Methodologies and protocols for the collection of midwave and longwave infrared emissivity spectra using a portable field spectrometer

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ABSTRACT

The development of highly portable field devices for measuring midwave and longwave infrared emissivity spectra has greatly enhanced the ability of scientists to develop and verify exploitation algorithms designed to operate in these spectral regions. These data, however, need to be collected properly in order to prove useful once the scientists return from the field. Attention to the removal of environmental factors such as reflected downwelling atmospheric and background radiance from the measured signal are of paramount importance. Proper separation of temperature and spectral emissivity is also a key factor in obtaining spectra of accurate shape and magnitude. A complete description of the physics governing the collection of field spectral emissivity data will be presented along with the assumptions necessary to obtain useful sample signatures. A detailed look at an example field collection device will be presented and the limitations and considerations when using such a device will be scrutinized. Attention will be drawn to the quality that can be expected from field measurements obtained and the limitations in their use that must be endured.

Keywords: longwave, midwave, spectral signatures, emissivity, ground truth, protocol, methodology

1. INTRODUCTION

The measurement of spectral radiance and the derivation of spectral emissivity or reflectivity in the field are processes that must be carried out carefully and thoughtfully. This is especially true in the longwave and midwave infrared portions of the spectrum, where phenomenology exists that is not always intuitive to many remote-sensing practitioners. Although modern instrumentation and software make the collection of these spectral values very easy to carry out, the quality of the collected data is still dependent on the ingenuity, foresight and phenomenological understanding of the field spectra collection team. The environmental conditions under which one is collecting spectra, the time of day, and the target's thermodynamic properties will all have a profound influence on the quality of the collected data.

For these reasons it is imperative that an organization that routinely collects spectral ground truth data in the field has a protocol to follow that will allow investigators to produce a spectral library of consistent and repeatable quality.

The field instrument used in this work was a Designs & Prototypes microFTIR Model 102[1,2]. The microFTIR is designed as a rugged field instrument capable of withstanding the rigorous treatment it receives. The members of the Spectral Information Technology Applications Center midwave and longwave field spectra collection team have used this instrument in a wide variety of climatic conditions and in some fairly rugged terrain. The results obtained under these circumstances have proven important and valuable to subsequent exploitation studies and research.

It is the intent of this paper to make the reader aware of the underlying phenomenology that is critical to making successful field radiance measurements. The "pitfalls" that exist will be accentuated and methodologies to overcome them proposed and tested. These methodologies and protocols are based on experiences making field measurements in support of real-world exploitation pursuits. The field is truly a hostile laboratory in which to do absolute radiometry, however, very good results can be obtained that prove invaluable to remote sensing research and development.

2. BACKGROUND

The total spectral energy field leaving terrestrial objects at wavelengths greater than 3 μm is dominated by self-emitted radiance from targets, background objects and the atmosphere. The reflective phenomenology that many remote sensing practitioners are used to dealing with is still present in this region, however, these phenomena are secondary contributors (in most circumstances) to the overall radiance field, especially beyond 4.2 μm. The often referred to crossover point, where reflected solar and self-emitted energy are equal contributors, usually occurs between 3.5 and 4.2 μm for a target with

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"typical" emissivity at ambient temperature. The actual position of this point is dependent upon sky clarity, solar zenith, and the reflectance and temperature of the surface being observed. Reflected sunlight is still a significant fraction of the entire radiance field in the 3.5 to 4.2 μm region of the spectrum under certain conditions. This can occur in relatively cold climates with highly reflective (*i.e.* a low emissivity) diffuse targets. Here the self-emission from the target would be low due to its low temperature and the reflected sunlight/skylight can dominate the radiance field. For more typical materials; *i.e.* those with smooth surfaces being viewed in other than specular geometry with respect to the sun, diffuse, high emissivity, and relatively warm with respect to the background, the self-emission term strongly dominates the total radiance field. Beyond the CO_2 absorption band ending at 4.4 μm, the reflected component is considered small in most instances.

As in the reflective portion of the spectrum, the background materials and intervening atmosphere serve as secondary sources of radiance due to reflection and scattering, respectively. In addition, these scene elements also emit energy due to their kinetic temperature at these wavelengths and introduce additional energy to the radiance field.

Atmospheric gases emit energy in the same narrow bands in which they absorb, but the distant wings of these emission bands make up what is referred to as "continuum emission" in regions that are otherwise acknowledged as atmospheric windows. Large aerosols and clouds tend to act like blackbody emitters at their respective temperatures. This becomes especially important when these emitters are low in the atmosphere where temperatures tend to be greater. When clouds are scattered in a scene, the variability in background radiance due to these emitters is greatly dependent on measurement geometry and time of acquisition.

