A Novel Approach to Temperature-Emissivity Separation Using a Multiple-Window Smoothness Criteria

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Abstract

A blackbody is any object that absorbs all the electromagnetic radiation incident upon it, and that emits spectral radiation that is solely dependent on the object’s kinetic temperature. Real-world objects seldom exhibit this behavior, and are termed spectral greybodies. A spectral greybody does not absorb all the incident energy, it differentially absorbs this energy as a function of wavelength. The ratio of energy radiated by a greybody to the energy radiated by a blackbody at the same temperature and wavelength, is called the spectral emissivity. Unlike spectroscopy in the reflective portion of the spectrum, the temperature of the object must be known in order to calculate the spectral emissivity. This presents a problem since a measure of the energy radiated by the object can be made at each wavelength, however, this only provides n measurements to solve for n+1 unknowns, including the object’s temperature. One is left with an ill-posed problem requiring an optimization approach. An optimization referred to as temperature-emissivity separation is used to best estimate the temperature of the object. There are previously published methods for accomplishing this, however, these methods only look at a small region of the full wavelength range for their optimization. This research proposes a novel approach that looks at multiple subregions, in multiple positions, using optimization to achieve a better estimate of the object’s temperature. A comparison of the results obtained using this new approach with methods previously employed are presented.

I. Introduction

It is very useful to be able to determine the temperature and emissivity of objects on the ground from collected aerial imagery. Previous research has determined multiple methods for estimating the emissivity of remotely sensed objects. Many of these methods are either optimized specifically for soils, or require previous knowledge of the optical surface properties of the material. These approaches are often impractical due to the variety of existing materials, other than soil, and the large area over which measurements are generally acquired. The optical surface properties of materials may be measured separately, but many of these properties can significantly change based on their environment. Therefore, measuring the optical surface properties in a laboratory, rather than in situ, may not be useful. Some of the existing temperature-emissivity methods are reference channel, blackbody fit, maximum spectral temperature, and spectral smoothing.

The reference channel, or maximum emissivity method, assumes that there will be some wavelength in the spectral region which will have an emissivity, \( \varepsilon \), of one. Using this assumption, the temperature at that wavelength, and the emissivity for the rest of the spectra may be calculated. Unfortunately, many materials do not have an emissivity equal to one at any wavelength in the range, therefore this assumption will cause an upward bias in the data. One way of correcting for this bias is by finding the maximum value in the spectrum, and calculating the \( \varepsilon \) based on that. Unless the maximum \( \varepsilon \) for the specific material is known, this method will not give an absolute value for this data[1].

Another previously introduced temperature-emissivity separation method is called the blackbody fit method, which compares a given maximum emissivity to the calculated one. Two temperatures are used to bound the actual temperature of the object, and the midpoint temperature is used to compute the spectral blackbody radiance. This radiance is then used to calculate the current emissivity estimate, the maximum of which is compared to the user specified maximum. The temperature is recalculated using a binary search method described as follows. Depending on whether the maximum of the estimate is larger or smaller than the user specified spectral maximum, either the lower
or upper temperature limit is changed to the middle temperature. This process is then repeated until the temperature is within a predefined limit[1].

A method called maximum spectral temperature requires that the user only knows at which wavelength the maximum emissivity occurs, but not its value. Assuming that the value of \( \varepsilon_{\text{max}} \) is constant over every wavelength, the radiance can be computed, and that value is used to solve for temperature. Since these systems include noise, the emissivity spectra is smoothed, and the emissivity computed, and compared until \( \varepsilon_{\text{max}} \). The value of the temperature is varied until the emissivity matches to within some tolerance[1].

II. Data Collection

For the purposes of this project, ground-based remote sensing techniques were used. These measurements make it much easier to obtain measurements of the true temperature of the target to compare with the calculated results. A Designs and Prototypes (D & P Instruments) Portable Fourier Transform Infrared Spectrometer, Model 102, was used to collect data from a variety of targets. In order to reduce the effect of nearby background structures on the sample, the measurements were taken on the roof of a building with an unobstructed view of the sky. These measurements should be taken away from large structures that may block the ambient, hemispherical contribution of atmospheric radiance. Since one set of measurements takes multiple minutes to collect, changes in the atmospheric water content, cloud cover, wind, and other aspects of the meteorological conditions at the time of measurement may have a large impact on the data. For this reason, days with low humidity, and little to no cloud cover were chosen for data collection.

