

The MWIR and LWIR Spectral Signatures of Water and Associated Materials

Herbert J. Mitchell^a and Carl Salvaggio^b

^aSpectral Information Technology Applications Center (SITAC)
11781 Lee Jackson Memorial Hwy, Suite 400, Fairfax, VA, 22033;

^bRochester Institute of Technology, Chester F. Carlson Center for Imaging Science,
54 Lomb Memorial Drive, Rochester, NY 14623

ABSTRACT

Spectral infrared emissivity measurements have been made of a variety of materials both with and without surface water. The surface water was either natural, in the form of dew or residual rainwater, or artificially introduced by manual wetting. Materials naturally high in water content were also measured. Despite the rather diverse spectral population of the underlying materials, they exhibited very similar, featureless, water-like spectra; spectrally flat with a very high magnitude across the emissive infrared region. The implication to exploitation personnel that may use emissive infrared hyperspectral image data is that in areas where condensation is likely (e.g. high humidity) or in areas populated with high water content background materials (e.g. highly vegetated areas), discrimination may prove an intractable problem with hyperspectral infrared sensing for ambient temperature targets. A target that exhibits a temperature either below or above ambient temperature may be detectable, but not identified, and may be more economically pursued with a far simpler, single-band midwave or longwave sensor.

Keywords: IR spectrometry, IR emissivity, Water Content

1. INTRODUCTION

SITAC scientists made infrared measurements of the spectral signatures of soils, plants, and various materials in a forested area of Oahu Island in Hawaii. This area approached rain forest conditions, so most of the material to be measured was wet or became wet with the first rain or morning dew. Even when specific actions were taken to dry a material out using the sun, the surfaces of the targets and background materials remained wet. The SITAC scientists attempted to find a material that when measured would produce a spectrum that did not look like water. Essentially all of the materials measured in this forest environment produced a water-dominated emissivity spectrum. As some materials appeared to contain only small amounts of water, the scientists wondered what amount of water reaches unit optical thickness (herein defined by the point where transmission drops to $1/e$).

Due to the unknown and uncontrollable amounts of water present in the field setting, SITAC investigators designed a series of experiments to determine the threshold for water's unit optical thickness in the infrared regions of the electromagnetic spectrum (LWIR). This paper summarizes the measurements made in Hawaii and the controlled experiment attempts to quantify that threshold. The paper also includes some general cautions about making infrared measurements in forested areas.

2. SPECTRAL SENSOR OVERVIEW

A Designs & Prototype Fourier Transform Spectrometer with a spectral resolution of 4 cm^{-1} over the 3-15 micron spectral region, was used in both the Hawaii field measurements and controlled experiments. Measurements were made in accordance with the published SITAC protocols for this sensor^{1,2}. The instrument was first calibrated with warm and cold blackbody sources. The calibration was followed by a sample measurement and then a measurement of the down-welling radiance off of a highly reflective gold panel. Temperature measurements of samples were made using a contact probe having a stated accuracy of 0.1 C. By applying the blackbody calibrations mentioned above, the data was processed to produce calibrated radiance data. Additionally, for the 7.5 to 14.5 micron spectral region, the data were also converted to emissivity units.

3. HAWAII FIELD EXPERIMENTS

3.1 Site Description

In January 2002, SITAC set out to make some measurements of various materials in a tropical forest environment on Oahu, Hawaii. The first day was quite clear, but with high humidity typical of the tropics. SITAC deployed some locally purchased materials to be used by other sensors for calibration and capability assessment purposes. These panels were deployed on a fairly flat sand area and also dispersed near/under some local trees. Once the panels were laid out, SITAC investigators began to make spectral measurements of them in the visible through infrared regions. The next morning, heavy dew had formed on the panels. The dew-coated panels were measured again. The dew remained on the panels and essentially all other materials in the area almost until noon, at which time rain started to move into the area. The rains continued for the most of the rest of the time the investigators remained in Hawaii. One of the rainstorms dumped 12" of rain in just one evening on the measurement area! Few spectra were taken from that point on.

3.2 Spectral Measurements

As one might expect, most of the spectra measured under dew and rain conditions resembled the spectra of water. Figure 1 that follows shows an assemblage of spectral emissivity data for 30 different materials that were measured during this campaign in the LWIR spectral region. Most of the spectra in Figure 1 are quite similar and have an emissivity of 0.9+ throughout the LWIR. The two spectra with the lowest emissivity are those of a dry blue tarp, which was measured shortly after it had been removed from the manufacturer's plastic bag, and Tyvek, which is a very white hydrophobic material made by DuPont used to wrap buildings for weatherproofing.