Meteorology also has great influence on the radiance field in the self-emitted regions. Solar loading combined with a target's broadband absorptivity greatly influences a material's temperature and therefore its self-emitted energy contribution. Wind speed is also an important factor since the wind can effectively cool the surface layer of the material very quickly. It is this surface layer that does the majority of the infrared emitting and these short-lived temperature changes result in very quick and shortly sustained changes in the radiance field which impose havoc on field measurements. Surface temperatures that change during a spectral scan will result in poor emissivity determination.

The spectral radiance field reaching the sensor has many components. In the spectral region where both self-emission and reflected solar energy are significant contributors, the radiance field reaching the sensor, $L(h,q,l)$, is defined by the following;

$$\begin{aligned}
L(h,q,l) &= t(h,q,l)\{L_{self-emitted} + L_{reflected-solar} + L_{reflected-background}\} + L_{upwelled} \\
&= t(h,q,l)\{e(q_t,l)L_{BB}(T_s,l) + \\
&\quad (1-e(q_t,l))\frac{E_s(l)}{p}t_s(q_s,l)\cos q_{st} + \\
&\quad (1-e(q,l))[L_{D,emit}(l) + L_{D,scat}(l) + \\
&\qquad \sum_{all\ backgrounds}([e_b(l)L_{b,emit}(T_b,l) + (1-e_b(l))L_{D,scat}(l)]t_{bt}(z,l) + L_{u,bt,emit}(z,l) + L_{u,bt,scat}(z,l))]\} + \\
&\quad L_{u,emit}(h,q,l) + L_{u,scat}(h,q,l)
\end{aligned} \tag{1}$$

where

h	is the altitude of the sensor,
z	is the distance between a background element and the target,
q	is the zenith angle of the sensor with respect to the earth normal,
q_t	is the zenith angle of the sensor with respect to the target normal,
q_s	is the solar zenith angle with respect to the earth normal,
q_{st}	is the solar zenith angle with respect to the target normal,
l	is the wavelength at which the radiance field is being defined,
T_s	is the target surface temperature,
T_b	is the temperature of a particular background element,
$e(q_t,l)$	is the spectral diffuse hemispheric target emissivity at a zenith angle of q_t taking into account the target geometry,
$e(q,l)$	is the spectral diffuse hemispheric target emissivity at a zenith angle of q assuming a flat target,
$e_b(l)$	is the integrated spectral diffuse emissivity of the background,
$E_s(l)$	is the spectral exoatmospheric solar irradiance,

$t_s(q_s, l)$	is the to-space spectral atmospheric transmission through a path q_s degrees off of the earth normal,
$t(h,q,l)$	is the to-sensor spectral atmospheric transmission through a path q degrees off of the earth normal to an altitude of h,
$t_{bt}(z,l)$	is the spectral transmittance along a path of length z between each background element and the target,
$L_{BB}(T_s, l)$	is the spectral blackbody radiance at a target surface temperature T_s,
$L_{b,emit}(T_b, l)$	is the spectral emitted background radiance from each background element in the scene,
$L_{D,emit}(l)$	is the spectral emitted downwelling atmospheric radiance,
$L_{D,scat}(l)$	is the spectral scattered downwelling atmospheric radiance,
$L_{u,bt,emit}(z,l)$	is the spectral emitted path radiance along a path of length z between a particular background element and the target,
$L_{u,bt,scat}(z,l)$	is the spectral scattered path radiance along a path of length z between a particular background element and the target,
$L_{u,emit}(h,q,l)$	is the spectral self-emitted path radiance from a path q degrees off the earth normal to an altitude of h, and
$L_{u,scat}(h,q,l)$	is the spectral scattered upwelling path radiance from a path q degrees off the earth normal to an altitude of h.

The transmissive and absorbing features of the earth's atmosphere beyond this point define the traditional windows that are thought of as the midwave infrared (MWIR) and the longwave infrared (LWIR). Many strong absorbing gas species exist in this portion of the spectrum, the most dominant and defining of which are water vapor, carbon dioxide, nitrous oxide and methane. The effects of these gases and primary regions of absorption are defined in Table 1.

Table 1 Primary atmospheric constituents that affect and define the midwave and longwave infrared windows commonly used for detection and imaging

Water Vapor	H_2O	Defines both sides of the 3 to 5 µm window, and the lower end of the 8 to 14 µm window by total absorption.
Carbon Dioxide	CO_2	Very strong absorption between 4.2 and 4.4 µm, defines the upper end of the 8 to 14 µm window by total absorption.
Nitrous Oxide	N_2O	Strong, deep band at 4.5 µm extending the CO_2 gap in the 3 to 5 µm window.
Methane	CH_4	Contributes to the H_2O absorption band at 3.0 and 3.5 µm.

