Infrared Emissivity of Seawater and Foam at Large Incidence Angles in the 3-14 μm Wavelength Range

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Abstract

The emissivity of the sea surface is an important parameter for infrared measurements at large incidence angles, and the increased radiance of foam from breaking wave crests, attributed to the higher emissivity of foam over foam-free water, has not been confirmed experimentally at angles above 65° . Here we report on outdoor laboratory experiments performed to confirm model predictions of a dramatic decrease in seawater emissivity at large incidence angles and to provide the first measurements of foam emissivity in this regime. A method is presented using Fourier transform infrared (FTIR) spectroscopy to measure the spectral emissivity of seawater and foam at incidence angles from 60° to 85° and wavelengths from 3.5-5.5 and 8-14 μm . The emissivity of water and foam are found to decrease dramatically for incidence angles above 65° , with the decrease being less dramatic for foam than for water. The emissivity of foam is found to be higher than that of water for all wavelengths and incidence angles above 65° where the difference is statistically significant. The difference between the emissivity of foam and the emissivity of water increases with incidence angle and reaches a maximum of 0.23 at 8.9 μm and 85° incidence. The significant difference between the emissivity of foam and water should be accounted for in infrared models of the sea surface at large incidence angles.

Keywords: thermal infrared, emissivity, sea surface, foam, large grazing angles

1. Introduction

The infrared emissivity of the sea surface is a key parameter for remote sensing applications such as sea surface temperature measurements, target detection, and wave parameter estimation [e.g. *Hanafin and Minnett, 2005; Hoff et al. 1990; Branch et al., 2014*]. A specific example where foam emissivity becomes important is in identifying the active, aerated wave roller, as done in *Carini et al. [2015]* to estimate breaking wave energy dissipation rates. Here, the contrast of the wave roller in thermal imagery, enhanced due to elevated emissivity of foam with respect to the surrounding non-foamy water, is exploited for identification of the roller via a brightness temperature threshold. The utility of the approach in *Carini et al. [2015]* is based on the near-grazing angles used ($> 65^\circ$) and the understanding of foam-seawater brightness temperature contrast, which in turn dependent on the predictability of emissivity differences from both types of surfaces. This can translate to improved understanding of ocean wave breaking in thermal images from manned and unmanned airborne platforms and ships .

The emissivity of seawater is close to unity at small incidence angles but models predict a dramatic decrease for angles above 70° , [*Masuda et al.1988; Masuda, 2006; Filipiak 2008; Embury et al. 2012*] with a concomitant increase in reflectivity due to Kirchoff's Law for an opaque surface. Extensive measurement results have been published of the emissivity at small to moderate incidence angles for sea surface temperature calculations [e.g. *Nalli et al. 2008; Niclòs et al., 2014*], but very few measurements have been made at large incidence angles where the dramatic decrease is predicted. The largest incidence angle for which the infrared emissivity of seawater has been published is 73.5° [*Smith et al. 1996*]. Emissivity models typically consider the sea surface as a distribution of facets of foam-free water, with many models accounting for the change in the distribution of tilt angles with wind speed as waves grow [*Masuda et al. 1988, Freund et al. 1997, Wu and Smith 1997*]. However, when breaking waves are present the sea surface is composed of foam and foam-free water, resulting in a more complex rough surface. Current models do not account for the difference in the emissivity between foam and foam-free

water.

Increased infrared radiance of breaking waves has been observed at grazing incidence but the cause of the increase has not been established [Eisner et al. 1962, Branch et al. 2014, Carini et al. 2015]. Eisner et al. [1962] hypothesized the increase is due to foam having a higher emissivity than water. The emissivity of foam has been found to be different from that of water in the infrared [Salisbury et al. 1993, Niclòs et al. 2007, hereafter N07]. Salisbury et al. [1993] calculated the emissivity at a 10° incidence angle and found foam to have a lower emissivity than water for the wavelength bands from 3-5 and 8-10 μm but a higher emissivity than water from 12-14 μm. N07 reported measurements at incidence angles from 25-65° at four wavelength bands between 8 and 14 μm and found foam to have a higher emissivity than water. The objective of this work was to determine the emissivity of water and foam at incidence angles larger than 65° to as close to grazing as possible.

In this paper a Fourier transform infrared, FTIR, spectrometer is used to measure the spectral emissivity of flat water and foam in the wavelength bands from 4-6 μm and 8-14 μm at incidence angles from 60-85°. Section 2 describes the method for calculating emissivity from FTIR measurements and outlines the details of the experiment. Section 3 gives the results and discussion and section 4 summarizes the conclusions.

