AATSR SST Validation using the M-AERI

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ABSTRACT

Establishing confidence in the accuracy of AATSR-derived skin sea-surface temperatures (SSTs) requires extensive validation of the algorithms used in their derivation. This is best achieved by comparison with independent measurements of the skin SST. An approach is described that uses an accurately calibrated Fourier-Transform Infrared spectroradiometer, the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI), which is used at sea on a variety of ships. Past experience in the validation of AVHRR and MODIS is presented, and the role of such validation approaches in the context AATSR is discussed.

1. INTRODUCTION

The main sources of uncertainty in the retrieval of skin SST are the accuracy of the top-of-atmosphere measurements of the spacecraft radiometers, which relies on good on-board calibration procedures and pre-launch calibration and characterization of the instruments, and on the accuracy of the algorithm applied to the calibrated spectral radiance measurements to correct for the effects of the intervening atmosphere. The infrared SST retrievals are usually made in spectral intervals where the atmosphere is relatively transparent, the so-called atmospheric windows, where the main atmospheric component that modifies the SST signal is water vapor. This, if course, is very variable and correction for its effects requires the use of an algorithm that is applied on a pixel-by-pixel basis and which must leave acceptably-small residual errors over a wide range of environmental conditions.

The SST errors that arise from uncertainties in the calibrated radiances measured by the spacecraft radiometers are usually small in comparison with those from the atmospheric correction algorithms, especially in the case of the AATSR which has undergone extensive pre-launch testing and characterization. Consequently, the validation of the AATSR skin SST retrievals is largely a determination of the error characteristics of the atmospheric correction algorithms and therefore must be determined in a wide range of conditions that capture the full variability of the cloud-free atmosphere. Otherwise systematic errors could exist that would go undetected and contaminate analyses of the data and possibly invalidate conclusions on which these are based.

There are many approaches to validating the AATSR-derived skin SSTs, such as comparison with comparable SST fields derived from other radiometers on other satellites [1], comparison with bulk, sub-surface SSTs measured from drifting or moored buoys [2, 3] or with independent measurements of the skin SST made by radiometers on ships or aircraft. The approach using radiometers on ships is the subject of this paper. It has inherent advantages over other techniques as it is a comparison of 'like with like' and the therefore can give a fairer determination of the uncertainties in the SST fields. The infrared signal detected over the oceans by spacecraft radiometers, such as the AATSR, is the surface skin layer, the temperature of which can be different from that measured below the surface because of the heat flow from the ocean to the atmosphere – the skin effect (e.g. [4]), and, during the day, through the absorption of insolation in low wind speed conditions – the diurnal thermocline (e.g. [2, 5, 6]). These vertical temperature gradients can be a significant source of error when the accuracy of the satellite-derived SSTs budget is determined using sub-surface temperature measurements, and the consequences of the sub-surface thermal variability is attributed to the satellite measurement. By using radiometric measurements of the oceanic skin temperature, this factor is removed, and the resulting estimate of the satellite-derived SSTs is a better determination of the true uncertainties in the satellite retrievals [7].

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MARINE-ATMOSPHERIC EMITTED RADIANCE INTERFEROMETER

The M-AERI [8] is a Fourier-Transform Infrared Interferometer that is based on the original concept of Michelson and Morley [9]. The radiation entering the instrument is split into two equal parts, one of which traverses a fixed distance to a plane mirror that directs is back to the beam splitter. The other beam is directed to a moving mirror that oscillates in the direction of the incident beam, so that the path length periodically varies. The two beams interfere on recombination at the beam splitter according to the path length difference in terms of the wavelength of the incoming radiation. The recombined beams are directed to the detectors which record the time-varying signal, referred to as an interferogram. The Fourier transform of the interferogram is the spectrum of the incoming radiation.

The M-AERI operates in the range of infrared wavelengths from ~3 to ~18µm and measures spectra with a resolution of ~0.5 cm^{-1}. It uses two infrared detectors to achieve this wide spectral range, and these are cooled to ~78^{o}K (i.e. close to the boiling point of liquid nitrogen) by a Stirling cycle mechanical cooler to reduce the noise equivalent temperature difference to levels well below 0.1K. The M-AERI includes two internal black-body cavities for accurate real-time calibration. A scan mirror directs the field of view from the interferometer to either of the black-body 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 a pre-selected time interval, usually a few tens of seconds, to obtain a satisfactory signal to noise ratio, and a typical cycle of measurements including two view angles to the atmosphere, one to the ocean, and calibration measurements, takes about ten 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. The radiometric calibration of the M-AERI is done continuously throughout its use. As with simpler self-calibrating radiometers, an FTIR spectroradiometer can be calibrated by using two black-body targets at known temperatures. These provide two reference spectra to determine the gains and offsets of the detectors and associated electronics. Since the instrument measures interferograms rather than spectra or spectrally integrated radiance (as is the case with a band-pass filter radiometer), it is important that the calibration be independent of the positions of the moving mirrors. This is achieved by very careful assembly, especially in position and alignment of the field-stop, so that the effective aperture size and its projection onto the detectors, is insensitive to path length differences. Further details of the technicalities of FTIR calibration are given elsewhere [10]. The mirror scan sequence includes measurements of the reference cavities before and after each set of spectra from the ocean and atmosphere.