NOTE: The 3 to 5 µm window does not fully open up until 3.5 µm and has a gap from 4.2 to 4.5 µm leaving this window less than favorable for spectral remote sensing in light of the low energy levels present.

As can be seen in Equation 1, the downwelling and upwelling path radiance show up as important contributors to the radiance field. If the goal of the analysis is to determine properties unique to the target of interest, then these terms add "noise" to the signal you have to work with. For this reason, dry environments are preferable to reduce the contribution of these terms as well as make their contribution stable over time since water vapor is usually the primary contributing component to atmospheric self-emission and scattering. This temporal stability is important since downwelling radiance is not typically measured simultaneously with ground leaving radiance due to current single-beam instrument designs for MWIR and LWIR measurements. The measurement of downwelling radiance is typically made sequentially to the target measurement, either right before or right after, or both (depending on conditions). If the downwelling radiance field changes between its explicit measurement and the measurement of the sample leaving radiance, then the emissivity computed for this sample will contain error that is proportional to the magnitude of this change. It is only by accurate accounting and recording of the reflected downwelling radiance that accurate target emissivity and temperature can be arrived at in ground-based measurements. The measurement conditions you will typically encounter will not be ideal so accurate and timely measurement of the downwelling radiance is critical.

While small, the contribution of reflected and emitted radiance from background objects within a scene to the measured target radiance can be significant. If the target measured is close to a man-made or natural structure, *e.g.* a building or a tree, then these background objects subtend a significant portion of the hemisphere above the target. The radiance from these objects are then significant contributors, especially since they are likely to be close to earth's surface temperature (significantly warmer than a cold sky background). The solid angle that these objects subtend should be reduced as much as possible by moving away from these elements.

The downwelling radiance field consists of many individual components as shown in Equation 1. These would be very difficult to measure individually since they emanate from all portions of the hemisphere above the sample being measured. The effective downwelling radiance field is the integral over the hemisphere of all of these elements. Treating this term as a single value, as well as the complementary upwelling radiance field, Equation 1 reduces to

$$L(h,q,l) = t(h,q,l)\{e(q_t,l)L_{BB}(T_s,l) + (1-e(q_t,l))L_{DWR}(l)\} + L_{UWR}(h,q,l) \tag{2}$$

where

$L_{DWR}(l)$	is the downwelling radiance field integrated over the hemisphere representing scattered, self-emitted and direct solar contributions, and
$L_{UWR}(h,q,l)$	is the upwelling scattered and self-emitted atmospheric path radiance reaching altitude h at zenith angle q.

As previously discussed and quantified in Equation 1, the radiance field that you observe with a sensor is a function of many contributing parameters. If all of the atmospheric and background effects can be accounted for (or their effects minimized) then the radiance you are left with is the radiance leaving a surface due to its self-emission. This self-emission term is complicated by the fact that it is a function of two parameters, the spectral diffuse hemispheric emissivity and the surface temperature of the target, $e(q,l)$ and T_s, respectively. From Equation 1, this self-emission term $L_s(q_t,T_s,l)$ is given by

$$L_s(q_t,T_s,l) = e(q_t,l)L_{BB}(T_s,l) \tag{3}$$

and, the spectral emissivity is defined as

$$e(q_t,l) = \frac{L_s(q_t,T_s,l)}{L_{BB}(T_s,l)} \tag{4}$$

In practice, this self-emission term cannot be measured directly due to atmospheric and environmental influences. The atmospheric effects can be minimized by taking measurements close to the material surface, *i.e.* $t(h,q,l) \sim 1$ and $L_{UWR}(l) \sim 0$. At this point, what is measured is the self-emission and reflected background term. By making these atmospheric minimizing assumptions, Equation 2 reduces to

$$L(h,q,l) = e(q_t,l)L_{BB}(T_s,l) + (1-e(q_t,l))L_{DWR}(l) \tag{5}$$

and solving for the spectral emissivity of the target yields

$$e(q_t,l) = \frac{L(h,q,l) - L_{DWR}(l)}{L_{BB}(T_s,l) - L_{DWR}(l)} \tag{6}$$

This result allows the computation of spectral emissivity from three components; the surface-leaving radiance from the target of interest, the downwelling radiance, and the surface temperature, T_s. If the surface temperature is unknown at the time of radiance measurement, you are posed with an under-constrained problem to derive both the temperature and spectral emissivity for the target of interest. Many algorithms exist for temperature-emissivity separation[1,2,3,4,5] , however, the discussion of the details is beyond the scope of this paper.

3. METHODOLOGY

3.1 General Measurement Considerations

Ground truth spectra of very high quality can be gathered using field spectrometers and a collection protocol that is cognizant of the phenomenology unique to the MWIR and LWIR portions of the spectrum. In addition, an understanding of the instrument that is being used and its operating limitations and intricacies is of paramount importance. Key points concerning both of these aspects are addressed here.

