Comparison of current methods to determine the downwelling atmospheric irradiance in the thermal infrared

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ABSTRACT - *Ground measurements of land surface temperature (LST) are necessary for the validation of LST products derived from thermal infrared (TIR) remote sensing data. In the validation campaigns, one important factor to take into account is the downwelling hemispheric irradiance (F¯HEM), which has to be measured near-simultaneously to the surface temperature measurements. Direct measurements of F¯HEM with a radiometer involve the measurement of sky radiances from all zenithal and azimuthal directions, and the integration over the upper hemisphere. Such measurements are time-consuming and are not useful because atmospheric conditions may change during the measurement process. Several methods to accurately determine F¯HEM in a short period of time are analyzed in this paper to evaluate which is the most suitable: the diffusive approximation, the use of a TIR diffuse reflectance panel, and the simulation of F¯HEM values by means of a radiative transfer code using both radiosounding data measured at the study area, and atmospheric profiles from the National Center for Environment Prediction. The results show that the fastest and most reliable method to obtain F¯HEM is to make measurements with a diffuse reflectance panel at zenith angles from nadir to 50°, at any azimuthal angle, and keeping a distance of about 80-90 cm between the panel and the radiometer.*

1 INTRODUCTION

Accurate land surface temperatures (LSTs) measurements using thermal infrared data needs to take into account two important factors: land surface emissivity (ε_{sur}) and the downwelling radiance coming from the surroundings and the atmosphere reflected by the surface. The radiative transfer equation of the land-leaving radiance from an area (L_{sur}) at surface level is:

$$L_{sur} = \varepsilon_{sur} B(LTS) + (1-\varepsilon_{sur}) \frac{F^{\downarrow}_{HEM}}{\pi} \qquad (1)$$

where B is Planck's function for a blackbody emitting at the LST, this procedure assumes a Lambertian behavior of the surface following Kirchhoff's law and $F^{\downarrow}_{HEM}$ is the downwelling irradiance.

The term $F^{\downarrow}_{HEM}/\pi$ is called hemispheric downwelling radiance ($L^{\downarrow}_{HEM}$) and can be written as:

$$\frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L^{\downarrow}(\theta,\varphi)\sin\theta\cos\theta\, d\theta\, d\varphi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \sin\theta\cos\theta\, d\theta\, d\varphi} \qquad (2)$$

where $L^{\downarrow}(\theta,\varphi)$ is the downwelling radiance at the zenithal and azimuthal direction (θ,φ). To correct the L_{sur} measurements in equation (1) for the emissivity effect and get accurate LST values, it is needed to measure $F^{\downarrow}_{HEM}$ in addition to ε_{sur}. The most exact way to obtain $L^{\downarrow}_{HEM}$ is to measure the radiance from all possible zenithal and azimuthal directions, $L^{\downarrow}(\theta,\varphi)$, and integrate these measurements in the upper hemisphere according with (2). Since take these measurements is a very time-consuming process which is critical with skies partially cloudy and changing. It is necessary alternative faster methods.

2 ALTERNATIVE METHODS

2.1 Diffusive Approximation

Proposed by Kondratyev (1969), this method needs homogeneous atmospheric conditions (cloudy or cloudless skies). A single radiance measurenet of the sky at an effective zenithal angle gives $L^{\downarrow}_{HEM}$:

$$L^{\downarrow}_{HEM} = L^{\downarrow}_{sky}(\theta_{eff}) \qquad (3)$$

In this study we choose an effective zenithal angle of 54°.

2.2 Alternative Diffusive Approximation

A modification of this method, was proposed by Rubio *et al.* (1997), suggesting take measurements of the sky at 0° and multiplaying this value by a factor γ:

$$L^{\downarrow}_{HEM} = \gamma L^{\downarrow}_{sky}(0°) \quad (4)$$

Values of γ vary from 1.1 to 1.7. This version of the diffusive approximation is more practical in the field, since it is not needed an accurate measurement of the viewing zenithal angle. These techniques are very fast but both of them require homogeneous atmospheric conditions (complete cloud cover or completely clear skies), and do not consider the possible radiative contribution of the surrounding elements. According with García-Santos *et al.* (2010), γ vary linearly with the wavelength and the water vapor content (W). Then it is necessary an indepent measuement of W to carry out this method.