2. Methodology

The emissivity of a water or foam surface can be calculated from the radiative transfer equation by measuring the radiance coming from the surface and the sky above the surface. The radiance measured when observing a surface at wavelength λ and incidence angle θ at close range is

$$L_m(\theta, \lambda) = \varepsilon(\theta, \lambda)L_s(\lambda) + \rho(\theta, \lambda)L_d \quad (1)$$

where L_m is the total radiance measured at the sensor, ε is the surface emissivity (water or foam), L_s is the surface radiance of the water or foam, ρ is the reflectivity, and L_d is the downwelling radiance. A surface can exhibit reflections ranging from diffuse (Lambertian) to specular. For a specular surface L_d is a direct

measure of the sky radiance at the reflected angle $L_{sky}(\theta, \lambda)$ and each wavelength. For a diffuse surface, L_d is the downwelling hemispherical irradiance, $E_{sky}(\lambda)/\pi$. Previously, the downwelling hemispherical irradiance has been estimated using three different methods: from a measurement of directional downwelling radiance at single angle [Minnett et al. 2001; Smith et al. 1996], measured with a gold diffuse plate [Salvaggio and Miller 2001], or modelled using atmospheric profile data [García-Santos et al. 2013]. The large incidence angles used in our experiment would require an unreasonably large gold diffuse plate to measure the downwelling hemispherical irradiance. Thus for Lambertian approximations of emissivity we fit our nightly angular measurements to a cloud-free radiance model [Rubio et al., 1997; N07].

$$L_{sky}(\theta, \lambda) \approx L_{sky}(0^\circ, \lambda) \cos^{-x_i}(\theta), \text{ and} \quad (2a)$$

$$E_{sky}(\lambda)/\pi \approx \frac{2}{2-x_i} L_{sky}(0^\circ, \lambda). \quad (2b)$$

This is a valid approximation, because we made our measurements under clear night skies on a building rooftop without surrounding structures and within a short amount of time, similar to García-Santos et al. [2013]. Using Kirchhoff's law to relate the emissivity to the reflectivity as

$$\varepsilon(\theta, \lambda) + \rho(\theta, \lambda) = 1, \quad (3)$$

the spectral emissivity can then be solved for as

$$\varepsilon(\theta, \lambda) = \frac{L_m(\theta, \lambda) - L_d}{L_s(\lambda) - L_d} \quad (4)$$

where L_m is the sensor radiance. The surface radiance, L_s , can be measured at an angle where the surface emissivity is high and known [Smith et al. 1996] or estimated as the Planck radiance corresponding to the surface skin temperature. In order to use the Planck radiance, the surface skin temperature can be measured radiometrically [Jessup and Branch, 2008] or estimated using a contact temperature and a modeled cool skin offset [N07]. A modeled cool skin offset is required when using a contact temperature because the infrared optical depth of O(10 μ m) is much less than the O(1 mm) thick thermal boundary layer, both of which are not resolvable with a contact measurement. Contact temperature measurements

with a constant cool skin offset were used by *N07*, but the cool skin offset is a function of atmospheric conditions and surface mixing [*Donlon et al. 2002*] and is unknown for foam. Alternatively, we measured L_s radiometrically using (2) with measurements of the surface and sky at an incidence angle of 10° , where the emissivity of the surface is well known and relatively insensitive to incidence angle near nadir [*Salisbury et al., 1993*]. Our method for calculating emissivity uses published values of the emissivity of water and foam and does not depend on a model of the cool skin effect. This is especially important for foam measurements since there are no models of the cool skin effect in foam and there is evidence that residual foam may cool differently than water [*Fogelberg, 2003; Marmorino and Smith, 2005*].

The radiance, $L(\lambda)$, observed by a FTIR spectrometer is linearly related to the uncalibrated instrument response (counts) at a wavelength $V(\lambda)$ in volts, by a responsivity, g , and offset, L_o [*Korb et al., 1996*],

$$L(\lambda) = gV(\lambda) + L_o. \quad (5)$$

If (2) is expressed in terms of V then the responsivity and offset terms cancel and it becomes

$$V_m(\theta, \lambda) = \varepsilon(\theta, \lambda)V_s(\lambda) + \rho(\theta, \lambda)V_d. \quad (6)$$

The linear nature of (5) combined with the fact that the responsivity and offset remained constant during our experiment eliminates the need for calibration of the FTIR spectrometer. All emissivity calculations can therefore be made from uncalibrated instrument radiance values.

The surface instrument response, $V_s(\lambda)$, is calculated using a measurement of the surface at an incidence angle of 10° and using published values of the emissivity of water and foam at 10° [*Salisbury et al. 1993*]. Measurements of the surface and sky at 10° are inserted into (6) as follows

$$V_m(10^\circ, \lambda) = \varepsilon(10^\circ, \lambda)V_s(\lambda) + (1 - \varepsilon(10^\circ, \lambda))V_{sky}(10^\circ, \lambda). \quad (7)$$

The surface radiance is solved for as

$$V_s(\lambda) = \frac{V_m(10^\circ, \lambda) - (1 - \varepsilon(10^\circ, \lambda))V_{sky}(10^\circ, \lambda)}{\varepsilon(10^\circ, \lambda)} \quad (8)$$