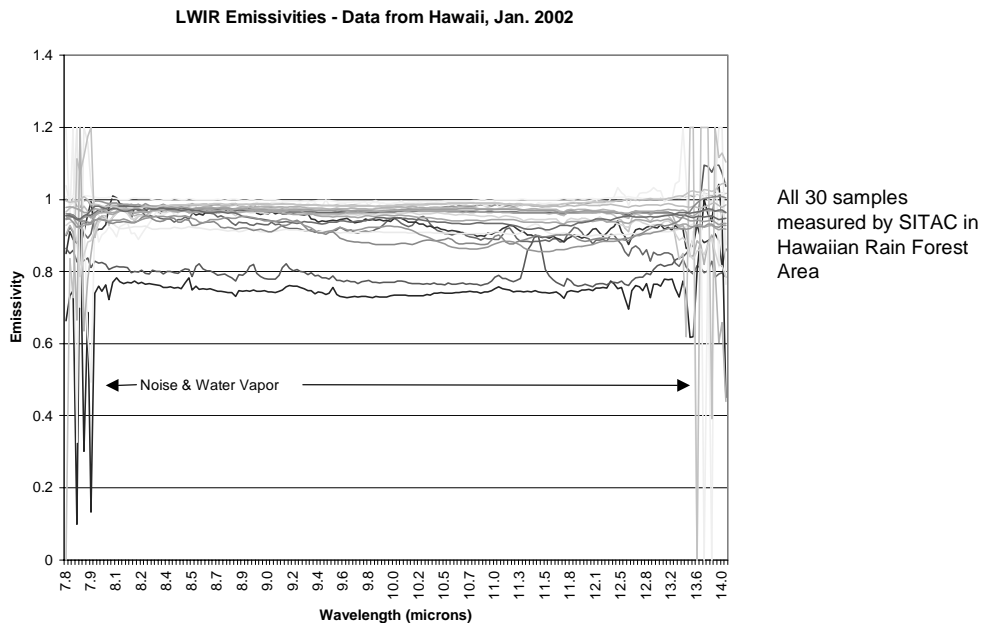


Figure 1 – Comparison of spectra from Hawaii measurements.

The blue tarp was measured again the following morning when it had a coating of dew on it. Figure 2 compares the dry and dew-covered blue tarp spectra. One can easily notice the increase in emissivity caused by the dew. The dew was beaded, so some areas had water drops and some areas did not. No micro scale examination was made of the tarp, so it is not known how much water was in the areas between beads or how the beads were distributed across the surface of the tarp. If one assumes that the wet and dry areas of the tarp linearly mix, then about 35% of the tarp was bare and 65% was beaded water. The investigators remember that visually, this 65/35 fraction was reasonable but unfortunately this cannot be proven from the scale of the field photos that were taken.

LWR Emissivities - Data from Hawaii, Jan. 2002

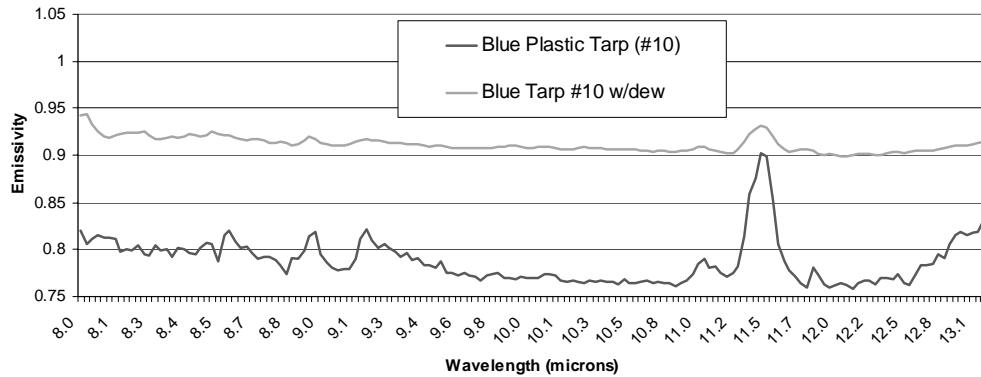


Figure 2 – Comparison of blue tarp spectra, with and without dew.

While waiting for the skies to fully clear for the other sensors to make their measurements of the panels and materials SITAC had laid out, the SITAC investigators scientists began to take measurements of whatever local items seemed of interest. These measurements included leaves from local plants, local soils, and even human skin. As the soil was quite wet, an attempt was made to dry some soil out in the sun. This soil sample was first screened (with common house screening) and then a thin layer was put on a section of dry blue tarp. Once an hour for 3 hours it was hand stirred to aid drying. It was then measured with the spectrometer. Only a very slight emissivity difference was seen after three hours of solar drying. Indeed, as Figure 3 shows, little if any emissivity difference was found between the solar dried soil, the plants, and the human skin. Not only is it quite difficult to distinguish what is plant versus what is human in Figure 3, but also the spectra of the dried soil background in the measurement area seem to be dramatically affected by the presence of water. Thus, even small amounts of water in a substance must drive the spectrum of that substance to that of water.