Keeping in mind the phenomenology mentioned in the previous section, and noting the need for repeatable ground-based measurements of radiance in the MWIR and LWIR portions of the spectrum, the following general items need to be considered during field collection efforts.

A blackbody calibration should be conducted for every target measured, or at least every 10 minutes, to reduce the effect of instrument drift (no matter how expensive your instrument, it drifts). Instruments drift when they undergo temperature changes. Temperature change will almost certainly happen in the field due to the variable environmental conditions present. A temperature-controlled instrument is preferable to a non-controlled model.

In general the cold blackbody should be set just below ambient (being careful that condensation does not form on its surface). The warm blackbody should be set just above the sample temperature anticipated. Remember that the slope between these points will be more accurate the further apart these points are as long as the instrument is linear within the region. *NOTE: Uncalibrated radiance spectra and blackbody radiance spectra will appear very similar since the instrument's self-emitted radiance is the dominant propagated radiance term. It is not until the spectrally dependent calibration factors are applied to the raw instrument counts that any spectral features become apparent in the radiance spectra*.

An instrument should be controlled to within 0.1°C between calibration and actual target measurements. Instruments will also drift significantly during their warm-up period (SITAC personnel have measured drift occurring for as long as 5 hours). Be sure to turn your instrument on when you are transporting it to the field (preferably using an alternate source of power to conserve battery life) so that this drift is reduced once measurements are commenced. If it is possible, let the instrument run for as long as possible (e.g. overnight) prior to making measurements. This "warm-up" period allows ample time for the instrument components within the enclosure to come to thermal equilibrium and establish a thermal mass (that will be more resistant to change once you head out to the field). It takes much less battery power for the instrument to heat than it does to cool itself. By adjusting the instrument set point higher than the instrument's natural starting temperature, you force the instrument to stay in heating mode for the better part of your collection period. Since the instrument components have also been elevated in temperature, it takes much less effort on the part of the instrument's temperature control circuitry to maintain this temperature. Know your instrument's requirements for warm up and try to avoid this period if possible. Determine this in the lab before you set out to the field. This can be accomplished by repeatedly measuring a known temperature blackbody over the course of many hours, being sure to calibrate before each measurement is taken. You can then use any set of calibration factors to calibrate any future radiance measurement and determine how much drift occurred during that period. This process will give you the knowledge of how quickly your instrument's response drifts and what period of time you should allow for stabilization before commencing data collection.

Most instruments can be considered linear over a limited range between temperature calibration points. Interpolation can be used successfully to arrive at intermediate temperatures derived from measured radiance without introducing significant error. Extrapolation to much lower temperatures than the low end of the calibration can prove troublesome and should be avoided.

Always be sure to overfill the field-of-view of the device since the field-of-view reported by the manufacturer is often smaller than actually encountered due to "beam spread" in the interferometer. You should map out your instrument's field-of-view in the laboratory using a small hot target such as a fine-tipped soldering iron.

Samples should be measured at a distance of no more than 1 meter if possible to minimize the effects of atmosphere.

Downwelling radiance should always be measured immediately following the sample measurement by collecting the reflected radiance off of a diffuse reflective plate, usually InfraGold or crinkled aluminum foil. The location, orientation and bi-directional reflectance distribution function (BRDF) of the reflective plate should be identical to those of the sample to accurately measure the downwelling radiance reflected off the sample. The location and orientation are fairly easy to mimic by placing the reflector on the sample, however, the BRDF of most natural objects is more diffuse than either reflective plate mentioned (man-made objects are less problematic). This is especially true in the 3 to 5 μm region where the reflected solar component can be significant (specular solar reflection must be avoided).

Measurements are best made in the early morning or late afternoon to avoid the rising thermal currents at the hottest point of the day. These currents contribute to instability in the downwelling radiance field. In addition, higher thermal contrast will exist in the late afternoon that will add to the accuracy of your measurements by boosting signal level. Specific considerations for the measurement of MWIR spectra will be addressed in detail later in this paper. For now, suffice it to say, these measurements are best made in the hours just after sunset when there is little scattered solar irradiance and target temperatures are still elevated from daytime heating.

For the Designs & Prototypes microFTIR Model 102 portable field spectrometer owned and operated by SITAC personnel, the temperature controller switches off while scans are being made. This allows the instrument's temperature to change so the number of scans to co-add must be limited in consideration of the time constraint imposed by this temperature rise. If the temperature changes by 0.2°C or more during measurements, the blackbody calibration points and downwelling radiance scans should be repeated.

3.2 Measuring Downwelling Radiance

In order to measure the integrated downwelling radiance field several approaches can be taken. One can take sky-pointing measurements in a very large number of directions attempting to cover the entire hemisphere. This presents a couple of real-world limitations. The most significant is the amount of time that such a measurement procedure would take. In addition to the length of time, the dynamic nature of the downwelling field would surely change before all measurements were completed making the accuracy of the measurement questionable.