The resulting value, $V_s(\lambda)$, is independent of incidence angle and can be substituted into (4) for calculations of ε at θ in terms of uncalibrated radiance measurements.

$$\varepsilon(\theta, \lambda) = \frac{V_m(\theta, \lambda) - V_d}{V_s(\lambda) - V_d} \quad (9)$$

Figure 1 shows the four measurements used in each emissivity calculation, where $V_m(10^\circ, \lambda)$ and $V_{sky}(10^\circ, \lambda)$ were used in (8) to calculate $V_s(\lambda)$. This surface radiance was then used in (9) with $V_m(\theta, \lambda)$ and measurements of $V_{sky}(\theta, \lambda)$, input for V_d , to calculate a specular estimate of $\varepsilon(\theta, \lambda)$. For a diffuse estimates of $\varepsilon(\theta, \lambda)$, $V_{sky}(\theta, \lambda)$ is first fit to the sky model (2a) using a nonlinear least squares routine at each wavelength and for each night multiple directional sky measurements were recorded to determine the full sky irradiance. The resulting $E_{sky}(\theta, \lambda)/\pi$ is used for V_d in (9). Only estimates where the calculated model skill in the fit for (2a) is higher than 0.98 are used to calculate Lambertian estimates of emissivity.

Error in $\varepsilon(10^\circ, \lambda)$ will propagate directly through to $\varepsilon(\theta, \lambda)$, but $\varepsilon(10^\circ, \lambda)$ was measured with a noise equivalent emissivity difference of 0.012 [Salisbury, 1990], which is an order of magnitude smaller than the changes in emissivity with incidence angle we report in section 4.

Figure 1. Four radiance measurements used in the emissivity calculation: a) two measurements view the water/foam surface, b) two measurements view the sky.

Measurements were made with a D & P Instruments model 102 FTIR spectrometer with 2.4° field-of-

view optics. The FTIR spectrometer is sensitive to 2-16 μm ($625\text{-}5,000\text{ cm}^{-1}$) radiation spanned by two two detectors with response peaks at 5.1 μm and 10.3 μm , which we will refer to as mid-wave (MW) and long-wave (LW) respectively. The spectral resolution varies with wavelength from 0.0061 μm at 4 μm to 0.04 μm at 10 μm . Observed water and foam surfaces were generated in a tank with dimensions 1.52 m long by 0.39 m wide and 0.17 m deep was filled with UV sterilized and filtered natural seawater. The salinity of the seawater was 31 ppt and the temperature was kept close to the air temperature by preventing solar heating during the day. Air and water temperatures were measured with a thermistor every fifteen minutes.

Porous tubing was submerged in the bottom of the tank and connected to an air compressor to produce foam with an approximate thickness of 2 cm and a maximum bubble diameter of approximately 1 cm. The tank and a foam surface example is shown in Figure 2. The tank was filled to the tank rim to avoid accidental reflection from exposed tank sidewalls at near-grazing angle measurements. For this reason, water measurements were made first followed by foam measurements, because the foam overflowed the edge of the tank and needed to be refilled with spare, ambient temperature sea water.

The experiment was conducted on a rooftop to ensure all downwelling radiance was overwhelmingly dominated by the sky. Measurements were made on 14 nights with clear skies and low wind to eliminate the added complications of variable sky conditions, wind ripples, and varied surface cooling. Water temperature varied from 15.6 $^{\circ}\text{C}$ to 24.3 $^{\circ}\text{C}$ over all the nights, and change 1.4 degrees on average during the course of a single night's observations, which lasted approximately 1 to 2 hours. Air temperature varied 15 $^{\circ}\text{C}$ to 23.9 $^{\circ}\text{C}$ over the course of all experiments and changed 1.7 degrees on average over a single night's observations. A range of angles was sampled every night resulting in 3-8 measurements at each angle by the end of the experiment, and each measurement set taking approximately 15 minutes. The total number of measurements at angles from 60-85 $^{\circ}$ for water and foam is shown in Table 1.

Table 1. Number of measurements of the emissivity of water and foam at each incidence angle

Incidence Angle (°)	Water	Foam
60	8	4
65	8	4
70	7	4
75	5	3
80	7	5
82.5	5	6
85	4	3

Figure. 2 (a) Seawater foam tank and FTIR spectrometer head observing the sky. The foam surface was filled to the tank rim during measurement. (b) Foam bubbles with a ruler showing centimeters.