LWR Emissivities - Data from Hawaii, Jan. 2002

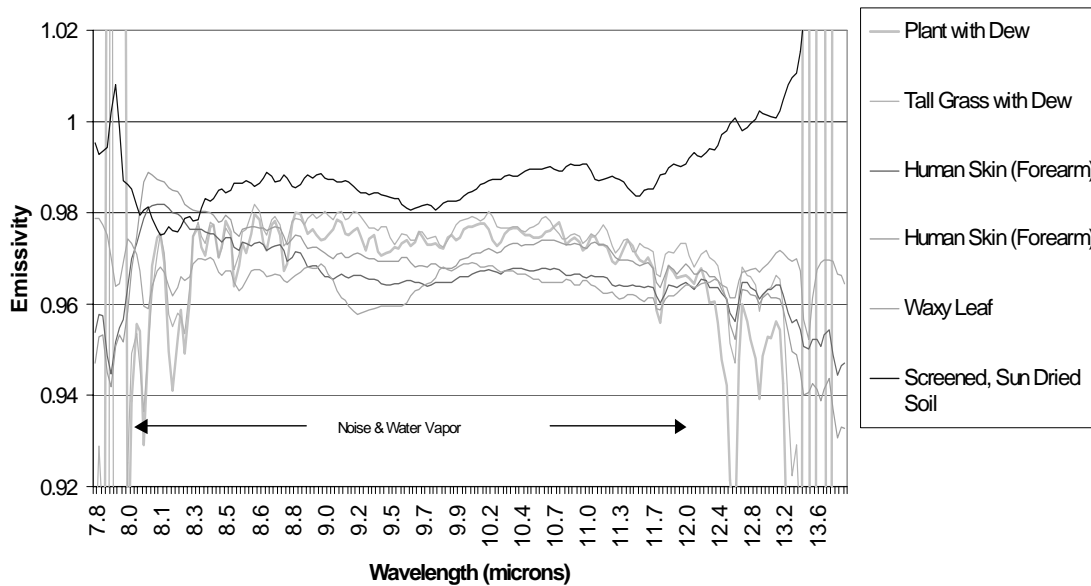


Figure 3 – Spectral comparison of wet background materials in Hawaii data.

3.3 Hohlraum Effect

As previously mentioned, measurements in Hawaii were made in areas that had some tree cover ranging from 1 to 99 % cover. Spectra taken in areas with much cover clearly approached that of pure water or a near blackbody. This phenomenon may be explained in part via the Hohlraum effect of the water dominated forest tree leaves. In a cavity with optically thick walls, or Hohlraum, a material surrounded in this cavity will achieve the same temperature in time as the surroundings and will become indistinguishable from the Hohlraum's surrounding walls. It becomes indistinguishable because everything in and surrounding the cavity is emitting at the same temperature and also reflecting the emissions of the cavity³. Since by Kirchhoff's law emissivity + reflectivity = 1, everything in the cavity appears the same. Whether the soil, tarp, tyvek, aluminum foil, or gold plate (for downwelling radiance measurements) was being measured, all the materials produced the same radiance. Since the downwelling radiance equaled the sample radiance, it was not possible to compute emissivity of materials in the canopy.

Another example of this Hohlraum effect can be seen in the process of ashing a chemical sample or firing clay in an oven. As everything in the oven comes to the same temperature, the individual objects inside the oven disappear and cannot be seen or at least are very hard to see. Radiatively, everything has to reach an equilibrium state where photons are continually absorbed or reflected and those absorbed are re-radiated, but all at the same blackbody temperature. Hence, everything optically blends together and contrast between the walls and the object effectively disappears.

In the Hawaii data, tree leaves and the earth surface become the optically thick Hohlraum walls for any sample under the leaf canopy. If one were to observe this Hohlraum through a hole in the leaves one would see the integrated radiance from everything in and around the Hohlraum. That is, an observer would see a blackbody emission at the average interior temperature that would not be recognizable from any material under the canopy.

Even though objects such as a flashlight or a cook fire produce light that escapes the canopy, these objects do not violate the Hohlraum effect. Rather, these objects introduce a local change away from an equilibrium state. The flashlight bulb likely emits as an approximately 3000K blackbody, while the Hohlraum walls and floor probably emit at about 300K. Because there is no way that the surroundings can ever be heated by the flashlight to 3000K, most of the flashlight light escapes to illuminate the ground and reflect up through the canopy holes. The same argument can be made for the cook fire, which emits at about 600K.

Given the effects of the Hohlraum-like canopy and the water content of leaves driving them to be optically thick, infrared sensing in the presence of trees does not make sense unless there is a significant temperature difference between the target material and the surroundings. In such cases, single band or few band multispectral sensors are likely adequate to detect and generally to characterize the emissions.

3.4 Oak Leaf Measurements

The question arose as to how dry does a leaf have to get before its spectra changes from a water-like substance. Unless they are freshly oven dried, leaves will contain 6-18% water depending on the ambient humidity. Will this be enough water to dominate the spectra? To partly test this, a spectrum was taken of extremely dry leaves that had fallen 9 months ago during drought conditions in the Washington D.C. area. This spectrum was compared to that of some freshly picked leaves that were on the tree directly above the fallen leaves. Figure 4 compares the two leaf sets and shows that except in the water bands, the leaves are nearly identical in the LWIR. Apparently the leaf still contains a sufficient amount of water to be optically thick in the LWIR.