A second approach that might be considered is using a cosine receptor on a sky-pointing sensor. The cosine receptor would perform the hemispheric integration of the radiance desired and would only require a single measurement. The downside of this sort of measurement is that the sky is typically a very cold target. The accuracy with which a calibrated measurement of this radiance field could be collected would be questionable due to the need to extrapolate outside of the calibrated temperature range of the instrument.

The third and most commonly employed approach is the use of a diffuse reflecting plate, placed in the same orientation and position as the target when possible. The radiance field leaving this plate is measured and the result compensated for the self-emitted component of the plate itself. This approach requires that the temperature and spectral nature of the plate be well known. At least three different plates are described in the literature as good standards for laboratory and field measurements; diffuse gold, aluminum foil and flame-sprayed brass. Each plate has advantages and disadvantages, and our experience with the first two will be discussed here.

A diffuse gold surface on an aluminum substrate, such as an InfraGold plate from Labsphere, serves as an excellent standard. The surface exhibits a relatively flat spectral behavior across the 3 to 5 μm and 8 to 14 μm windows with a reflectivity between 0.94 and 0.96. This surface is not truly diffuse and therefore care must be taken to avoid collecting measurements at the specularly reflected angle to the sun/source. Measurement/collection geometry for the sample and the standard must remain consistent. This plate is ideal for laboratory use but great care must be taken when using it in the field as it is easily contaminated (SITAC personnel commonly use this plate in the field, protecting it from contaminants and significant solar heating by keeping it in a wooden enclosure between measurements). The cost is also very high. The extremely low emissivity and relatively high thermal mass result in accurate downwelling radiance retrieval. Fluctuating ambient air temperature does not quickly affect the plate temperature due to its mass. Some error in determining the plate temperature is inconsequential due to the very low emissivity of the plate surface.

Heavy-duty aluminum foil also serves as a good standard. If the foil is randomly crinkled and placed over a stiff cardboard or light plywood panel, this presents a light, easily renewable and inexpensive reflectance standard. SITAC personnel have found that nearly identical results can be obtained to those measured using the InfraGold panel if a diffuse reflectivity in the MWIR and LWIR of 98% is used. The "bright" side of the aluminum foil is faced up and the foil is crinkled in multiple directions. The low density and thermal inertia of aluminum foil allow it to quickly change temperature and remain very close to the ambient air temperature so the surface temperature is easily determined.

As with most things, there is an upside and a downside to using these types of plates. The low emissivity of the panels does not require a very accurate knowledge of the surface temperature since the self-emitted portion of the signal is very small. The downside of this is that the overall magnitude of the radiance field is low, therefore, accurate, calibrated measurements are difficult to make.

SITAC personnel have been very successful in the field using an InfraGold standard reflecting plate and measuring its temperature with an Exergen Series-D Microscanner. This device is a radiometric thermometer in its design that unitizes emissivity of surfaces whose temperature you want to measure. It does so by using a hemispherical reflector with the detector at its apex in its probe. The probe is placed in complete contact with the sample which causes all the surface leaving radiance to be multiply reflected between the hemispherical reflector and the sample surface, eventually reaching the detector (thus driving the effective emissivity of the surface to unity).

This device comes along with a NIST-traceable calibration and reports accuracy of better than 0.1°C for flat, solid, opaque surfaces. The surface area of the probe and target that are actually in contact is small (the rim at the equator of the hemisphere) which keeps the amount of heat lost by the surface to the probe through conduction to a minimum. Care must be taken on surfaces with low thermal inertia values (*e.g.* thin metals, vegetation, etc.) not to shade the surface for too long. Prolonged shading will cause the surface to lose heat quickly through convection.

In addition to measuring the temperature of the reflectance standard, the Series-D Microscanner is also used to record the temperature of the sample being measured. This aids in the temperature-emissivity separation (TES) process as well as serving as a sanity check for the derived blackbody temperature from the TES algorithm.

3.3 Target and Measurement Considerations

Solids are the most common targets encountered in typical field collection campaigns. These include metals, soils, rocks, vegetation, man-made building materials, etc. Solids primarily exhibit reflective and absorptive properties, however, they do at times exhibit transmissive properties also. A remote sensing practitioner who is not used to working in the MWIR and LWIR portions of the spectrum may have a little trouble at first identifying targets that exhibit transmissive properties in these regions. For example, glass is a sample commonly considered as transmissive. It is common to look out the window everyday to see if it is sunny or if a raincoat is needed. In the visible portion of the spectrum, glass is indeed transparent. In the MWIR and LWIR portions of the spectrum, however, glass is very opaque. Therefore it is easy to measure the radiance of a sheet of glass by laying it on the ground and measuring its radiance with little to no regard for what the underlying background is. Intuition is not on your side in making this determination and therefore great care in deciding which samples are transparent and how to conduct a measurement must be taken.