Our measurements of $\varepsilon(\theta, \lambda)$ depend on observed radiances of foam, water, and sky. Observed radiances of foam, water, and sky vary with wavelength and incidence angle due to both the spectral sensitivity of the instrument and the physical characteristics of the surface and sky. Figure 3 shows a comparison of uncalibrated and calibrated radiances of foam, water, and sky at incidence angles of 65°, 75°, and 85°. The uncalibrated radiance plots in the left column show the maximum sensitivities of the instrument are between 4-5.5 μm and 6-15 μm , which correspond to the ranges of the FTIR spectrometer's two detectors. The calibrated radiances in the right column resemble Planck's function at the water temperature with a decrease in the sky radiance at wavelengths where the sky is relatively transparent. The sky radiance is comparable to that of water or foam at wavelengths where radiation is preferentially absorbed by molecules in the atmosphere. Three example absorption peaks of CO_2 , H_2O , and O_3 are

labeled in the calibrated sky radiance spectra of Figure 3. The sky radiance increases with incidence angle due to the increased path length through the atmosphere near the horizon. The water and foam radiances decrease as incidence angle increases due to lower emissivity values and therefore more reflection of the sky, which is typically cooler than the water even though its radiance increases with incidence angle. The difference between the foam (dashed black) and water (solid black) radiances is larger at 85° (bottom) than at 65° (top) due to an increase in the difference of the emissivity values of foam and water as the incidence angle increases. The difference between the sky radiance and both the foam and water radiance decreases as incidence angle increases due to both the increase in the sky radiance at larger incidence angles and the decrease of the surface radiance.

The emissivity calculation given by (9) depends on the difference between the measured surface radiance and the sky irradiance. The difference between the sky radiance and both the foam and water radiances is shown in Figure 4 for incidence angles of 65° (top), 75° (middle) and 85° (bottom). As the difference decreases, the signal (emission radiance) to background (reflected) ratio decreases to the point where an emissivity calculation is not considered valid. Therefore, the best wavelengths for emissivity calculations are where the difference between the sky and surface radiance is large. The absorption bands which were labeled in Figure 3 near 7 μm , 9.5 μm , and 13.5 μm are the same wavelengths where the differences plotted in Figure 4 decrease, thus a noisier estimate is expected. A minimum difference needed for the emissivity calculation in (9) was chosen by inspection to be 0.00025 counts, which is plotted as a dashed gray line on the graphs of Figure 4. Emissivity values were only considered valid where the difference was above the threshold. The range of wavelengths where the difference was above the threshold decreases as the incidence angle increases.

While the FTIR spectrometer used in this experiment is sensitive to radiation between 2 and 16 μm , emissivity could not be measured at all wavelengths due to the low radiance at the detector limits. Both high detector response and high contrast between the surface and sky radiances are required for the emissivity calculation. The bandwidth of measureable emissivity values narrowed for both LW and MW bands as the incidence angle increased. This is evident in Figures 6 and 7 of the results section as a

210 decrease in the number of emissivity values as the incidence angle increases.

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213 **Figure 3.** Example uncalibrated instrument output (left, a, c, e) and calibrated radiance (right,

214 b, d, f) of foam (dashed), water (solid black), and sky (solid gray) at incidence angles of 65°

215 (top, 1, b), 75° (middle, c, d), and 85° (bottom, e, f). Wavelengths where the sky has an

216 elevated radiance due to absorption of H₂O, O₃, and CO₂ are labeled in the top right plot.

217
218 **Figure 4.** Differences between uncalibrated measurements of water, foam, and sky at
219 incidence angles of 65° (a), 75° (b), and 85° (c). A threshold of 0.00025 counts (dashed gray
220 line) was set as the minimum difference required for an emissivity calculation.

222 3. Results and Discussion

223 The mean emissivity of water and foam were measured for MW and LW bands at incidence angles

ranging from 60-85°. Both were found to decrease as the incidence angle increased for all wavelengths. Figure 5 shows an example of emissivity change with angle for water and foam at 8.86 μm . The difference between water and foam emissivity increased with incidence angle to a maximum at 85° for a specular (Figure 5a) and a Lambertian estimate for the emissivity (Figure 5b). The diffuse estimate for foam does not roll off as quickly and is slightly less than than water for incidence angles of 60° and 65°. Foam and water emissivity values were considered significantly different if error bars centered on the mean emissivity, +/- the standard deviation of the measurements set, did not overlap. The mean foam surface Lambertian emissivity is lower than that for water at 60° and 65° at 8.86 μm (Figure 5b), however the distribution of measurements denoted by the error bars show this measurement set is slightly noisier than the neighboring points and is likely an anomaly and not a meaningful difference.

Figure 5. Decrease of the 8.86 μm emissivity of foam (dashed black) and water (solid gray) as incidence angle increases for (a) specular reflection assumption for foam, and (b) Lambertian reflection from the foam. Error bars span twice the standard deviation ($\pm$ one standard deviation) centered on the mean emissivity. Circles are filled where the error bars do not overlap implying there is a statistically significant difference between the foam and water measurements.

