At-Sea Measurements of Surface Emissivity in the Thermal Infrared

Peter J. Minnett* and Jennifer A. Hanafin#

Rosenstiel School of Marine and Atmospheric Science, University of Miami.

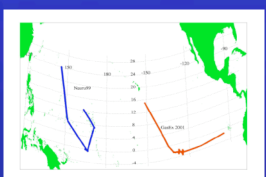
#Now at Department of Space and Atmospheric Physics, Imperial College London, South Kensington, London, UK.

Introduction

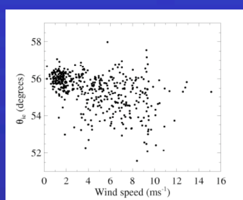
To make accurate SST retrievals from satellite, air-borne, or ship-based radiometers, the sea surface emissivity (_) must be well known. Emissivity is the ratio of the thermal radiation emitted by a body to that from a perfect blackbody, and it is wavelength (_) and emission angle (_) dependent for most materials. The emissivity is related the surface reflectivity (_) through _ + _ = 1. The radiometric measurement of SST is very sensitive to uncertainties in _ through its modulation of the surface emission, and the reflection of downwelling atmospheric radiation. A 1% change in _ corresponds to a change in retrieved SST of 0.66 K (at _ = 10 _m), 0.73 K (at _ = 12 _m), or 0.24 K (at _ = 3.5 _m). So, to reach the SST measurement accuracy required for climate research, _ must be known to >0.5% uncertainty in the 8–12 _m wavelength region, and >1% in the 3–4.5 _m window.

The spectral and emission angle properties of the sea water emissivity are imperfectly known. Algorithms applied to near-surface radiometric measurements of the skin temperature used to validate satellite retrievals require a specification of _. Discrepancies that result from uncertainties in _ are attributed to the satellite measurements, thereby inflating their apparent errors.

The tilting of facets of the sea surface under the influence of waves leads to an apparent wind speed dependence of _ through the emission angle dependence. Models have been used to predict _ and its wind speed dependence (Masuda et al., 1988; Watts et al., 1996; Wu and Smith, 1997; Nalli et al, 2001). Here we derive some of the properties of _ pertinent to the measurement of sea-surface temperature from spectral measurements of the infrared emission from the sea surface and overlying atmosphere taken at sea using the M-AERI. Measurements from two cruises in the Pacific Ocean are used: the R/V *Mirai* in the Nauru99 campaign, and the NOAA S *Ronald H Brown* in the 2001 Gas Exchange cruise, GasEx1001. A full discussion of the data, analysis technique and results are given by Hanafin and Minnett, 2005.



Cruise tracks of the R/V *Mirai* during Nauru99 and of the NOAA Ship *Ronald H. Brown* during GasEx 2001.



Scatter plot of _ie with wind speed

Method

The spectral resolution of the M-AERI (0.5 cm-1) is high enough to resolve many individual atmospheric emission features in the spectra. These features are visible in the upwelling radiance spectra as a result of reflection at the sea surface of the atmospheric emission and are also visible in the brightness spectra derived from these radiances. By using vibrational techniques to minimize the appearance of the atmospheric emission lines in the down looking M-AERI measurements, both the emissivity, _, and effective emission angle, _ie, can be derived (Hanafin, 2002; Hanafin and Minnett, 2005).

Summary

The wavelength, emission angle, temperature, and wind-speed dependences are shown in the figures at right.

The emissivity, _, is generally higher than predicted by the models, and the wind-speed dependency is smaller. The situation appears to be more simple than the models suggest.

The temperature dependence, determined in controlled conditions in an open-air laboratory setting, is strongly wavelength dependent. This introduces temperature-dependent bias errors in the radiometric SST measurements used to validate the satellite-derived fields.