Solids, as well as all other targets, should be measured *in situ* if they are to be used as ground truth for remote sensing studies. This maintains as best as possible any contaminants and weathering that may exist on the specific target of interest and makes the general class of samples more representative of their natural state.

When encountering a solid sample, the following considerations should be made and questions asked with regard to both an airborne remote sensing platform's as well as a field spectrometer's field-of-view. Is the target uniform in composition and makeup? Is the target surface multi-faceted? Is the surface texture rough or smooth compared to wavelength in the particular frequency range? Can the background be seen through the target (transparency or porosity)?

Target uniformity is important since individual components that make a solid surface may have unique spectral signatures. For example, concrete that has a coarse aggregate dispersed in the cement may have large visible stones at the surface. These stones will have a different spectral signature than the cement that binds them together. Therefore it is important to identify the reason for collecting this spectrum. If the reason is for remote sensing purposes with an airborne sensor whose field-of-view is on the order of a foot or more, then the individual stones will not be uniquely visible, they will be part of a mixed signature of stone and cement. For this purpose, one must be sure to collect the spectra such that a similar mixture is obtained. As always, documentation of what is included in the field-of-view of the field spectrometer and photographs of the actual sampled area are imperative.

When measuring solid materials, the field collection team should be aware of the thermodynamic and bulk properties of the material. A composite term that incorporates a material's density, specific heat and conductivity is known as thermal inertia. Thermal inertia can simply be thought of as a material's resistance to forces trying to change its temperature. This is important to spectral radiance measurements because a varying sample temperature during the series of interferogram scans will cause inaccurate radiance spectra to be computed. If a material exhibits a high thermal inertia, showing great resistance to temperature change, then the likelihood of the temperature changing during the series of scans is minimal. Materials such as concrete, asphalt, rocks, water all exhibit high thermal inertia. The presence of wind or strong solar heating will not affect these types of materials significantly during a measurement. Materials such as vegetation and thin metals do change quickly under these conditions and therefore should be measured at times when these effects are at a minimum.

The field spectrometer must be set up, if possible, so that the direct sunlight falling on the sample is unobstructed. For example, if the sun is in the southern sky, the foreoptic of the instrument should be to the South side of the instrument with the operator to the North side.

Background influence on sample radiance measurements is great in the MWIR and LWIR wavelength regions. Trees, buildings, vehicles, clouds and "spectrometer operators" all emit and reflect energy in the direction of the sample that is subsequently reflected to the sensor. These "background" contributions are easily removed from the sample radiance field as described previously, however, in practice any dynamic change needs to be minimized between sample radiance collection and background radiance characterization. What this means is that if there are any moving objects that are visible in the hemisphere above the target, measurements should be made when this motion has stopped. Once a measurement series has commenced, the field collection team members should assume a fixed position and not move from it during either the sample or downwelling radiance measurements. If movement is necessary between these measurements (*e.g.* to place the InfraGold standard in place) then the previous positions should be taken up before the next measurement is made. This ensures that the hemispherical background radiance contribution to the sample field does not change dramatically.

Clouds are significant sources of radiance and dramatically influence the amount of direct and diffuse solar irradiance that impinge on a target. It is best to make measurements on those severe clear days that the remote sensing textbooks always hope for. If measurements need to be made on cloudy days, great care should be taken to ensure that the cloud cover and its influence on the downwelling radiance field is as constant as possible. In order to accomplish this, the operator needs to survey the sky before measurements are made and must be sure they can collect all the required data before a significant change in cloud position or cover occurs.

The blackbody calibration is best performed with every sample measured (when time and conditions permit). This minimizes sensor drift effects on measurements since calibration is performed so close to the actual sample measurements. The cold blackbody temperature is typically set 10°C below that of the sample or InfraGold, whichever is cooler, and conversely, the warm blackbody temperature is set just above the warmest object expected. Care must be taken to ensure that the temperature of the cold blackbody does not fall below the dew point temperature that would cause condensation or even frost to form on the blackbody surface and therefore affect the accuracy of the calibration. If it is necessary, the cold blackbody may have to exceed the sample temperature to avoid condensate formation and extrapolation relied upon for calibration purposes. This is not the preferred mode of operation, however, it may at times be necessary, especially in cold or some extremely humid environments.

