievals, a project that is in its initial stages and will be reported upon in the future.

Acknowledgements

Members of the M-AERI group at RSMAS, who have contributed to the collection, processing and analysis of the data discussed here, includes O.B. Brown, R.H. Evans, J. Hanafin, D. Heaton, E. Kearns, E. Key, A Kumar, J. Leff, R. Sikorski, R. Skovron (MAST Academy) M. Szczodrak, and D. Wilson-Diaz. Thanks are also extended to P. Evans (NCSU), R. Knuteson (SSEC), W. McKeown (NRL) B. Osborne (Curtin University of Technology, Perth, Australia) and J. Short (SSEC) or at-sea support, and the AERI Group at SSEC, University of Wisconsin-Madison, for technical support. The captains, officers and crews of the NOAA S *Discoverer*, R/V *Roger Revelle*, NOAA S *Ronald H. Brown*, and CCGS *Pierre Radisson* are acknowledged. Funding was provided from NASA, NSF and DOE, through the ARM program.

References:

Casey, K.S. and P. Cornillon, 1999. A comparison of satellite and in situ based sea surface temperature climatologies, Journal of Climate. In press.

Kannenberg, R. 1998. Infrared (IR) instrument comparison workshop at the Rosenstiel School of Marine and Atmospheric Science (RSMAS). The Earth Observer, 1998.

Mather, J.H., T.P. Ackerman, W. Clements, F. Barnes, M. Ivey, L. Hatfield, and R.M. Reynolds, An Atmospheric Radiation and Cloud Station in the Tropical Western Pacific. Bull. Amer. Meteor. Soc., 78, 627-642, 1998.

Revercomb, H. E., H. Buijs, H. B. Howell, D. D. Laporte, W. L. Smith, and L. A. Sromovsky, 1988: Radiometric Calibration of IR Fourier Transformation Spectrometers: Solution to a problem with the High-Spectral Resolution Interferometer Sounder. Appl. Optics, 27, 3210-3218.

Reynolds, R. W. and D. C. Marisco, 1993. An improved real-time global sea surface temperature analysis. J. Climate, 6, 114-119.

Smith, W.L., R.O. Knuteson, H.E. Revercomb, W. Feltz, H.B. Howell, W.P. Menzel, N.R. Nalli, O. B. Brown, J. Brown, P.J. Minnett and W. McKeown, 1996. Observations of the infrared radiative properties of the ocean - implications for the measurement of sea-surface temperature via satellite remote sensing. Bull. Am. Met. Soc., 77, 1996, 41-51.

Stokes, G.M. and S.E. Schwartz, 1994. The atmospheric Radiation Measurement (ARM) Program: Programmatic Background and Design of the Cloud and Radiation Test Bed. Bull. Am. Met. Soc., 75, 1201-1221.

Wu, X. and W.L. Smith, 1997. Emissivity of rough sea surface for 8-13 μm: modeling and validation. Applied Optics, 36, 1-11.