The absolute accuracy of the infrared spectra produced by the M-AERI is determined by the effectiveness of the black-body cavities as calibration targets. The black-body cavities are copper cylinders with conical end plates, one with a circular orifice to allow the radiation to emerge. The internal walls are painted matte black and the cavity has an effective emissivity of >0.998. During construction, the black-body thermistors are calibrated against thermometers traceable to NIST (National Institute of Standards and Technology) standards.

A water-bath black-body calibration target [11] is used periodically to check the accuracy of the internal calibration of the M-AERI and typical results of the measurements in two clear parts of the spectrum, from each of the two M-AERI detectors, are shown in Table 1. The radiometric properties of the water-bath black-body calibration target have recently been characterized against the NIST EOS Transfer Radiometer [12-14]

Table 1. Laboratory tests of M-AERI accuracy

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

The mean discrepancies in the M-AERI 02 measurements of the NIST water bath blackbody calibration target in two spectral intervals where the atmosphere absorption and emission are low. Discrepancies are M-AERI minus NIST temperatures. The increase of discrepancy with increasing target temperature is consistent with an effective emissivity of the target of 0.998. [8]

The M-AERIs, of which there are three, have been deployed on a number of cruises in the past several years that span a wide range of conditions (Figure 1). Most of these deployments are on research vessels. The tracks of two cruises that have been made since the ENVISAT launch, and which will be used for AATSR validation are shown in Figure 2.

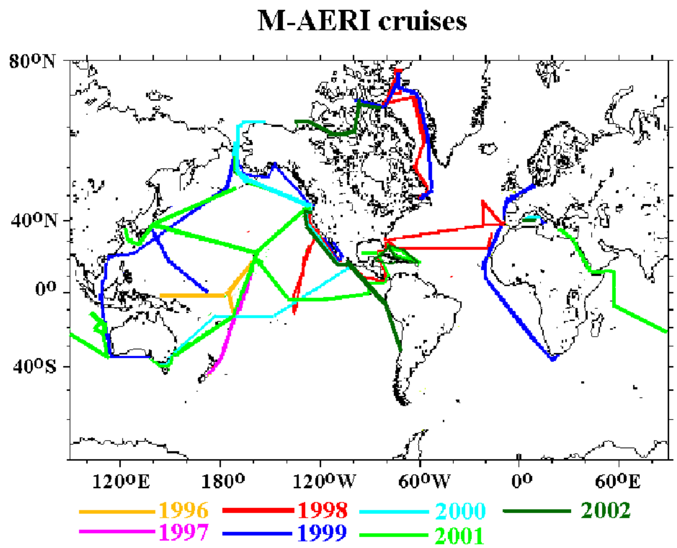

Figure 1. Cruise tracks of M-AERI deployments.

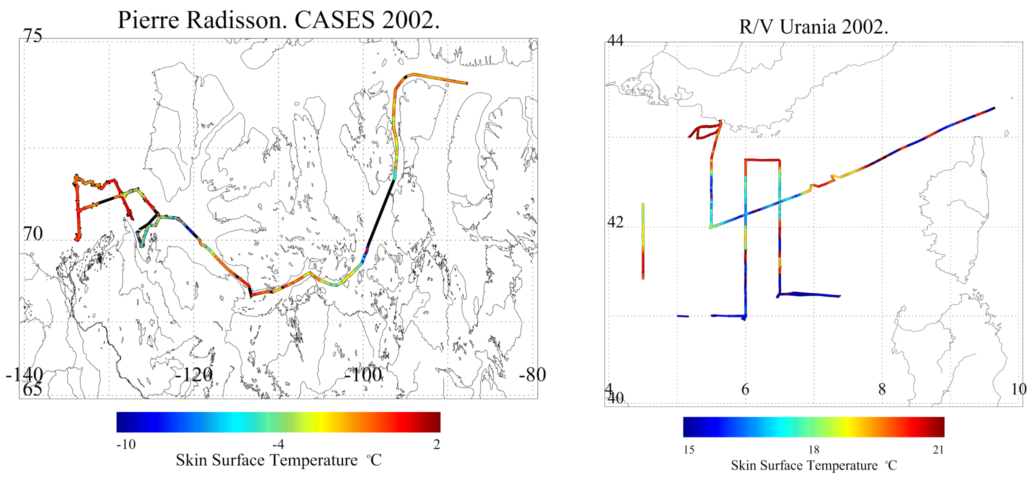

Figure 2. Tracks for M-AERI cruises on research ships since the launch of Envisat. Left – in the Arctic on the Canadian Coast Guard Icebreaker *Pierre Radisson* (September 23 - October 18, 2002. Right – in the Mediterranean Sea on the Italian research vessel *Urania* (September 29 – October 8, 2002). The tracks are coloured by the M-AERI surface temperature measurements.