The D & P Instruments spectrometer requires liquid nitrogen to cool the detector, in order to reduce noise in the measurements. The D & P Instruments spectrometer has a spectral range from 2 - 16 micrometers, taken in evenly spaced frequency intervals. Generally, for each target, multiple measurements, or co-adds, are taken, which are then averaged. During this research, either 8 or 16 co-adds were used for each measurement, depending on atmospheric stability. A thermoelectrically stabilized blackbody was used to create blackbody spectra at two different temperatures, which were then measured by the spectrometer, in order to calibrate the instrument for each sample. A warm blackbody spectra was taken at a temperature higher than the measured temperature of the object, and a cold blackbody spectra taken at a temperature lower than that of the target. The blackbodies were measured before each target measurement. The temperature of the target, and a gold plate, which serves as a diffuse downwelling radiance reflector, were measured using an Exergen Handheld Infrared (IR) Thermometer, Model DX501-RS. Once the warm and cold blackbodies were measured, the actual target was measured, recording the temperature of the target at the time of measurement. It is important that those individuals taking the measurements stand in the same spot, a few feet away from the target, for data.

Figure 1: Photograph of the instruments used in this study in the typical data collection configuration.
each collection, since the operator is likely one of the greatest sources of thermal infrared radiation nearby, and occupying a significant portion of the hemisphere above the target. Once the target measurement is taken, a diffuse gold plate is placed in front of the spectrometer, and the temperature and raw spectra are measured. The emissivity of the diffuse gold plate is very nearly one, so it is used to measure the downwelling radiance of the atmosphere, which will later be removed from the target measurement. Once these four raw spectra and temperatures are recorded for each target, the data is ready for analysis. Atmospheric conditions such as cloud cover, wind, and the time of each measurement should all be recorded.

III. Calculations

Before any analysis on the data retrieved from the scene may be done, the data from the instrument must be converted from raw digital count, which has little physical meaning, to scene radiance. Using the measured radiance from the scene, and the temperature of the targets, the radiometric equations may then be arranged to give an equation for estimating the emissivity of the target.

I. Instrumental Calibration

Once the spectra of the target scene have been collected, the instrument digital count values must be converted to spectral radiance at the sensor, \( L(\lambda) \). The digital count at the sensor is a function of instrumental factors, and target radiance. This is shown by

\[
DN(\lambda) = R(\lambda)L(\lambda) + O(\lambda),
\]

where \( O(\lambda) \) is a wavelength-dependent offset due to electronic factors, as well as self-emissions from the instrument, and \( R(\lambda) \) is the instrument’s spectral response. The blackbody radiance collected at two different temperatures provides a way of measuring the instrument response, assuming detector linearity\(^{[2]}\). Using the two blackbodies, \( DN_w(\lambda) \) and \( DN_c(\lambda) \), the response can be calculated by

\[
R(\lambda) = \frac{DN_w(\lambda) - DN_c(\lambda)}{B(T_w,\lambda) - B(T_c,\lambda)},
\]

where \( B(T_w,\lambda) \) and \( B(T_c,\lambda) \) are the Planck blackbody spectral radiances at the temperature of the warm and cold calibrated blackbodies. Next, the offset can be calculated from either blackbody by

\[
O(\lambda) = DN(\lambda) - R(\lambda)B(T_c,\lambda).
\]

Once the instrument response and the offset have been calculated, the scene spectral radiance, \( L_{meas}(\lambda) \), can be computed as

\[
L_{meas}(\lambda) = \frac{DN_{meas}(\lambda) - O(\lambda)}{R(\lambda)}.
\]