2.3 Atmospheric Profiles

An alternative way to obtain $L^{\downarrow}_{HEM}$ is introducing an atmospheric profile, acquired with a radiosonde launched concurrently to the surface measurements, in a radiative transference code (RTC) such as MODTRAN 4v3r (Berk et al. 1999). If there are not radiosondes available, another possibility is to use atmospheric profiles resulting from reanalysis techniques, provided by weather forecast centers such as the National Center for Environmental Prediction (NCEP). These profiles need to be interpolated temporally and spatially at the time and place of the measurements (Kalnay et al. 1995) using the coordinates of the desired zone and the central hour of the measurement session. Simulation procedures present also some drawbacks: radiosondes are not always available, and the NCEP profiles are predicted from data obtained from spatial and temporal interpolation, whereas the atmospheric conditions can be different in the region nearest to the interest zone, and changing with time.

2.4 Diffuse Reflectance Panel

The last possibility proposed is the use of a diffuse reflectance panel with Lambertian behavior, which allows obtaining $L^{\downarrow}_{HEM}$ measuring the reflected radiance by the panel from any viewing direction. This panel can be used under any atmospheric condition, and it takes into account the radiative contribution of the surroundings elements in addition to the atmosphere.

The objective of the present work is to compare all the previous methods and assess which of them could be the most suitable. With this aim a simple experimental setup was designed allowing us to obtain radiance measurements, both from a golden diffuse reflectance panel at different combinations of zenithal and azimuthal angles, and also with both diffusive approximation methods on cloudless days. Simulated values of $L^{\downarrow}_{HEM}$ calculated from introducing atmospheric profiles provided by different sources into a RTC were also included.

3 INSTRUMENTATION

3.1 Multispectral Radiometer

At the present study was used a radiometer CIMEL Electronique (CE312-1) (Brogniez et al. 2003), which is a multi-spectral sensor that measures the radiance emitted by a surface in the TIR region (8-14 µm). This radiometer is composed composed of an optical head, which points to the surface, and a data-logger joined to the optical head, responsible for registering the measurements. The CE312-1 has four filters that allow us to measure in a wide spectral interval (channel 1: 8.0 µm -13.3 µm), and three narrow spectral intervals within the wide channel (channel 2: 11.5 µm -12.4 µm; channel 3: 10.2 µm -11.3 µm; channel 4: 8.3 µm -9.3 µm). The field of view (FOV) of the optical head is 10°.

A previous calibration of the CE312-1 shows a linear relationship between the black-body and the radiometer with an uncertainty for the channels 1 to 4, in units of $mWm^{-2}sr^{-1}cm$, of: ± 0.0019, ± 0.02, ± 0.01 and ± 0.02, respectively (or equivalently: ± 0.013 K, ± 0.012 K, ± 0.011 K and ± 0.03 K, in the radiative temperature).

3.2 Diffuse TIR Reflectance Panel

The diffuse reflectance panel used in this work corresponds to the model Infragold Reflectance Target IRT-94-100 from Labsphere®. It is a gold rugged surface with dimensions of 25.4 x 25.4 cm^2 and a height of 1 cm. This panel has a high reflectivity in the TIR region, with values of 0.923, 0.925, 0.925 and 0.918, respectively, for CE312-1 channels 1 to 4, with an error of ±0.009. Consequently, following Kirchhoff's law the emissivities of the panel in each channel are 0.077, 0.075, 0.075 and 0.082, respectively.