An important M-AERI installation is on the Royal Caribbean Cruise Lines vessel *Explorer of the Seas* (http://www.rsmas.miami.edu/rccl/) which operates a weekly cruise schedule from the Port of Miami, and on which a M-AERI has been installed since November 2000 [15]. The M-AERI operates continuously while the ship does two alternate circuits round the Caribbean (Figure 3) on a bi-weekly basis, leaving Miami on Saturday evenings and returning the following Saturday morning.

In all cases the M-AERIs are mounted so that the measurements are taken beyond the influence of the ship (Figure 4). For the *Explorer of the Seas* deployment, the skin SST is retrieved form the measured spectra in real-time and transmitted to RSMAS via a satellite link within about ten-minutes. These data are sent to the University of Leicester on a daily basis for inclusion in the AATSR SST validation procedure, and for onward transmission to the NILU data base. In other cases the data are treated off-line, post-cruise.

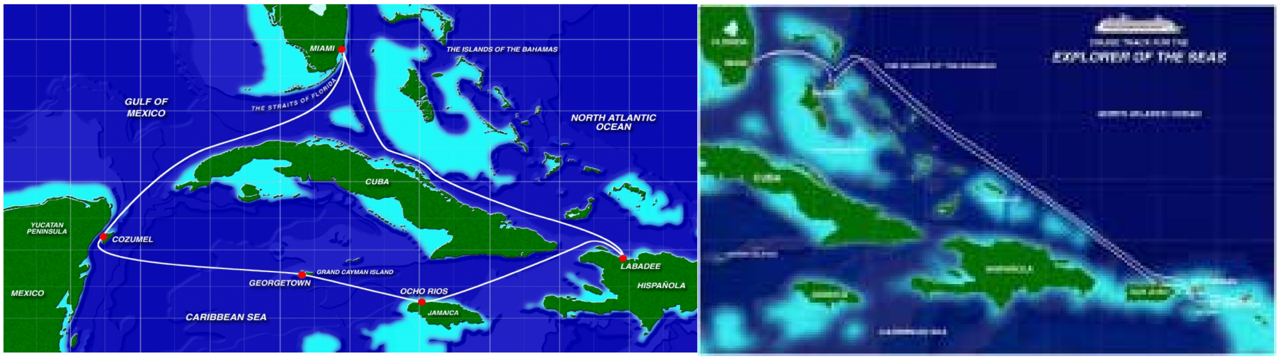

Figure 3. Tracks of the Explorer of the Seas. The western (left) and eastern (tracks) are done on alternate weeks.

Figure 4. M-AERIs installed on the *Pierre Radisson* (top left), the *Urania* (top right) and the *Explorer of the Seas* (left). In all cases the sea-viewing measurements are taken ahead of the bow wave and the influence of the ship.

PRIOR RESULTS

Although at the time of writing, the skin SSTs from the AATSR have not been validated by the M-AERI, due to the hitherto lack of availability of the satellite data, the technique has been applied to data from other satellites, specifically the AVHRR (Advanced Very High Resolution Radiometer) [7] and the MODIS (Moderate Resolution Imaging Spectroradiometer) on the NASA EOS *Terra* and *Aqua* satellites [1, 16]. In both cases the residual uncertainty of the satellite-derived SSTs is about 0.3K (rms) with a bias of 0.1K or less, indicating that the M-AERI is capable of providing validation data at the level of accuracy required for the AATSR.

COMPLEMENTARY APPROACHES

While there are good arguments for using the M-AERI, and other filter radiometers (see [14] and other papers in this volume), as the basis for validating AATSR skin SST retrievals, the narrow swath of the sensor will lead to a sparse data set than may not sample enough of the parameter space of environmental variability to reveal regional or seasonal error characteristics of the retrievals. It will therefore be necessary to utilize the much larger data set of match-ups between the AATSR and the drifting and moored buoys to provide a wider-ranging validation exercise [3]. By restricting the matchups to those at night, the relationship between the skin SST, retrieved from the AATSR measurements, and the bulk SST measured form the buoys is reasonably well behaved, and although it does contribute another term to the satellite SST validation error budget, this does not seem to be dominant [4, 17]. A further approach would be to relate the AATSR SSTs to those measured by broad swath imagers, such as MODIS, that have been independently validated. In particular, the MODIS on *Terra* has a comparable equator crossing time, thereby helping to reduce uncertainties that arise from the growth and decay of the diurnal thermocline [18, 19]. Again, however, night-time comparisons would be preferred.

SUMMARY

The M-AERI is an instrument that can make a significant contribution to the validation of AATSR skin SST retrievals. It is a very well-calibrated radiometer, with traceability to NIST standards, and is well-tried with many successful field deployments undertaken, and validation results already achieved. The procedures for the AATSR validation are in place and will be applied to the AATSR measurements in the near future.

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