Although the measured radiance of the scene may now be calculated, this data is a sum of all the sources of radiance entering the device. This includes not only the target radiance, but also the reflected downwelling atmospheric radiance, and the radiance between the sensor and the target, which can be given by

\[
L_{meas}(\lambda) = B(T_T,\lambda)\varepsilon_T(\lambda)\tau_p(\lambda) + (1 - \varepsilon_T(\lambda))L_{DW}(\lambda)\tau_p(\lambda) + L_p(\lambda)
\]

where \( B(T_T,\lambda) \) is the blackbody spectral radiance at the target temperature, \( T_T \); \( \varepsilon_T(\lambda) \) is the spectral emissivity of the target; \( \tau_p(\lambda) \) is the atmospheric spectral transmissivity of the path between the target and the instrument; \( L_{DW}(\lambda) \) is the downwelling spectral radiance onto the target; and \( L_p(\lambda) \) is the spectral path radiance between the target and the instrument. These three terms on the right-hand side of this equation represent the spectral radiance from the target, the spectral radiance of the atmosphere reflected from the target, and the direct path atmospheric radiance between the
sensor and target. According to an example given in Horton et al.\cite{2}, since the distance between the sensor and the target is on the order of 1 meter, the atmospheric transmissivity and path radiance between the wavelengths of 8 and 14 micrometers is negligible. Over this range, the atmospheric transmissivity, $\tau_p(\lambda)$, is greater than 0.99, and the path radiance, $L_p(\lambda)$, is less than 0.5% of the total radiance. This can be confirmed using MODTRAN\cite{2}. Considering this, Eq. (5) may be simplified to

$$L_{\text{meas}}(\lambda) = B(T_T, \lambda)\varepsilon_T(\lambda) + (1 - \varepsilon_T(\lambda))L_{\text{DW}}(\lambda) \quad (6)$$

Figure 3: An illustration of the combination of all of the radiances entering the sensor.

II. Downwelling Radiance Calculation

Since the reflectivity of the diffuse gold plate is not exactly one, there is a small amount of error which is introduced to the measurements. In order to correct for this, the self-emitted radiance of the plate must be calculated. The radiance of the diffuse gold plate, $L_G(\lambda)$, is a function of the spectral emissivity of the gold plate, $\varepsilon_G(\lambda)$, and the Planck blackbody spectral radiance of the plate at temperature $T_G$, as shown by

$$L_G(\lambda) = \varepsilon_G(\lambda)B(T_G, \lambda) + (1 - \varepsilon_G(\lambda))L_{\text{DW}}(\lambda) \quad (7)$$

This equation may then be rearranged as

$$L_{\text{DW}}(\lambda) = \frac{L_G(\lambda) - \varepsilon_G(\lambda)B(T_G, \lambda)}{1 - \varepsilon_G(\lambda)}, \quad (8)$$

to obtain the downwelling spectral radiance required for Eq. (6). The temperature of the plate was measured, as stated above, with a handheld infrared thermometer. The spectral reflectivity of the diffuse gold plate is very flat, being between 0.94 and 0.97\cite{3}\cite{4}, and a spectral emissivity between 0.03 and 0.06. Since the gold plate is so highly reflective, any change in the downwelling radiance can have a significant effect on the calculated emissivity of the target. These variations primarily occur if clouds or other objects in the scene directly overhead change, which causes radiational change, or when it is very windy, causes convective change.

III. Emissivity Calculation

Once the measured spectral radiance of the target, and the downwelling radiance have been calculated, the spectral emissivity for the target can be found. This can be done by rearranging Eq. (6) as

$$\varepsilon_T(\lambda) = \frac{L_{\text{meas}}(\lambda) - L_{\text{DW}}(\lambda)}{B(T_T, \lambda) - L_{\text{DW}}(\lambda)} \quad (9)$$

Equation (9) is used to find the spectral emissivity of the target over the user specified range of temperatures\cite{2}.