Spectral emissivity plots of water and foam at each of the seven incidence angles measured are shown in Figure 6 for LW and Figure 7 for MW. Average emissivity values of foam at each wavelength are shown as black dots (specular) and blue dots (Lambertian), and specular emissivity values of foam-free

water are plotted as gray dots. The averages were calculated for the number of measurements shown in Table 1 and the dotted lines on the plots are twice the standard deviation centered on the mean. Average and root-mean-square (rms) differences between water and foam specular emissivity are given for three wavelength bands in Table 2. All emissivities were found to decrease as the incidence angle increased. Diffusive estimates of foam emissivity are the highest estimates at any of the angle tested for LW bands and remain greater than 0.75 for all the angles tested, however specular and Lambertian estimates of foam emissivity are nearly equal through 75° incidence angle. Lambertian emissivity estimates for MW bands show a more complicated response, varying widely with wavelength, though the diffusive emissivity estimates are less than that for water or specular foam from 60° through 75°, with exceptions for wavelengths approximately greater than 4 μm . We speculate that this is a result of the smaller signal in MW bands and combined with the variation in atmospheric radiance near 4.5 to 5 μm (Figure 3) due to a CO₂ absorption peak.

In general, water emissivity spectra are smoother than foam emissivity spectra, which is due to the dominance of specular reflection for water and diffuse reflection for foam. The specular nature of reflection by the foam-free water is evident in the similarity of the spectral fluctuations of the water and sky radiances at 85° in Figure 3. The subtraction of these similar, or paired, fluctuations in the right-hand-side denominator of (9), $V_s - V_d$, results in the smooth water emissivity spectra in Figure 6. In contrast, the diffuse reflection from foam leads to a foam radiance spectrum that is noisier than that of water. The difference between the fluctuating sky spectrum and the smooth foam radiance spectrum in $V_s - V_d$ results in a fluctuating foam emissivity spectrum. The fluctuations in the foam emissivity values increase with incidence angle and would not be present if the sky radiance was constant at all wavelengths or more closely matched variations in the reflected radiance. This is evident in the LW Lambertian emissivity estimates in Figure 6, which are less variable due to the hemispherical sky irradiance, $E_{sky}(\lambda)/\pi$, used in the calculation.

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Figure 6. Comparison of specular emissivity values for foam-free water (gray), specular emissivity from foam (black), and Lambertian emissivity from foam (blue) in the LW region

for 7 incidence angles. Dotted lines indicate twice the standard deviation ($\pm$ one standard deviation) centered on the mean emissivity.

Figure 7. Comparison of emissivity values for foam-free water (gray), specular reflection from foam (black), and Lambertian reflection from foam (blue) in the MW region for 7 incidence

angles. Dotted lines indicate twice the standard deviation (+/- one standard deviation) centered on the mean emissivity.

Table 2 Average $\pm$ rms difference between ϵ_{foam} and ϵ_{water} for 7 incidence angles and 3 wavelength bands

Incidence angle (°)	3.86-4.18 μm	4.56-5.08 μm	7.96-13.23 μm
60	-0.01 $\pm$ 0.01	0.00 $\pm$ 0.00	0.01 $\pm$ 0.01
65	-0.04 $\pm$ 0.04	-0.03 $\pm$ 0.03	0.01 $\pm$ 0.02
70	0.00 $\pm$ 0.01	0.00 $\pm$ 0.01	0.04 $\pm$ 0.04
75	0.04 $\pm$ 0.05	0.01 $\pm$ 0.05	0.07 $\pm$ 0.07
80	0.09 $\pm$ 0.10	0.04 $\pm$ 0.05	0.10 $\pm$ 0.11
82.5	0.11 $\pm$ 0.11	0.03 $\pm$ 0.03	0.10 $\pm$ 0.11
85	0.19 $\pm$ 0.19	0.05 $\pm$ 0.05	0.10 $\pm$ 0.13

Our specular water and foam emissivity measurements were compared with previously published values [N07] at incidence angles of 60° and 65°. The radiometer used in N07 had wavelength bands of 8.2-9.2 μm , 10.5-11.5 μm , 11.5-12.5 μm , with an 8-14 μm with response function, R , for those wavelength bands reported in Legrand *et al.*, [2000]. R was determined from transmittance of the instrument reported in Legrand *et al.*, [2000] and is needed to more directly compare the measurements used by N07 and the FTIR spectrometer used here (M. Legrand, pers. comm.). A comparison was done by integrating the product of our emissivity values, ϵ , with R , divided by the integral of the response over the corresponding wavebands.

$$\epsilon_{band} = \frac{\int \epsilon R d\lambda}{\int R d\lambda} \quad (10)$$

Our emissivity values for water and foam agreed with the N07 values within the error bars at all four wavelength bands. A comparison of the emissivity values for the 8-14 μm band is shown in Figure 8. The N07 values are shown for angles from 25° to 65° and our values are shown at where they overlap with N07 at 60° and 65°. The right axis of Figure 8 shows the full range of emissivity for an extension of our estimates values from 70° to 85°, a region where the emissivity decreases rapidly.

Figure 8. Comparison of our emissivity values of foam and water with published values from *N07* for the band from 8-14 μm (left axis). All data plotted assumes a specular reflection. Emissivity values of foam and water from this study, for the band from 8-14 μm at incidence angles of 70-85°, are plotted in the expanded axis on the right.