Future Research

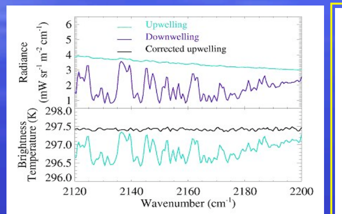
These results represent the magnitude and behavior of the infrared emissivity of the sea surface determined under field conditions, directly from well-calibrated data. They fill only a relatively small part of the possible parameter space. Future research should be directed at extending the ranges of emission angle, wavelengths, wind-speed and temperatures of the measurements.

Improvements in our understanding of the behavior of the surface emissivity will reduce the uncertainties in the near-surface radiometric measurements of the ocean skin temperature used in the validation of the satellite retrievals of sea-surface temperature.

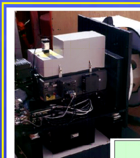
Looking to the future, the generation of at-launch atmospheric correction algorithms for new sensors, e.g. VIIRS (Visible/Infrared Imager/Radiometer Suite) for NPOESS (National Polar-orbiting Operational Environment Satellite System) and NPP (NPOESS Preparatory Project), using numerical radiative transfer simulations are likely to lead to systematic errors when these algorithms are applied to on-orbit measurements.

The M-AERI

The radiometric measurements are provided by the Marine-Atmospheric Emitted Radiance Interferometer (M-AERI; *Minnett et al., 2001).* The M-AERI is a Fourier Transform InfraRed (FTIR) Spectroradiometer that measures infrared spectra in the wavelength range of ~3 to ~18 µm. It has two very stable internal black-body cavities for real-time calibration. This is periodically checked against a laboratory water-bath black-body calibration target, built to a NIST (National Institute of Standards and Technology) design (*Fowler, 1995*), which has been characterized by the NIST EOS TXR (Thermal-infrared Transfer Radiometer; *Rice et al., 2000*), providing radiometric traceability to NIST standards *(Rice, et al., 2004).*



Sample of M-AERI radiance and corresponding brightness temperatures showing high degree of correlation between upwelling uncorrected BT and downwelling radiance and reduction of BT variance from ±0.5K to ±0.05K when the correction for reflected radiance is applied.



Specifications

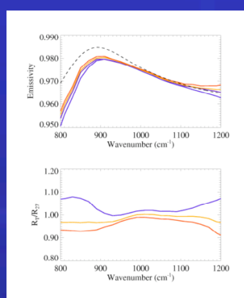
Spectral interval	~3 to ~18µm
Spectral resolution	0.5 cm $^{-1}$
Interferogram rate	1Hz
Aperture	2.5 cm
Detectors	InSb, HgCdTe
Detector temperature	78°K
Calibration	Two black-body cavities
SST retrieval uncertainty	<< 0.1K (absolute)

Laboratory tests of M-AERI accuracy

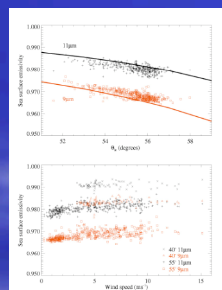
Target Temp.	LW (980-985 cm $^{-1}$)	SW (2510-2515 cm $^{-1}$)
20°C	+0.013 K	+0.010 K
30°C	-0.024 K	-0.030 K
60°C	-0.122 K	-0.086 K

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.

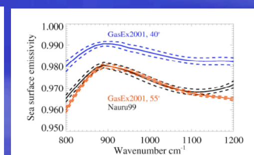
M-AERI specifications and accuracies



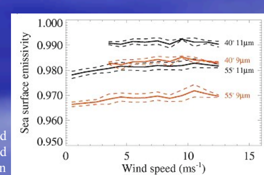
Measured temperature dependence of water surface spectral emissivity, _, taken in controlled, open-air laboratory conditions. Top - The emissivities are averaged in 5K bins, centered on 22.5°C (dark blue), 27.5°C (purple), 32.5°C (red) and 37.5°C (yellow). The dashed line shows the emissivity predicted from Fresnel equations using Bertie and Lan's (1996) refractive index data. Bottom - Ratio of measured reflectances of 22.5°C, 32.5°C and 37.5°C water to 27.5°C water.