IV. Methods

If the temperature of the target is known, after the measured and downwelling radiances have been calculated, the emissivity of the target may be calculated. In this case though, the actual temperature of the target is not known, therefore, both the temperature and the emissivity must be estimated. The current spectral smoothness method uses a single subsection of the spectra, which works fairly well for soils, but it may not be the best for other materials. Soils have a doublet in their spectra which becomes overwhelmed by the atmospheric transmission lines, but this doublet does not exist for many other objects that do not contain the signature quartz feature\cite{2}. It is also more difficult to determine the emissivity of highly reflective objects, since any change in the downwelling radiance while the measurements are being taken will cause a larger change in the calculated emissivity. Therefore, three other methods were created, in the hopes of finding one which works well across this range of materials. They are called the moving window, variable-width moving window, and multiple-moving windows methods.
I. Current Method

Once the downwelling and measured target radiances have been calculated, the emissivity and temperature of the target may be estimated. Since a Fourier transform infrared spectrometer was used in this case, the data was taken in evenly spaced, increasing frequency increments. In the spatial domain this corresponds to unevenly spaced, decreasing wavelength data. Since this data is being analyzed in the spatial domain, the order of the data is next reversed, so that it is in order of increasing wavelength. As previously mentioned, only wavelengths between 8 and 14 $\mu m$ are used for these calculations, because of the minimal effects of the atmosphere over this range, but the spectrometer measures over a larger range of wavelength values. Therefore, only the radiance data which correspond to wavelengths within that range were used during these calculations. At this point, the subset of the data, or window, which will be used to calculate smoothness is also found, which in this case is $8.12 - 8.6\mu m$. In this region, soils have a Reststrahlen doublet, which is inherently smooth, but the atmospheric emission lines are very strong\cite{2}. Due to this, the temperature of the blackbody at the target temperature may be changed to minimize the emission lines in this region. A range of temperatures surrounding the target's expected temperature were used to calculate the emissivity within the window.

In order to calculate which temperature produces the smoothest spectral emissivity over the window, the spectral average of the squared second derivative of each curve is found, at each candidate temperature. The first derivative of a discrete function is the slope between each of the points in that function. If the smoothest curve happens to exhibit a non-zero slope, though, this method may not produce the correct result, which is why the second derivative is used instead. Since the data are unevenly spaced, in order to find the first derivative of each function, the difference between each consecutive value in the emissivity function is divided by the difference between consecutive wavelength values. This is repeated with the first derivative in place of emissivity to find the second derivative. These values are squared so that the magnitudes are used, and the spectral average of the magnitude is found. Once the average squared second derivative has been found for each of the temperatures, the values are compared. Since a curve which is more smooth will have less changes in slope, the minimum value corresponds to the smoothest curve. Therefore, the temperature which produces the smallest average squared second derivative is the best estimate for the actual temperature of the target. Once the temperature has been estimated, a blackbody curve at that temperature is created, and the final emissivity curve for the entire spectra, from $8 - 14\mu m$, is calculated using Eq. (9).

**Figure 4:** An image of some of the targets used in this study.

An emissivity curve changes shape and magnitude with a change in the temperature used to calculate it. Figure 5 shows an example of these changes on the emissivity of sand at, above, and below the temperature calculated for the sand using this method. This example demonstrates the increased magnitude at a lower temperature, and decreased magnitude at a higher temperature, in addition to exhibiting more emission lines. This is because as the temperature of a blackbody is varied, a change occurs not only for the wavelength corresponding to the maximum irradiance, but to the maximum itself. As the temperature of a blackbody increases, the irradiance increases, and visa versa. As seen in Eq. (5), in order to keep the measured radiance constant as the blackbody temperature is varied, the target emissivity must change conversely.

II. Moving-Window Method

The second method is very similar to the first, except, as the name suggests, the window moves throughout the spectral range, rather than being fixed. The width of the window remains fixed in this approach, and was set to a value of 0.5 micrometers for this study, which is close to the original window width used by Horton et al. for soils\cite{2}. Initially, the window starts out at the short end of the wavelength range, performing the
same calculations as in the previous method. Once these calculations have been performed, and the smallest average squared derivative has been found, then the position of the window is moved along the spectra so that it begins at the next, larger, wavelength. This process is repeated until the window has reached the end of the spectral range. At this point, an average squared second derivative value, and temperature are known for each interval. Out of these, the minimum average squared second derivative is found, and based on that result, the final emissivity is calculated using the corresponding temperature.