4 METHODOLOGY

An experiment was conducted on 28th May of 2009 in order to compare the different procedures to determine $L^{\downarrow}_{HEM}$, in a large and flat area of rice fields of the Albufera of Valencia, Spain, to minimize the effect of the surroundings. The site is located at 39° 15' 53''N, 0° 18' 15''O. This day the sky was completely clear assuring a minimal variation of $L^{\downarrow}_{HEM}$ during the measurement process. The measurements were performed following the next procedure. One radiometer was fixed in a goniometer taking angular measurements over the panel from 0° to 65° zenithal angles, at intervals of 5º. Three consecutive readings at each angle were made, calculating the average value. Each zenithal sweep was made for two different azimuthal angles (0°, respect to the complementary solar plane and 90°, on the corresponding perpendicular), were chosen only two azimuthal angles because the time of measurements session was close to an hour, exactly the time consumed by a radiosonde launched concurrently to the measurements. Simultaneously, another identical radiometer took readings vertically from the sky to obtain the radiance $L^{\downarrow}(0°)$, required in Eq. (4) and sometimes this radiometer was placed measuring $L^{\downarrow}(54°)$ according with Eq. (3), to get a value of $L^{\downarrow}_{HEM}$ according to the diffusive approximation. The experimental setup can be seen in Figure 1.

(FIGURE.1)

In the case of the alternative diffusive approximation method proposed by Rubio *et al.* (1997) an adequate value of the γ coefficient must be set, since it depends on the channel and also on W. To this end, a previous simulation study (García-Santos *et al.* 2010) was carried out using the radiosonde data contained in the Cloudless Land Atmosphere Radiosonde (CLAR) database (Galve *et al.* 2008), which spans a W interval from 0.02 to 5.61 cm. For each of these radiosondes, the parameters W, $L^{\downarrow}(0°)$ and $L^{\downarrow}_{HEM}$ were obtained by simulation, from both radiance the γ coefficient was derived according with Eq. (4). Finally it was obtained a linear relationship between γ and W using these data for the 4 channels of the CE312-1:

$$\gamma_{ch1} = -0.04W + 1.43 \quad (5)$$

$$\gamma_{ch2} = -0.09W + 1.61 \quad (6)$$

$$\gamma_{ch3} = -0.09W + 1.73 \quad (7)$$

$$\gamma_{ch4} = -0.03W + 1.44 \quad (8)$$

A radiosonde was launched to get an atmospheric profile concurrent to the radiance measurements. This radiosonde provides values of pressure (in mbar), atmospheric temperature (in K) and relative humidity (in %). From that profile it was derived an W of 1.3 ± 0.2 cm, which allowed calculating the coefficient using Eqs. (5) to (8), for the CE312-1 channels 1 to 4, yielding 1.38, 1.49, 1.61 and 1.40, respectively. Additionally $L^{\downarrow}_{HEM}$ values were calculated using atmospheric profiles into the MODTRAN 4v3r code (Berk et al. 1999). The profiles came from two different sources. One was the profile acquired concurrently with the radiosonde mentioned above. The other one was a profile provided by NCEP reanalyses interpolated spatially and temporally at the place and time of the radiance measurements. In both cases the profiles were processed with a RTC, which provided $L^{\downarrow}(\theta,\varphi)$ values for the zenithal angles 0.0°, 11.6°, 26.1°, 40.3°, 53.7°, 65.0°, 70.0°, 75.0°, 80.0°, 87.0° and 89.0°, $L^{\downarrow}_{HEM}$ was calculated introducing these values into eq. (2).

5 RESULTS

Figure 2 shows the results of the comparison for all the different methods to obtain $L^{\downarrow}_{HEM}$ at the four spectral channels of the CE 312-1 thermal radiometer.

(FIGURE.2)