We also compared our water emissivity values to a model for both MW and LW values in Figure 9. The model is for water with the emissivity values calculated from the Fresnel equations assuming a flat surface [Filipiak 2008, Embury et al. 2012, hereafter *Embury model*]. The *Embury* model was chosen for the comparison because its emissivity values were tabulated for a range of wavelengths and angles. The Fresnel equations calculate the horizontal reflectance, ρ^s , and the vertical reflectance, ρ^p , from the complex refractive index, $\tilde{n}(\lambda)$, the incidence angle, θ , and the refracted angle, θ_r ,

$$\rho^s(\lambda, \theta) = \left| \frac{\cos(\theta) - \tilde{n}(\lambda)\cos(\theta_r)}{\cos(\theta) + \tilde{n}(\lambda)\cos(\theta_r)} \right|^2 \quad (11)$$

$$\rho^p(\lambda, \theta) = \left| \frac{\tilde{n}(\lambda)\cos(\theta) - \cos(\theta_r)}{\tilde{n}(\lambda)\cos(\theta) + \cos(\theta_r)} \right|^2. \quad (12)$$

The refractive indices used in the model were corrected for salinity and a water temperature of 27 °C. Our water temperatures ranged from 15-24 °C but the temperature dependence of emissivity is small

enough to make this a valid comparison [Newman et al. 2005]. The model included a surface emitted- surface reflected contribution which is similar to the approach of Masuda [2006]. The emissivity is computed using (3) for each polarization component as

$$\varepsilon^{s,p} = 1 - \rho^{s,p}. \quad (13)$$

The average of ε^s and ε^p is plotted for each incidence angle and wavelength as a gray line in Figure 9.

Figure 9. Comparison of water emissivity data and model [Embury et al. 2012] for 7 incidence angles from 60-85°.

Figure 9 shows a wide range of water emissivity data/model agreement. The agreement is best in the

LW region at the smallest incidence angle. An offset develops showing our data have higher values than the model predicts until 85° when the mean value of our data is closer to the model predictions. The agreement is best in the MW region around 80° where there is not a large offset between the data and the model and the scatter is small.

Table 3. Comparison of water emissivity data and the *Embury* emissivity model for seven incidence angles and three wavelength bands. Mean difference $\pm$ rms difference are shown for each wavelength band and incidence angle.

incidence angle (°)	3.86-4.18 μm	4.56-5.08 μm	7.96-13.23 μm
60	-0.02 $\pm$ 0.02	-0.01 $\pm$ 0.01	0.00 $\pm$ 0.00
65	-0.01 $\pm$ 0.01	0.00 $\pm$ 0.00	0.01 $\pm$ 0.01
70	-0.02 $\pm$ 0.03	-0.01 $\pm$ 0.01	0.01 $\pm$ 0.01
75	-0.02 $\pm$ 0.02	0.00 $\pm$ 0.00	0.02 $\pm$ 0.02
80	0.00 $\pm$ 0.01	0.00 $\pm$ 0.00	0.02 $\pm$ 0.02
82.5	0.00 $\pm$ 0.00	-0.01 $\pm$ 0.01	0.02 $\pm$ 0.02
85	-0.01 $\pm$ 0.01	-0.03 $\pm$ 0.03	-0.01 $\pm$ 0.01

The mean and RMS of the difference between the data and the model were computed for three wavelength bands and seven incidence angles as shown in Table 3. The mean and RMS of the difference varied with wavelength and incidence angle. The largest mean and RMS of the difference was at an incidence angle of 85° and wavelength band of 4.56-5.08. The LW data had no offset or RMS difference with the model at an incidence angle of 60° but did at larger incidence angles. At 85° the offset became negative and the RMS of the difference decreased slightly.

A possible explanation for the difference between the data and model is polarization sensitivity of the FTIR spectrometer. Longwave radiation of the sea surface is partially vertically polarized because the vertically polarized emission is larger than the horizontally-polarized reflection. *Shaw* [2002] found that FTIR spectrometers often have a polarization sensitivity in which they measure a higher response for vertically polarized radiation than horizontally polarized radiation. The combination of the vertically polarized radiation from the sea surface and a FTIR spectrometer which is more sensitive to vertically-polarized radiation will cause an overestimation of the emissivity. This is evident by separating (2) into

its two polarization components as:

$$L_m^s(\theta, \lambda) = \varepsilon^s(\theta, \lambda)L_s(\lambda) + \rho^s(\theta, \lambda)L_{sky}(\theta, \lambda) \quad (14)$$

and

$$L_m^p(\theta, \lambda) = \varepsilon^p(\theta, \lambda)L_s(\lambda) + \rho^p(\theta, \lambda)L_{sky}(\theta, \lambda), \quad (15)$$

where, following the notation of *Shaw* [2002], superscript s is polarization perpendicular to the plane of incidence and p is parallel. The degree of polarization (dop) of measured radiance from water is defined as

$$dop = \frac{L_m^s - L_m^p}{L_m^s + L_m^p}, \quad (16)$$

and is dependent upon wavelength and incidence angle. Our emissivity calculation should be most affected by polarization sensitivity of the FTIR spectrometer at the incidence angle with maximum dop , which is 75° for radiation between 8 and 14 μm [*Shaw 2002b*]. To test this hypothesis, we added a vertical polarization sensitivity to the model until the difference between the data and model was minimized, which occurred with the addition of only 6.3% vertical polarization. The resulting comparison between our measurements and the model with and without the added vertical polarization for an incidence angle of 75° is shown in Figure 10. The offset between the data and model is significantly reduced between 8 μm and 11 μm , which suggests that our FTIR could have a LW polarization sensitivity.