III. Variable-Width Moving-Window Method

A second approach is taken that allows the window width to change, in addition to moving across the spectral range of interest. For each of the different window widths, the window moves through the spectra computing the smoothness for each window. Once this has been done for each of the widths, all of the smoothness values are compared, to find the best temperature, and the emissivity is re-calculated. Window widths of 0.25, 0.5, 0.75, and 1.0 \( \mu m \) were arbitrarily used.

IV. Multiple-Moving Windows Method

A combination of four windows, at different positions along the spectra, was next used. This is done in order to find a temperature which causes a majority of the spectra to be smooth, rather than a small subset, while still allowing real variations in some areas. Although the number of windows may be varied when calling the function, four were used throughout this work. The windows begin at the short wavelength end of the range, with each window consecutively aligned. The smoothness is found in each window, and averaged. The last window then moves to the next wavelength, and the calculations are repeated. Once the last window has reached the end of the spectral range, then the second to last window moves to the next position, and the last window steps once more to the end of the spectra. Then the second to last window moves again, and this process is repeated until all of the windows have gone through all combinations, and are stacked at the long end of the wavelength range. The windows do not overlap in this method. The smoothness was then found for each combination of windows, and the best temperature was found.

V. Data and Results

In order to test the accuracy of each of these methods, the spectra of a variety of materials were measured. Since one of the goals of this study is to find a method which will work on highly reflective objects, a polished aluminum box and a sheet of aluminum foil were used as targets, as well as a semi-polished aluminum box which has slightly higher emissivity. The emissivities of each of the seventeen samples were calculated using each of the discussed methods, in addition to calculating the smoothness over the entire wavelength range. A comparison of the measured temperature of each target and the calculated temperature found using each of the methods, is given in Table 1. Figures 6 - 20 show the spectral emissivity calculated for each method and

Figure 5: Here is an example of the emissivity of sand using the temperature calculated with the current method (312.5 K), a temperature which is too low (311 K), and a temperature which is too high (320 K). This shows an example of the changes in the shape and magnitude of the emissivity curve with changes in temperature.
target, except the polished metal targets, which pro-
duced a negative emissivity. An unpaired t-test was
performed between the measured temperature and the
calculated temperature for each of the methods, indi-
vidually, using the GraphPad online calculator. Using
an $\alpha$ value of 0.05, this resulted in $p$-values of 0.4711,
0.2553, 0.3365, 0.4677, and 0.4827, respectively. None
of these values are considered statistically significant.
The same unpaired t-test was performed between the
values found using the current method, and each of
the new methods, with resulting $p$-values of 0.5624,
0.7566, 0.9780, and 0.9829, respectively, none of which
are statistically significant.

VI. Discussion

In order to compare the accuracy of each of the meth-
ods outlined in this study, the calculated temperatures
are compared to the measured temperatures. Unfortu-
nately, measuring the temperature using the handheld
IR thermometer is not completely accurate, as the tem-
perature of the target may change during the process
of taking the measurements. Also, if the thermometer
is not held perfectly perpendicular to the target, the
temperature may be slightly in error. Nearly all of the
calculated temperatures were larger than the measured
ones, generally within about 5 K, which may be due to
instrumental error.

One of the goals of this study was to find a method
which works well with highly reflective objects. None
of the methods which were tested were able to accu-
rately estimate the temperature or emissivity of these
objects. This may be due to faulty data, as even the
smallest change in the atmosphere during or between
measurements may cause a significant change in the cal-
culated emissivity. Equation (9) shows that if the down-
welling radiance increases between measurements, and
the measured radiance of the object is low enough, then
a negative emissivity may result. This was the case for
a few targets.

Although none of the new methods results are sta-
tistically significantly different from the measured tem-
peratures, or the current method, none of the methods
are statistically significantly different from each other.
A one-way analysis of the variance of the data was per-
formed using Matlab, with an $\alpha$ value of 0.05, which
returned a $p$-value of 0.9509. This value is large, which
means that none of the methods are significantly better
than any of the others.

VII. Future Work

Although these methods produce usable results, there
is more work to be done. When using multiple win-
dows, the number of combinations can easily be in the
millions, which equate to a long processing time. In or-
der to reduce this processing time, some optimization
of the code will need to be done. It would be helpful
to calculate the smoothness and best temperature for
each possible position of the windows before running
through the combinations, rather than calculating these
inside the loop, which is how this code is implemented.