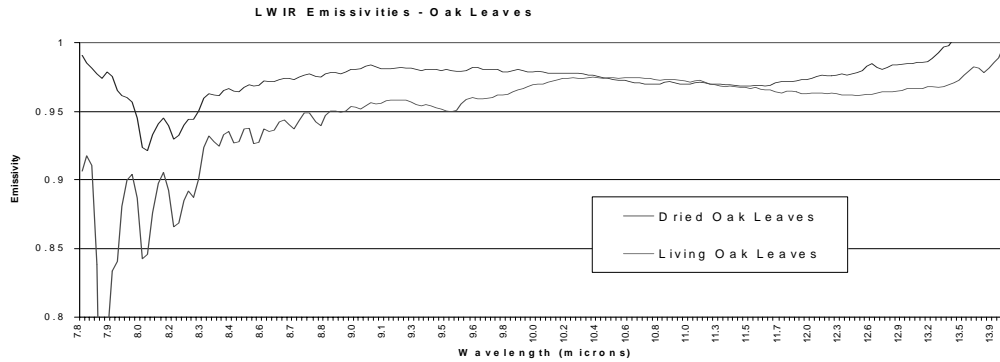


Figure 4 Fresh and Dried Oak Leaf Spectra

4. CONTROLLED OPTICAL THICKNESS EXPERIMENTS

4.1 Procedure 1: Fill and Dump Technique

To examine the question of just how much liquid water it takes to produce an optically thick coating, SITAC began a series of controlled measurements of thin water layers. SITAC made its first measurements of water in an aluminum pie plate. The spectra and weight of the plate were first measured while the plate was dry. Then water with a trace amount of soap was put in the plate, swirled around and then emptied to leave a thin film of water on the plate. The trace amount of soap was employed to obtain a uniform water coating and to prevent the water from beading. To insure that the soap had no effect, SITAC separately measured the water soap combination and then water without any soap. The plate with its water film was then measured with the spectrometer and weighed to determine the amount of water remaining in the plate. The measurements are shown in Figure 5 below.

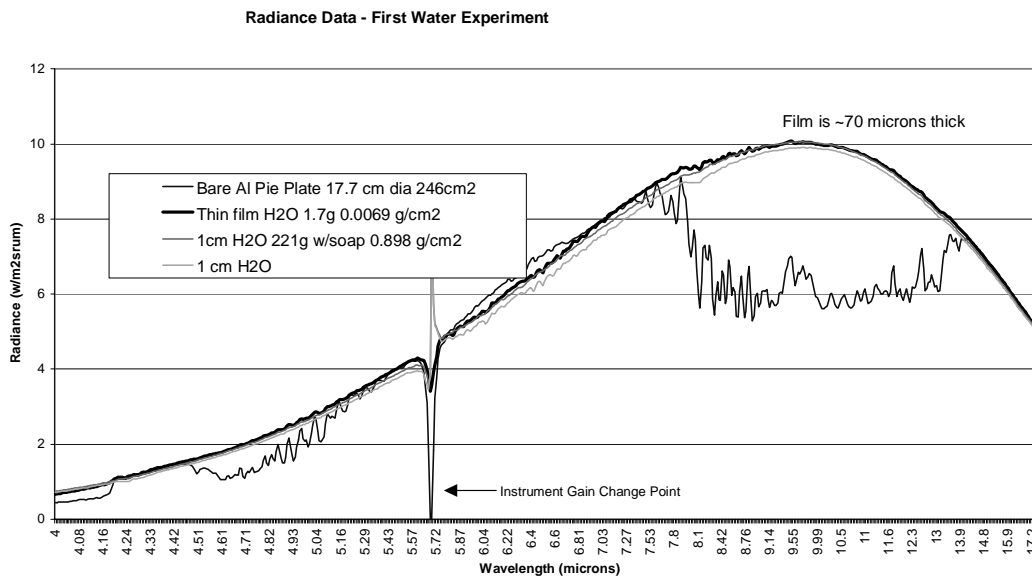


Figure 5 – Spectral data of pie plate, water, and water/soap mixture used in first controlled experiment.

As can be seen in this figure, the soap, 1cm thick water, and thin water film produce about equal radiance with the bare aluminum pan producing generally much less due to its low emissivity and the clear skies on that day. The water and the sample with the trace soap are about equal indicating that the soap had no significant effect on the IR signature. The difference between the small amount of water and the bare aluminum plate is dramatic. If the water evenly coated the pie plate, then the average of .0069g/cm² is a thickness of about 70 microns. Since this produces radiance essentially identical to 1 cm of water, one can conclude that 70 microns of water is fully optically thick from 4 microns through 15 microns.

Though the “fill and dump” technique used in this experiment proved that 70 microns of water is optically thick, it was inadequate at providing small enough amounts of water to show the transition from being thin to thick. Also, the pie plate had small ribs in its bottom that might have slightly affected the uniform coating of water, which may have resulted in underestimation of the optical thickness of water.

4.2 Procedure 2: Aluminum Sheet Measurements

To correct these deficiencies, SITAC used a flat sheet of aluminum to make further measurements. An aluminum sheet with a shiny surface was cut to a dimension of 3.5 x 6 inches (135 cm²). The bare, dry aluminum was first measured spectrally as it sat on a scale that read to 0.01g. There was a very slight 1-2 knot wind that lifted the aluminum sheet slightly causing about a 0.05g uncertainty in the weight measurements. After its tare weight was determined, the aluminum plate was wet with water, put back on the scale and sampled about every minute as the water evaporated. At each measurement point, the weight of the sheet and water combination was recorded. As before, the water had a trace amount of soap in it to insure uniform wetting of the surface.