L_{panel} is the direct measurement of $L^{\downarrow}_{HEM}$ obtained from the panel. L_{desc} is the direct measurement of $L^{\downarrow}_{HEM}$ obtained from the panel correcting its emissivity effect. The uncertainty assigned at each channel of both parameters is: ±1.2(CH1), ±1.8(CH2), ±1.9(CH3) and ±1.2(CH4) $mWm^{-2}sr^{-1}cm$. L_{Kond} is the average value of the continuous measurements of $L^{\downarrow}_{HEM}$ by means of diffusive approximation proposed by Kondratyev (1969). The uncertainty assigned at each channel is: ±0.3(CH1), ±0.6(CH2), ±0.4(CH3) and ±0.2(CH4) $mWm^{-2}sr^{-1}cm$. L_{Rubio} is the average value of the continuous measurements of $L^{\downarrow}_{HEM}$ by means of diffusive approximation proposed by Rubio *et al.* (1997). The uncertainty assigned at each channel is: ±2(CH1), ±3(CH2), ±3(CH3) and ±2(CH4) mWm-2sr^{-1}cm. L_{Radio} is the simulated value of $L^{\downarrow}_{HEM}$ obtained from introducing the atmospheric profile retrieved by the radiosonde into the RTC. The uncertainty assigned at each channel is: ±2(CH1), ±4(CH2), ±3(CH3) and ±2(CH4) $mWm^{-2}sr^{-1}cm$. L_{NCEP} is the simulated value of $L^{\downarrow}_{HEM}$ obtained from introducing the atmospheric profile retrieved by the NCEP database into the RTC. The uncertainty assigned at each channel is: ±2(CH1), ±4(CH2), ±3(CH3) and ±2(CH4) mWm-2sr-1cm.

5.1 Radiative effect of the panel's emissivity

The results for L_{panel} show that the panel presents a near Lambertian behavior, since the measured radiance is almost constant with viewing angle. The increase of radiance at 45º and 60º is probably due to the measurement of the reflected radiance coming from the radiometer itself, known as Narcissus effect. For these angles the radiometer is placed closer to the panel to assure that the field of view lies within the panel area. This means that for measuring the sky radiance with the panel, the most adequate viewing angles are those within 30º and 40º, to minimize the Narcissus effect and observe the largest panel's area possible. It can be also observed in Figure 2 that there is a significant difference between L_{panel}, and the values provided by the other approaches considered (L_{radio}, L_{Kond}, L_{Rubio} and L_{NCEP}). This can be attributed to the contribution of the panel, since it is not a perfect reflector, its emissivity being different from 0 (Korb *et al.* 1996). Thus, this effect must be corrected for taking into account that the radiance measured over the panel is given by:

$$L_{panel} = \varepsilon_{panel} B(LTS) + (1 - \varepsilon_{panel}) L_{desc} \quad (9)$$

where T_{panel} is the temperature of the panel, ε_{panel} is its emissivity for a given channel, and L_{desc} is the hemispheric radiance of the surroundings and the atmosphere, which is actually what we want to measure. Inverting Eq. (9), this last term can be calculated obtaining the downwelling radiance corrected for the panel emissivity effect:

$$L_{desc} = \frac{L_{panel} - \varepsilon_{panel} B(T_{panel})}{1 - \varepsilon_{panel}} \quad (10)$$

To obtain the radiance in Eq. (10) T_{panel} must be known to calculate Planck's function, $B(T_{panel})$; therefore it is necessary to have an independent estimation of this temperature. A contact thermometer, with a precision of ±1 K, was used to take measurements of the panel on five different points on its surface and taking the average value. The measurement error of panel temperature implies an error in L_{desc} for channels 1 to 4 of the CE312-1 of: ±0.12, ± 0.14, ±0.13 and ±0.12 $mWm^{-2}sr^{-1}cm$, respectively, which correspond to an error in terms of temperature of: 0.2, ±0.2, ±0.3 and ±0.3 K, respectively.