Since the multiple window method took so long to
run, it was impractical to test it using different window
combinations. It would be helpful to test this method
using a smaller window size, since four 1µm windows
is two thirds of the entire wavelength range. Testing dif-
ferent numbers of windows may also show improved
results.

It would be very helpful to have a larger collection
of data on which to test these methods. More sets of
data, and for a larger variety of targets, and highly
accurate data for very reflective targets would be ideal.

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Table 1: Comparison of the measured and calculated temperatures, in Kelvin, for each of the targets, and each of methods. Dashes indicate where the corresponding method failed to compute a temperature. The last four rows show, respectively, the average error between the measured and calculated temperatures for each method, if they are statistically significant, the average error between the calculated temperatures for the current method and each of the new methods, and if these are statistically significant.

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<th>Target</th>
<th>Temperature [K]</th>
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<td>Measured</td>
<td>Current</td>
<td>Moving Window</td>
<td>Variable Width Window</td>
<td>Multiple Windows (4, 1µm)</td>
<td>Entire Range</td>
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Average Error from Measured: $1.88 \pm 1.67$  $3.28 \pm 4.54$  $2.45 \pm 2.95$  $1.95 \pm 1.61$  $1.83 \pm 1.58$
Statistically significant?: No  No  No  No  No

Average Error from Current: $1.67 \pm 4.55$  $0.78 \pm 2.81$  $0.07 \pm 0.98$  $-0.05 \pm 0.25$
Statistically significant?: No  No  No  No  No
Figure 6: Comparison of the emissivities, and temperatures, produced using each of the methods, for the first measurement of sand. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
(a) Current method

(b) Moving window method

(c) Variable width moving window method, 0.5\(\mu\)m wide.

(d) Multiple moving windows method, 1\(\mu\)m wide.

(e) Smoothness over entire wavelength range.

**Figure 7:** Comparison of the emissivities, and temperatures, produced using each of the methods, for the second measurement of sand. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 8: Comparison of the emissivities, and temperatures, produced using each of the methods, for the third measurement of sand. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 9: Comparison of the emissivities, and temperatures, produced using each of the methods, for the sample of fine sand. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 10: Comparison of the emissivities, and temperatures, produced using each of the methods, for the sample of coarse sand. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 11: Comparison of the emissivities, and temperatures, produced using each of the methods, for the sample of fine sand with oil. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 12: *Comparison of the emissivities, and temperatures, produced using each of the methods, for the sample of coarse sand with oil. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.*
Figure 13: Comparison of the emissivities, and temperatures, produced using each of the methods, for the first measurement of semi-polished metal. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 14: Comparison of the emissivities, and temperatures, produced using each of the methods, for the second measurement of semi-polished metal. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 15: Comparison of the emissivities, and temperatures, produced using each of the methods, for the measurement of aluminum foil. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
(a) Current method

(b) Moving window method

(c) Variable width moving window method, 1µm wide.

(d) Multiple moving windows method, 1µm wide.

(e) Smoothness over entire wavelength range.

Figure 16: Comparison of the emissivities, and temperatures, produced using each of the methods, for the first measurement of black matte metal. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
(a) Current method

(b) Moving window method

(c) Variable width moving window method, 1µm wide.

(d) Multiple moving windows method, 1µm wide.

(e) Smoothness over entire wavelength range.

**Figure 17:** Comparison of the emissivities, and temperatures, produced using each of the methods, for the second measurement of black matte metal. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 18: Comparison of the emissivities, and temperatures, produced using each of the methods, for the sample of Styrofoam. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
Figure 19: Comparison of the emissivities, and temperatures, produced using each of the methods, for the first measurement of roofing rubber. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.
(a) Current method

(b) Moving window method

(c) Variable width moving window method, 1\(\mu\)m wide.

(d) Multiple moving windows method, 1\(\mu\)m wide.

(e) Smoothness over entire wavelength range.

Figure 20: Comparison of the emissivities, and temperatures, produced using each of the methods, for the second measurement of roofing rubber. Each of the vertical bars represents the position of a window used to calculate the final emissivity for each method.