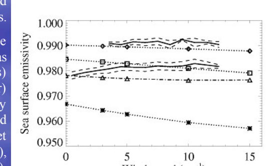
Nauru99 and GasEx 2001 55° measured 910 and 1100cm-1 emissivity values plotted as functions of computed _ie (top) and 40° and 55° emissivities as a function of wind speed (bottom).



Spectral sea surface emissivity from 800-1200cm-1 (12.5-8.33 _m) computed using a piecewise linear variance minimization technique from GasEx 2001 data at viewing angles of 55° and 40° and Nauru99 data at a 55° view angle. The standard deviations are plotted as a dashed line.



Above right - Observed mean (solid lines) and standard deviation (dashed lines) of the sea surface emissivity in 1ms-1 wind speed bins for 9 _m and 11 _m at 40° and 55° incidence angles.



Below right -Wind-speed dependence of sea-surface emissivity at 11 _m as measured by this study (solid curves) at 40° (upper) and 55° (lower) incidence angles and that predicted by the Watts et al. model (dot-dashed curve) at 52°–55° and the Masuda et Al model (dotted curves) at 40° (◊), 50° (_), and 60° (*).

References

Bertie, J.E. and Z. Lan (1996), Infrared intensities of liquids: the intensity of the OH stretching band of liquid water revisited and the best current values of the optical constants of H_2O (l) at 25°C between 15,000 and 1cm-1, *Applied Spectroscopy*, 50 (8), pp. 1047-1057.

Fowler, J.B. (1995), A third generation water bath based blackbody source., *J. Res. Natl.Inst. Stand. Technol.*, 100 (5), 591-599.

Hanafin, J. A. (2002), On the infrared properties of the sea surface., Ph.D. thesis, 111pp. pp, University of Miami, Miami.

Hanafin, J. A., and P. J. Minnett (2005), Infrared-emissivity measurements of a wind-roughened sea surface, *Applied Optics*., 44, 398-411.

Masuda, K., T. Takashima, and Y. Takayama (1988), Emissivity of pure and sea waters for the model sea surface in the infrared window region, *Remote Sensing of Environment*, 24, 313-329.

Minnett, P.J., R.O. Knuteson, F.A. Best, B.J. Osborne, J.A. Hanafin, and O.B. Brown (2001), The Marine-Atmospheric Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer, *Journal of Atmospheric and Oceanic Technology*, 18 (6), 994-1013.

Nalli, N. R., W. L. Smith, and B. Huang (2001), Quasi-specular model for calculating the reflection of atmospheric-emitted infrared radiation from a rough water surface., *Applied Optics*, 40, 1343-1353.

Rice, J.P., S.C. Bender, and W.H. Atkins, Thermal-infrared scale verifications at 10 micrometers using the NIST EOS TXR, *Proc. SPIE*, 4135, 96-107, 2000.

Rice, J.P., J.J. Butler, B.C. Johnson, P.J. Minnett, K.A. Maillet, T.J. Nightingale, S.J. Hook, A. Abtahi, C.J. Donlon, and I.J. Barton, The Miami2001 Infrared Radiometer Calibration and Intercomparison: 1. Laboratory Characterization of Blackbody Targets , *Journal of Atmospheric and Oceanic Technology*., 21, 258-267, 2004.

Watts, P., M. Allen, and T. Nightingale (1996), Sea surface emission and reflection for radiometric measurements made with the along-track scanning radiometer, *Journal of Atmospheric and Oceanic Technology*., 13, 126-141.

Wu, X., and W. L. Smith (1997), Emissivity of rough sea surface for 8-13 _m: modeling and verification, *Applied Optics*, 36, 2609-2619.

*pminnett@rsmas.miami.edu