3.4 MWIR Considerations

The spectral emissivity for a sample, $e(q_t, l)$, can be derived from radiance data collected using a field spectrometer as shown in Equation 6. The sample leaving spectral radiance, $L(h,q,l)$, measured at a height h above and at an angle of depression q with respect to the sample surface normal is a function of both its emissive and reflective properties. Equation 6 removes the effects of reflective energy leaving only the sample's efficiency as a blackbody radiator, *i.e.* emissivity. This form, however, results in mathematical instability when the magnitude of the equivalent blackbody at the sample temperature and the downwelling radiance terms are close in magnitude across the bandpass, resulting in a denominator that tends toward zero. The numerator will also tend toward zero or result in negative values as the magnitude of the sample leaving radiance and downwelling field approach each other. This situation occurs as the magnitude of the solar component in the MWIR (3 to 5 µm) portion of the spectrum builds in when measurements are made during daylight hours. It also occurs when the sample temperature is relatively cool (*i.e.* near or below ambient air temperature), as is typically the case at night or in cold environments. Therefore, measurements are very difficult to execute. A large temperature differential between sample surface temperature and ambient air temperature is desired, which occurs during the daytime heating hours, and it is preferable to have no scattered or direct solar irradiance, which occurs only at night.

Early morning measurements, those taken before sunrise, result in small or even negative differentials in radiance in the MWIR band between the sample and downwelling radiance for wavelengths to the red side of the CO_2 absorption band. Early evening measurements, after sunset, are better since samples still possess residual heat from the daytime warming and the direct and scattered solar irradiance has disappeared. Surface temperatures for samples with moderate to low thermal inertia values, however, can be changing very rapidly at this time.

Figure 1 illustrates the influence that the direct and scattered downwelling solar radiance has on the measured downwelling radiance field. Figure 1(a) illustrates data collected prior to sunrise. The sample radiance depicted is the sum of the emitted energy from the sample due to its kinetic temperature and the reflected downwelling radiance. The sample measured in this study was a painted metal surface with very high spectral emissivity (thus possessing a low spectral reflectance). The downwelling radiance is that energy incident on the InfraGold diffuse reflectance standard. The InfraGold standard has a flat spectral emissivity in this bandpass with a magnitude approximately equal to 0.05. The surface temperature of the InfraGold standard is measured during collection and its emitted radiance removed as

$$L_{DWR}(l) = \frac{L_{InfraGold}(l) - e_{InfraGold}(l) L_{BB}(T_{InfraGold}, l)}{1 - e_{InfraGold}(l)} \tag{7}$$

The near equality of the magnitudes of these two components in Figure 1(a) leads to the mathematical instability referred to previously. As solar irradiance is introduced to the measurement scenario, the marked increase in the downwelling radiance field to the red side of the 4.2 to 4.5 μm CO_2/NO absorption bands is evident in Figures 1(b) through 1(d). The inherent highly structured nature of the atmospheric transmission and absorption spectra in this region leads to multiple crossings of these two terms, leading to instability at a large number of points. This results in extremely “noisy” and unreliable emissivity spectra in this region rendering the data of little use. Figure 1(e) illustrates a reduction in the solar component as would be expected down to similar levels as seen in the early morning data shown in Figure 1(b). This instability in emissivity computation has been observed and can be expected under a wide range of environmental conditions from mid-latitude summer to desert climates.

Making field measurements of emissivity in the midwave infrared (MWIR) portion of the spectrum (from 3 to 5 μm) is problematic to say the least. Low signal levels, the effects of direct and scattered solar irradiance, and the need for high sample surface temperatures all combine to make the protocol one uses in this region of the spectrum an exercise in compromises, none of which yield an optimum measurement condition. The only comforting fact is the knowledge that a remote sensor collecting information in this region is experiencing the same conditions. If remote sensing is to occur using hyper- or ultraspectral sensors in this bandpass, it is prudent to perform field measurements prior to the onset of sensor design to assess whether signatures for samples/targets of concern are discernable under real-world collection conditions. Laboratory spectra prove of little value in this region since the environment encountered in the field or with actual collection systems has a profound effect on the observed spectra, often completely masking features that fingerprint your sample/target. Laboratory measurements only become useful when direct measurements of radiance field components can be made or when an accurate atmospheric model with parameters of high fidelity for the exact geographic position is available. As a general rule-of-thumb, the only valid portion of spectra measured in the MWIR falls between 4.6 and 5.0 μm. The open window between 3.5 and 4.2 μm is contaminated with solar irradiance when making daytime measurements and is plagued by low signal levels at night.