Figure 10. Comparison of water emissivity values (circles) with error bars of standard deviation to an emissivity model with (thick gray line) and without (thin gray line) polarization. The incidence angle is 75°.

The two MW bands vary widely in their agreement with the model at the seven incidence angles. The data from 3.86-4.18 μm agree best with the model at 82.5° but the data from 4.56-5.08 μm agree best with the model at 65°, 75°, and 80°. The *dop* of the surface radiance at MW wavelengths is a complicated function which is dependent upon the sky conditions and fluctuates rapidly with wavelength [Shaw 2002]. Estimating the effect of FTIR polarization sensitivity in the MW is impractical due to the complicated nature of the *dop* of the surface radiance. Characterization of the polarization sensitivity of this FTIR spectrometer will be the topic of a future paper.

4. Conclusions

A new method was developed to measure the emissivity of water and foam with an FTIR and was

used to measure the emissivity of water and foam for wavelengths of 4-6 μm and 8-14 μm and incidence angles from 60° to 85°. The method does not depend upon instrument calibration and eliminates the ambiguity of the surface temperature caused by the cool skin effect. Instead, the method uses previously characterized sea foam emissivity spectra measured at 10° incidence to calibrate results.

These measurements confirm model predictions for a still water surface (no waves or roughness) of the dramatic decrease in the emissivity of water from 60°-85° for both MW and LW infrared radiation. While they do confirm the decrease of emissivity as incidence angle increases, the values are higher than model predictions. The measurement and model agreement varies with incidence angle and is best at 60° and 85°. The largest offset between the measurements and the model is at 75°. Our results support *Shaw's* [2002] finding that FTIR spectrometers are most sensitive to the degree of polarization of the surface around 75°. These polarization sensitivities could explain the disagreement between our measurements with the model and should be taken into consideration with future modeling and validation.

The emissivity of foam was also measured and found to decrease from 60°-85° for both wavelength ranges but at a slower rate than for water. The difference between the emissivity of foam and the emissivity of water increased with incidence angle for both MW and LW regions and had a maximum of 0.23 at 8.9 μm and an incidence angle of 85°. The significant difference between the emissivity of water and the emissivity of foam at large incidence angles warrants development of new emissivity models which include the higher emissivity of foam for the fraction of the surface which is covered with foam.

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References

- Branch, R., C. C. Chickadel, and A. T. Jessup (2014), Thermal infrared multipath reflection from breaking waves observed at large incidence angles, *Trans. Geosci. Remote Sens.*, 52(1), 249-256.
- Carini, R. J., C. C. Chickadel, A. T. Jessup, and J. Thomson (2015), Estimating wave energy dissipation in the surf zone using thermal infrared imagery, *J. Geophys. Res.*, doi: 10.1002/2014JC010561.
- Donlon, C. J., P. J. Minnett, C. Gentemann, T. J. Nightingale, I. J. Barton, B. Ward, and M. J. Murray (2002), Toward improved validation of satellite sea surface skin temperature measurements for climate research, *J. Clim.*, 15(4), 353-369.
- Eisner, L., E. E. Bell, J. Young, and R. A. Oetjen (1962), Spectral radiance of sky and terrain at wavelengths between 1 and 20 μ . III. Terrain Measurements, *J. of the Optical Society of America*, 52, 201-209.
- Embury, O., C. J. Merchant, M. J. Filipiak (2012), A reprocessing for climate of sea surface temperature from the along-track scanning radiometers: Basis in radiative transfer, *Remote Sens. Environ.*, 116, 32-46.
- Filipiak, M. (2008), Refractive indices (500-3500 cm^{-1}) and emissivity (600-3350 cm^{-1}) of pure and seawater [Dataset], permanent identifier: <http://hdl.handle.net/10283/17>.
- Fogelberg, R. (2003), Field measurements of ocean surface properties using infrared and radar techniques, M. S. thesis, University of Washington.
- Freund, D. E., R. I. Joseph, D. J. Donohue, and K. T. Constantikes (1997), Numerical computations of rough sea surface emissivity using the interaction probability density, *J. Opt. Soc. Am.*, 14(8), 1836-1849.
- García-Santos, V., E. Valor, V. Caselles, M. Mira, J. M. Galve, and César Coll (2013), Evaluation of different methods to retrieve the hemispherical downwelling irradiance in the thermal infrared region for field measurements, *IEEE Trans. on Geoscience and Remote Sensing*, 51(4), 2155-2165.
- Hanafin, J. A. and P. J. Minnett (2005), Measurements of the infrared emissivity of a wind-roughened sea surface, *Appl. Opt.*, 44, 398-411.