If the effect of the panel emissivity is ignored (considering it to be zero), there is an overestimation of the downwelling radiance for the channels 1 to 4 of: +7, +9, +9 and +6 $mWm^{-2}sr^{-1}cm$, respectively, as can be seen in the graphs of Figure 2. In terms of atmospheric temperature this means differences of: +10, +10, +15 and +10 K, respectively, for channels 1 to 4. An alternative way to see the effect of ignoring the emissivity of the panel is to calculate the difference in terms of LST obtained from eq. (1), when we substitute, the measurement taken directly from the panel (L_{panel}) or the value corrected for the panel emissivity (L_{desc}) for a given value of surface brightness temperature. This temperature difference, $\Delta T = LST_{ign} - LST_{corr}$ (difference between the temperature, if the panel's emissivity is ignored, and the temperature, if this emissivity is considered and corrected), is shown in Figure 3, for the case of a surface whose brightness temperature is 303 K and for different values of surface emissivity. The difference increases when the surface emissivity decreases, and for an emissivity of 0.9 temperature differences for channels 1 to 4 of: +0.4, +0.5, +0.5 and +0.4 K, respectively, can be seen. However, for surface emissivities larger than 0.94, the effect of the panel emissivity is not significant. In any case, when the emissivity effect is corrected, a better agreement between the measurements of the panel and the other approaches (diffusive approximation and use of atmospheric profiles) is obtained, as can be observed in Figure 2 in the angular interval between 0° and 50°. Beyond 50º there is still a radiance increase related to the Narcissus effect as explained above. However, there is still a radiance difference that could be due to two sources. One the one hand, the contribution of the used goniometer; in this case it would be needed to use a material with a lower emissivity to minimize its radiative contribution. On the other hand, the panel is also accounting for the contribution of surrounding elements (experimenters, instrumentation, etc.), which is not possible with the other methodologies, but which in fact should be considered since this contribution do affect ulterior LST measurements.

(FIGURE.3)

CONCLUSIONS

The hemispheric downwelling radiance ($L^{\downarrow}_{HEM}$) in the thermal infrared is a parameter which has a big importance in field radiometry. Some different methods exist to obtain $L^{\downarrow}_{HEM}$. It is possible to determine the irradiance by two ways, the first one by means of direct measurements either pointing to the sky, in the so called diffusive approximation method, or pointing to a diffuse panel with a high reflectivity value in the TIR. The second way to obtain $L^{\downarrow}_{HEM}$ is introducing an atmospheric profile in a RTC obtaining the radiance by simulation procedures. In this study, a profile obtained from a radiosonde launched concurrently to the measurements in the interest zone, and another provided by NCEP reanalyzes, were used. In the present study it has been carried out a comparison of these different methods already in use to obtain $L^{\downarrow}_{HEM}$, since to date no evaluation has been made to determine which of them could be the most suitable. Analyzing the results obtained from the comparison of the four different methods, the first conclusion extracted is that the uncertainties in all the techniques are very similar for the four spectral channels of the radiometer. These uncertainties vary in an interval, in terms of hemispheric downwelling radiance, from ± 1.5 to ± 4 $mWm^{-2}sr^{-1}cm$, or equivalently from ±1.3 to ±3.2 K in the atmospheric radiative temperature. Although it is worth noting that the lowest uncertainty corresponds to the in situ measurements method. The comparison of the different methods proposed here concludes that the most suitable of them is the use of a diffuse reflectance panel, since that method offers two key advantages over the others. The first one is that the panel can be used under any atmospheric condition, including heterogeneous skies, which are problematic for the diffusive approximation method. The second advantage is that the panel takes into account the radiative contribution of the surrounding elements (trees, experimenters, instrumental, etc.), which doesn't occur either in the case of the simulation methods or the diffusive approximation.

REFERENCES

Berk, A., Anderson, G. P., Acharya P. K., Chetwynd J. H., Bernstein L. S., Shettle, E. P., Matthew M. W. and Adler-Golden, S. M., 1999, MODTRAN 4 user's manual. *Air Force Research Laboratory, Space Vehicles Directorate*, Air Force Materiel Command, Hascom AFB, MA, 95.

Brogniez, G., Pietras, C., Legrand, M., Dubuisson P., and Haeffelin, M., 2003, A high-accuracy multiwavelength radiometer for in situ measurements in the thermal infrared. Part II: Behavior infield experiments. *Journal of Atmospheric and Oceanic Technology*, 20, 1023-1033.

Galve, J.M., Coll, C., Caselles, V., and Valor, E., 2008, An atmospheric Radiosounding Database for generating land Surface Temperature Algorithms. *IEEE Transactions on Geoscience and remote Sensing*, 46, 1547-1557, DOI:10.1109/TGRS.2008.916084.

García-Santos, V., Galve, J. M., Valor, E., Caselles, V., and Coll, C., 2010, Determination of atmospheric water vapour content from direct measurements of radiance in the thermal infrared region. *International Journal of Remote Sensing* (In Press).