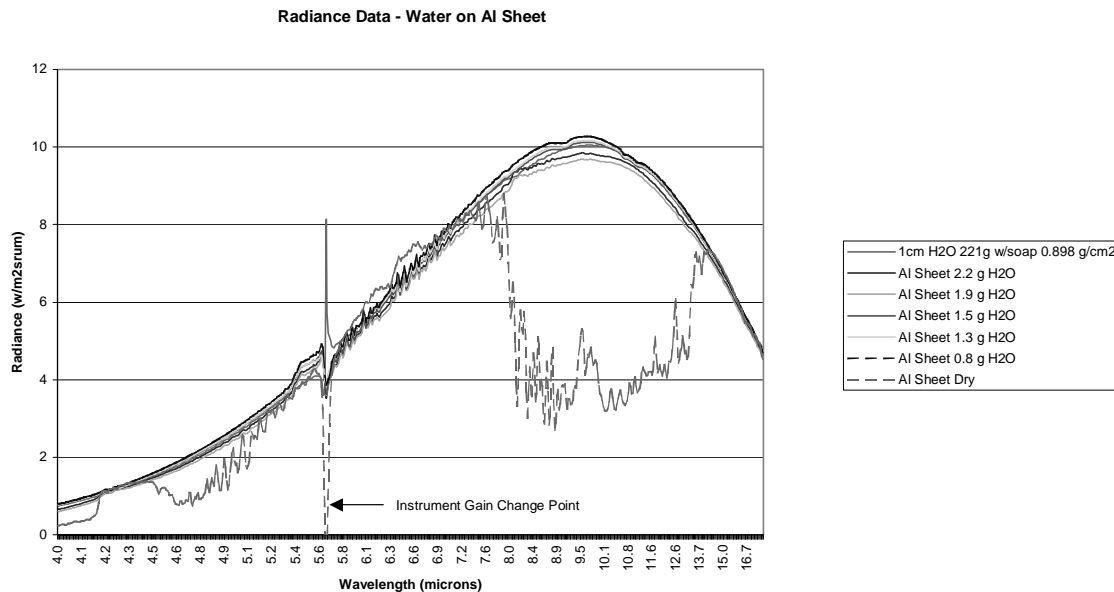


Figure 6 – First aluminum sheet experiment

The water amounts used in this first aluminum sheet experiment produced radiances that were about that of the 1cm thick water. In other words, all the samples were optically thick. Clearly the evaporation of water from the sheet should have been continued for a longer time. For this reason, a second experiment was done which started with less water on the sheet and continued until the sheet became dry. Figure 7 shows the measured radiances for these measurements.

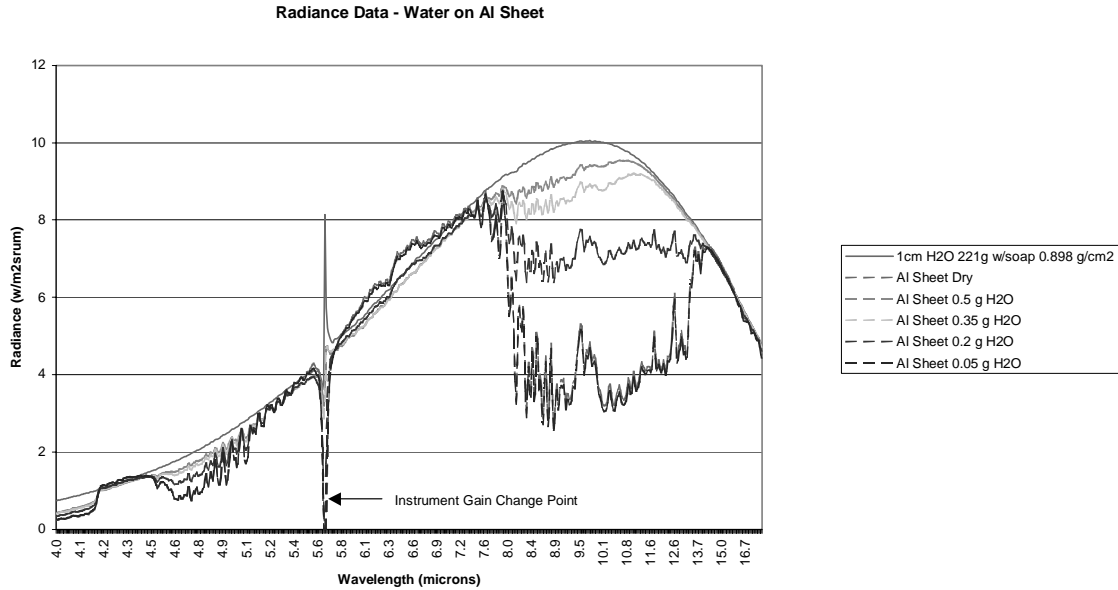


Figure 7 – Second aluminum sheet experiment.

This figure shows the water increasing the radiance of the aluminum sheet almost to the point of it becoming a blackbody at the local temperature. This range of samples cover the range from being optically thin to the point where the thin water layer is very optically thick. As previously noted, optical thickness is equal to 1.0 at the point where transmission drops to $1/e$ (approximately the 37% transmission point). As the optical thickness increases beyond 1, the radiance will exponentially approach that of the emissivity of an infinitely thick layer of the substance as it did in the previous figure.

One can plot the information in figure 7 differently. In figure 8, at randomly selected wavelengths, the water radiance is plotted against the water thickness. To produce this plot, the grams of water on the sheet for each spectrum are replaced with the thickness of the water in microns. This conversion assumes uniform water coverage over the sheet, which should be a reasonable assumption given the trace soap in the water and the visible appearance of uniform coating of the sheet.