4. CONCLUSIONS

In spite of all the problems and pitfalls associated with the measurement of spectral radiance in the field and the subsequent derivation of spectral emissivity, quality data can be obtained. As long as the scientist is aware of all the collection and environmental conditions that affect these measurements and compensates for them, accurate spectral data is within reach. Spectra collected in the longwave infrared portion of the spectrum, from 8 to 14 μm, can be obtained day or night and under a wide variety of climatic conditions. The midwave portion of the spectrum, from 3 to 5 μm, offers its own unique challenges to consider and is severely limited in the useful data that can be obtained therein. Spectrally derived emissivity in the region between 4.6 to 5.0 μm proves accurate and consistent for most applications while the rest of the band should be used only with great caution. The Designs & Prototypes microFTIR Model 102, used as the basis for all the field data and conclusions derived in this paper, has been in use by the personnel of the Spectral Information Technology Applications Center for one year. The recommendations contained here are for solid materials only and are based on that experience. Future papers and presentations will address protocols and methodologies for the measurement of spectra for liquids, gases and crystalline materials (such as snow and ice) as that experience is gained.

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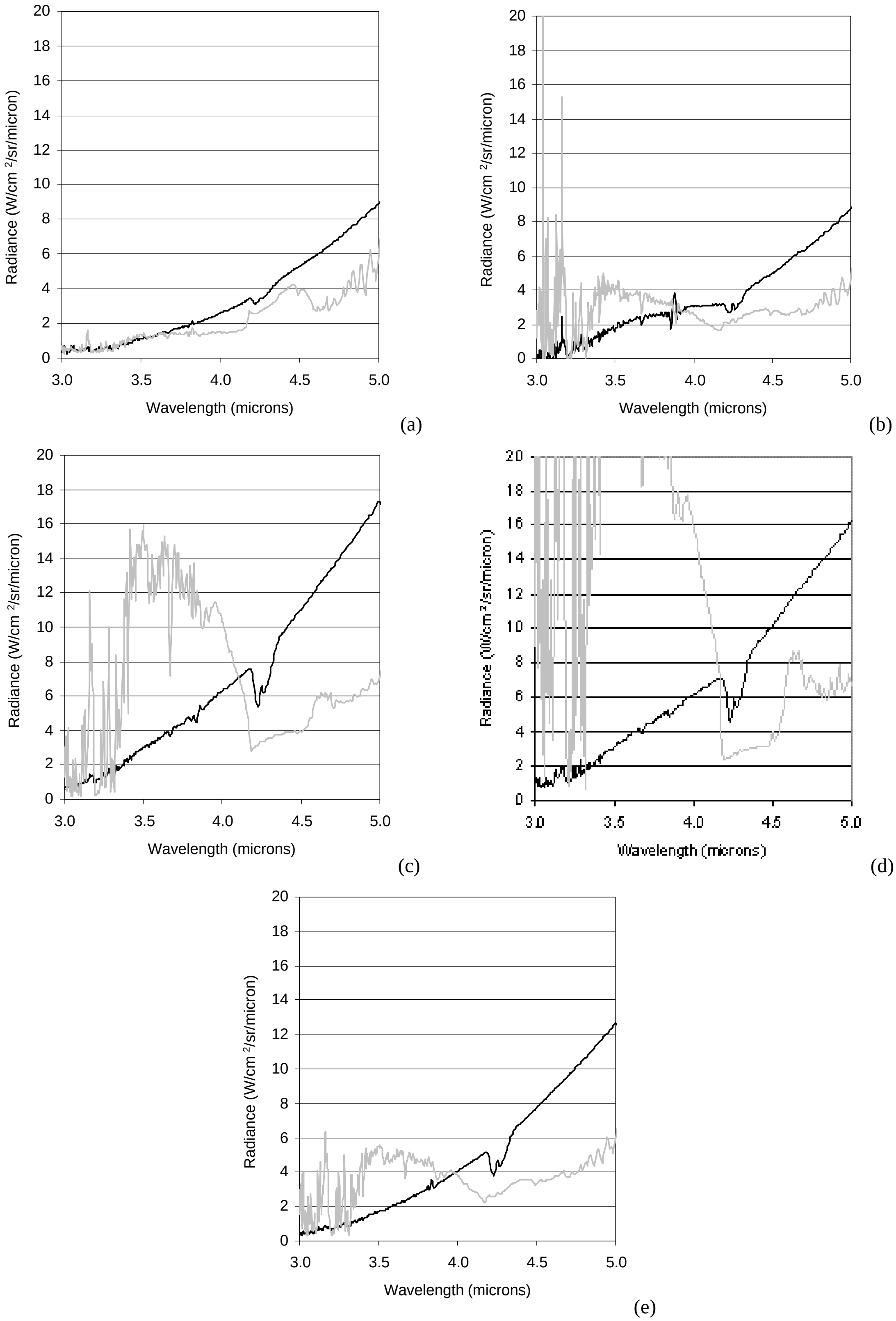

(a) (b) (c) (d) (e)

Figure 1 Sample leaving (black) and downwelling (gray) radiance collected at (a) 0520 (local), (b) 0910 (local), (c) 1106 (local), (d) 1357 (local), and (e) 1611 (local) (Location: Fairfax, VA, 03 October 2000)