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebissuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D., 1995, NCEP/NCAR 40 Year Reanalysis Project. *Bulletin of the American Meteorological Society*, 437-471.

Kondratyev, K.Y., 1969, Radiation in the Atmosphere. *New York and London: Academic Press*.

Korb, A.R., Dybwad, P., Wadsworth W., and Salisbury, J.W., 1996, Portable Fourier transform infrared spectroradiometer for field measurements of radiance and emissivity. A*pplied Optics*, 35, 1679-1692.

Rubio, E., Caselles V., and Badenas, C., 1997, Emissivity Measurements of Several Soils and Vegetation Types in the 8-14 µm Wave Band. *Remote Sensing of Environment*, 59, 490-521.

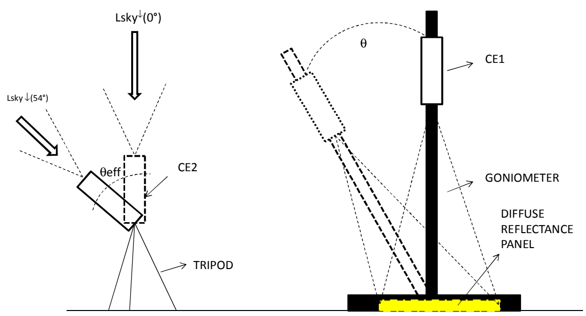

Figure 1: Experimental assembly used to perform the angular measurements over the diffuse reflectance panel, with the CE312-1, here called CE1, and the sky, with another radiometer called CE2.

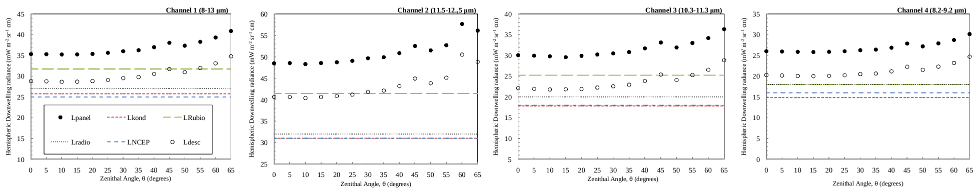

Figure 2:Radiance measurements as a function of the observation angle, using the goniometer setup for the 4 channels of the CE312: Direct measurements from the panel (L_{panel}); measurements corrected for the panel's emissivity (L_{desc}); values of radiance calculated from the diffusive approximation, eq.(3), from radiance measurements of the sky at 54°, (L_{Kond}) and values of radiance calculated by eq.(4) from radiance measurements of the sky at 0°, (L_{Rubio}); simulated values obtained from NCEP profiles (L_{NCEP}); and from radiosonde made at the same place and time of the measurements (L_{radio}), introduced in a RTC.

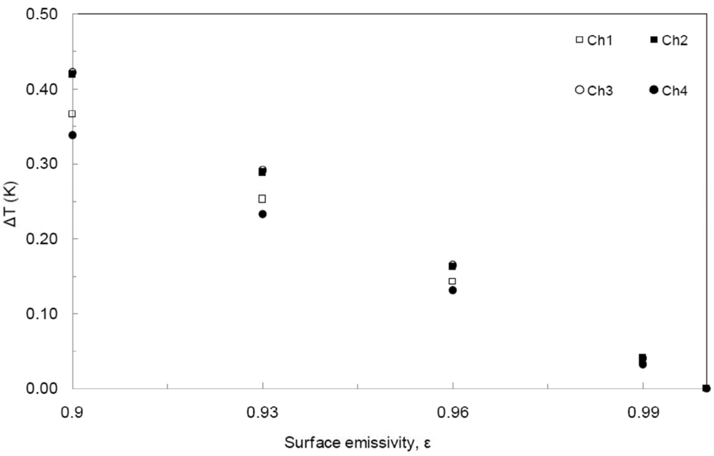

Figure 3: Systematic error in the retrieved LST from a surface, whose brightness temperature is 303 K, if we neglect the effect of emissivity of the panel, depending on the value of surface emissivity.