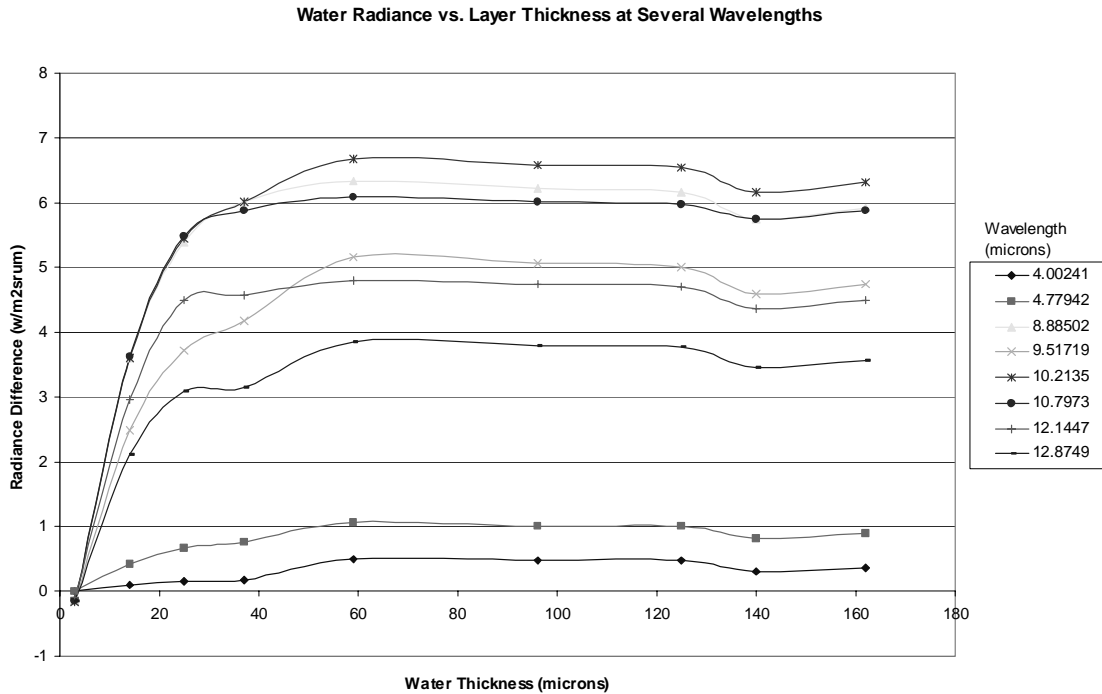


Figure 8 – Water radiance vs. water thickness at various wavelengths.

Note how the curves flatten at water thickness levels between 25 and 60 microns thick. In this region, the water layers are approaching the point where, optically, they might as well be infinitely thick. The declines at 140-160 microns thick and near 37 microns thick are probably due to surface cooling in the slight (~1-2 knot) wind that was present at the time of measurement. Such effects can be removed by normalizing each thickness measurement spectra to a blackbody at an appropriate temperature for the measurement. When this is normalization is performed, it becomes clear that these points were about 1.5-2 degrees cooler than most of the other points.

4.3 Calculating optical thickness from the aluminum sheet data

From the aluminum sheet data, it should be possible to calculate the spectral absorptivity of liquid water and the amount of liquid water it takes to reach unit optical thickness at each wavelength.

The measured radiance is a combination of the emissions from the water layer, the emissions from the aluminum sheet, and the reflection of the downwelling radiation off of the water and the aluminum sheet. The downwelling radiation is essentially that radiance measured off the bare aluminum sheet and is effectively much colder (smaller radiance) than other materials in the scene. Water has an IR reflectivity of only a few percent so its reflection of the downwelling radiance can be neglected. The downwelling radiation that is reflected off the aluminum passes through the water layer twice, as it goes down to the aluminum and back up through the layer. If the one-way transmission is much below 33%, then the two-way path transmission will be less than about 10%. As the downwelling radiation is largely from the relatively cold sky, the radiance will be fairly small and, when combined with the two-path attenuation, it should be small enough to neglect for most purposes. The emissions of the aluminum also contribute. However, since the emissivity of the aluminum sheet is about 0.03, and the light must pass through the water layer, the self-emission contribution from aluminum is fairly negligible.

One is now left with the expression that the measured radiance should approximately equal the quantity (one minus the wavelength dependent transmission) times the blackbody radiance at each wavelength. Figure 9 solves for the wavelength dependent transmission utilizing the assumption that the downwelling terms and the aluminum self-emission term are small compared to the water emission term.