Hoff, L. E., J. R. Evans, and L. E. Bunney (1990), Detection of targets in terrain clutter by using multispectral infrared image processing, Naval Ocean Systems Center (NOSC) Report TD 1404.

Jessup, A. T. and R. Branch (2008), Integrated ocean skin and bulk temperature measurements using the calibrated infrared in situ measurement system (CIRIMS) and through-hull ports, *J. Atmos. Oceanic Technol.*, 25, 579-597.

Korb, A. R., P. Dybwad, W. Wadsworth, and J. W. Salisbury (1996), Portable Fourier transform infrared spectroradiometers for field measurements of radiance and emissivity, *Appl. Opt.*, 35, 1679-1692.

Legrand, M., C. Pietras, G. Brogniez, and M. Haeffelin (2000), A high-accuracy multi-wavelength radiometer for in situ measurements in measurements in the thermal infrared. Part I: Characterization of the instrument, *J. Atmos. Oceanic Technol.*, 17, 1203-1214.

Marmorino, G. O. and G. B. Smith (2005), Bright and dark ocean whitecaps observed in the infrared, *Geophys. Res. Letters*, 32, L11604, doi 10.1029/2005GL023176.

Masuda, K., (2006), Infrared sea surface emissivity including multiple reflection effect for isotropic Gaussian slope distribution model, *Remote Sens. Environ.*, 103, 488-496.

Masuda, K, T. Takashima, and Y. Takayama (1988), Emissivity of Pure and Sea Waters for the Model Sea Surface in the Infrared Window Regions, *Remote Sens. Environ.*, 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: a high-accuracy, seagoing infrared spectroradiometers, *J. Atmos. Oceanic Technol.*, 18, 994-1013.

Nalli, N, R., P. J. Minnett, E. Maddy, W. W. McMillan, and M. D. Goldberg (2008), Emissivity and reflection model for calculating unpolarized isotropic water surface-leaving radiance in the infrared. 2: Validation using Fourier transform spectrometers, *Appl. Opt.*, 47, 4649-4671.

Newman, S. M., J. A. Smith, M. D. Glew, S. M. Rogers, and J. P. Taylor (2005), Temperature and salinity dependence of sea surface emissivity in the thermal infrared, *Q. J. R. Meteorol. Soc.* 31, 2539-2557.

Niclòs, R., V. Caselles, E. Valor, and C. Coll (2007), Foam effect on the sea surface emissivity in the 8-

14 μm region, J. Geophys. Res., 112(C1), 2020, doi: 10.1029/2007JC004521.

Niclòs, R.; Dona, C.; Valor, E.; Bisquert, M. (2014), Thermal-infrared spectral and angular characterization of crude oil and seawater emissivities for oil slick identification, IEEE Trans. on Geoscience and Remote Sensing , 52, 5387-5395.

Rubio, E., Caselles, V., and Badenas, C. (1997) Emissivity measurements of several soils and vegetation types in the 8–14, μm wave band: analysis of two field methods, *Remote Sensing of Environment*, 59, 3. doi:/10.1016/S0034-4257(96)00123-X.

Salisbury, J. W. (1990), First use of a new portable thermal infrared spectrometer, 10th Annual International Symposium on Geoscience and Remote Sensing, 1775-1778.

Salisbury, J. W., D. M. D’Aria, and F. F. Sabins (1993), Thermal infrared remote sensing of crude oil slicks, Remote Sens. Environ., 45, 225-231.

Salvaggio, C. and C. J. Miller (2001), Comparison of field and laboratory collected midwave and longwave infrared emissivity spectra / data reduction techniques, Algorithms for multispectral, hyperspectral, and ultraspectral imagery VII, SPIE, 4381, 549-558.

Shaw, J. (2002), The effect of instrument polarization sensitivity on sea surface remote sensing with infrared spectroradiometers, J. Atmos. Oceanic Technol. 19 820-827.

Shaw, J (2002b), Infrared polarization in the natural Earth environment, Polarization Measurement, Analysis, and Applications V, Dennis H. Goldstein, David B. Chenault, Editors, Proceedings of SPIE Vol. 4819.

Smith, W. L., R. O. Knuteson, H. E. Revercomb, W. Feltz, H. B. Howell, W. P. Menzel, N. R. Nalli, O. Brown, J. Brown, P. 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, Bulletin of the American Meteorological Society, 77 (1), 41-51.

Wu, X., and W. L. Smith (1997), Emissivity of rough sea surface for 8-13 μm : Modeling and verification, Appl. Opt., 36, 2609-2619.