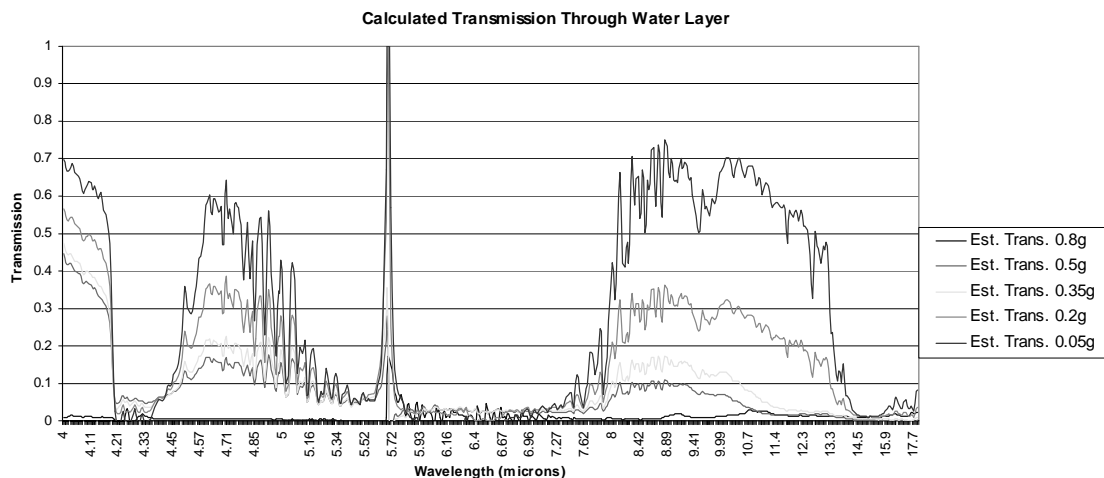


Figure 9 – Estimated transmission of water samples of varying thickness.

In this figure, the transmission through the 0.05g water sample is fairly high and two-way transmission is approximately 36%. This transmission is too great for downwelling and aluminum sheet emission terms to be ignored. So this measurement was not used to calculate water absorbency. It was also rejected, as the weight was too close to the scale accuracy limit that day. The 0.2g measurement produced a one-way transmission of 0.3, which when squared produces a number like 10%. This transmission is small enough that one can neglect the downwelling term and the small self-emission term from the reflective aluminum sheet. The 0.2g and higher measurements were then used to calculate the spectral absorbency of water.

This process consisted of first converting the weight of the material on the aluminum sheet to a thickness using the conversion factor of water having a density of 1 g/cc and the plate having an area of 135 cm². Having the amount of water over the path and the spectral transmission, Beer's Law was used to calculate the spectral absorbency for each measurement per micron of water. These absorbencies were then blended together by simple averaging to produce an approximate composite spectral plot of the absorbency of liquid water. This average infrared absorbency for liquid water is shown in figure 10. Some shadowed boxes have been added in figure 10 to show where atmospheric absorption bands cause the measurements to not be reliable for liquid water. It is suggested that one should linearly average across the bands when using this data.

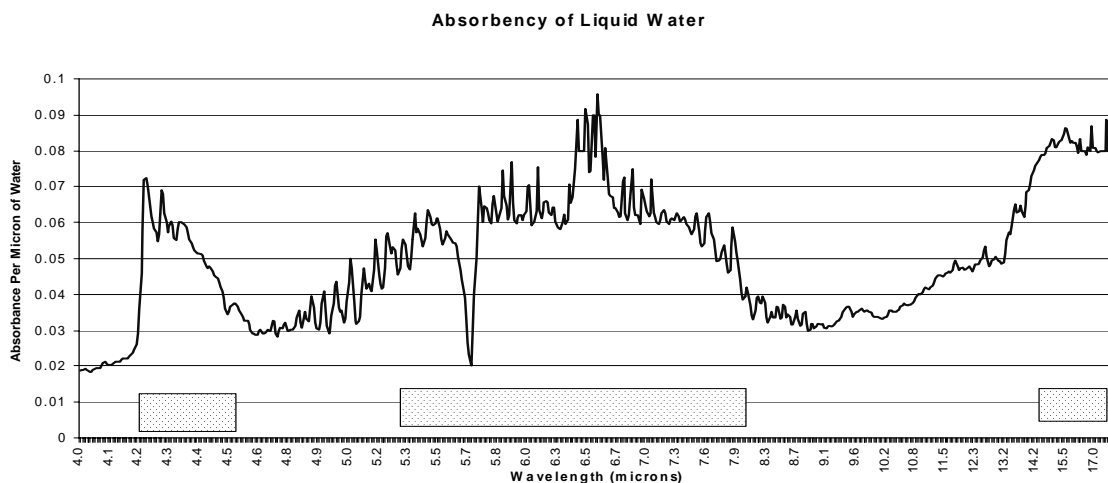


Figure 10 – Average spectral absorbency of liquid water.

Having these results, SITAC investigators calculated the amount of water in microns that would produce unit optical thickness. This data is shown in figure 11. Again, boxes have been added to point out where atmospheric absorption bands of carbon dioxide and water make the data not very reliable.

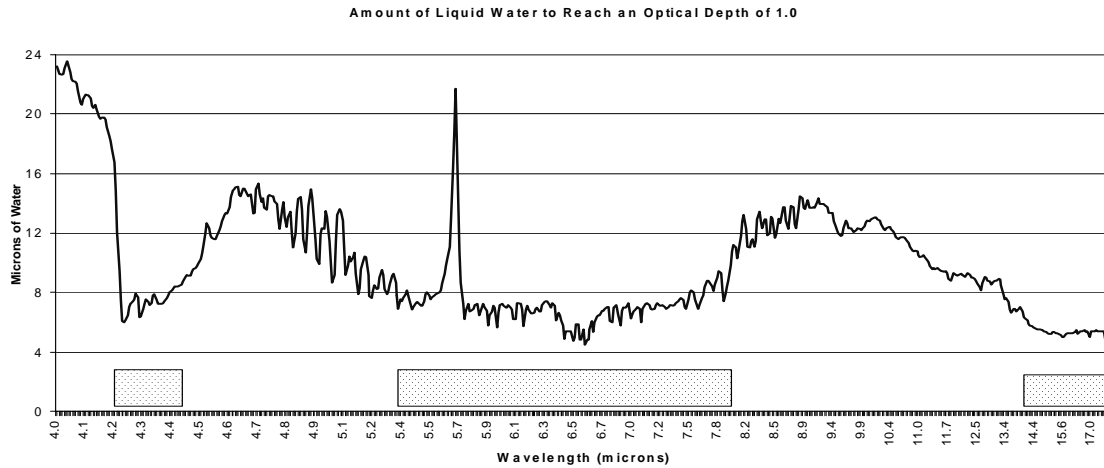


Figure 11 – Amount of water in microns that produces unit optical thickness.

This determination of optical thickness leads to a comparison between liquid water and water vapor. A water column of 1 micron contains approximately 3.5×10^{18} molecules per cm^2 , which is roughly equivalent to a gas concentration of about 1340 ppmv-m. Using the Hanst⁴ library spectra for water, the comparison of Figure 12 is obtained.

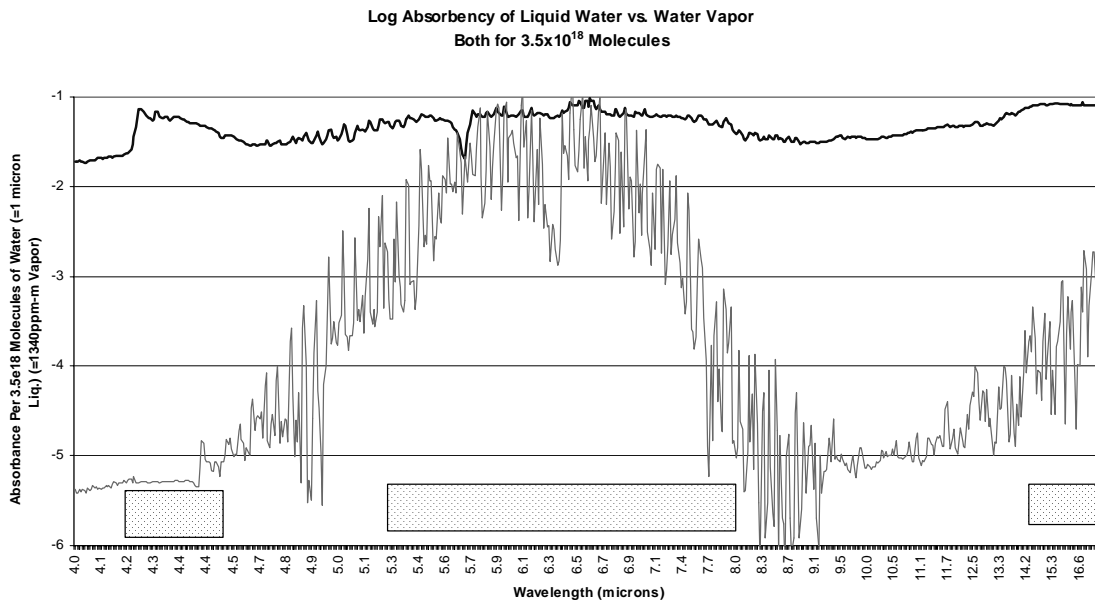


Figure 12 – Comparison of the Absorbency of Liquid Water and Water Vapor

The LWIR absorbance of the water vapor can be seen to be several thousand times less absorptive than for liquid water. Hence if liquid water is present it easily can be more important in a scene than water vapor.

5. CONCLUSION

These measurements show that it takes a thickness of about 10 microns for liquid water to be optically thick in most of the IR, which has serious importance for IR sensing. Liquid water is so strong an absorber that it must be accounted for in all IR field measurements. Water adheres to and is often bound to surfaces. This water can dominate IR measurements made in wet or tropical environments.

Ten microns of water is a small amount of water. A human hair, about 100 microns in diameter, will contain this much water. A leaf, unless it is measured quickly after being oven dried, will contain this much water. Kiln dried wood, once it cools after leaving the kiln, will be about 12% water, so even a human hair's worth of wood will be thick with water.

Sensing in tropical or even moderate latitude vegetated environments must account for any liquid water. In these environments, most objects will approach becoming a near blackbody emitter, so the value of spectrally sensing in these environments is greatly diminished. The value lies in detecting temperature differences between materials, not the spectral differences. Thus, it may be far more efficient to use a single or a few spectral bands in the emissive infrared to sense objects in these environments.

Acknowledgements

The authors would like to thank the Central MASINT Organization, its Technology Coordination Office, and SITAC for the sponsoring and support of these collections. Bob Satterwhite and Joe Leckie from SITAC provided able assistance with the measurements. Dr. Gerard Jellison of SITAC provided valuable editing advice.

REFERENCES

1. Salvaggio, C., *Infrared Field Spectra Collection Protocol*, SITAC report, 8 Nov. 2000.
2. Salvaggio, C. and C. J. Miller, "Methodologies and Protocols for the Collection of Midwave and Longwave Infrared Emissivity Spectra Using a Portable Field Spectrometer," *Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery VII*, SPIE vol. 4381 (2001), pp. 539-548.
3. Halliday, D., R. Resnick, J. Walker, *Fundamentals of Physics, Extended, With Modern Physics, Fourth Edition*, John Wiley & Sons, Inc., New York, 1993, p.1139.
4. Hanst, P.L., *Library of Gas Spectra*, Infrared Analysis Inc., 1998.