Issues in Reflectance Measurement

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1. INTRODUCTION

Behind much of the current work we are planning for data series standardisation, atmospheric correction, spectral unmixing using spectral libraries and the use of remotely derived spectral measurements in models, there is an implicit use of ‘reflectances’ or ‘reflectance factors’ as the primary information. At the base of atmospheric correction to a surface reflectance is the principle that these data are properties of the surface and that spectral features in the resulting data belong to the surface and that changes represent changes in the surface. To support such spectral studies, measurements of reflectance are made in the laboratory and field.

However, it is not at all clear at times what relationships exist between such spectra and those derived from remotely sensed data. This note has been put together to instigate discussion of the differences that will exist between different measurements under different conditions. In order to relate the output of atmospheric correction to both field and other remotely sensed data as well as models these differences and the way to accommodate them must be made very clear.

Remote sensors and field instruments used to calibrate and/or validate remotely sensed data measure spectral bands of radiation entering across the field of view of one of a number of instruments. In order that there be a fundamental consistency between such measurements it is important that the instruments be cross calibrated when they are measuring similar information and that enough information be collected for the data to be interpretable and relatable to the eventual application taking them serves.

The measurements are of three basic types:

- radiance,
- irradiance and
- reflectance

Provided that basic measurements are consistent and the relationships between radiance and irradiance taken into account, the most important area of concern for us will be the consistent definition and derivation of reflectance factors. It is important to realise that, in practice, there will be a number of ways of defining these, that they will normally not be independent of the conditions under which they are measured and the inter-relationship between different measurements will be complex. Many of these differences arise from the geometry of reflectance measurements and Nicodemus *et al.* (1977) contains probably the most extensive classification of possible geometries.

These rough notes discuss the main issues confronting us in our field campaigns, supporting laboratory measurements, atmospheric correction processing and theoretical modelling of surface spectral sensing from aircraft and satellites in the visible, NIR and SWIR regions. They emphasise the role of the BRDF and the need to take account of it in all these situations (even in the calibration of a field reflectance standard panel) if they are to be effectively related to one another.

2. RADIANCE & IRRADIANCE

The radiance of a source or target is the radiant flux per unit solid angle per unit area normal to the source. It is denoted L and is the quantity to which a narrow angle radiometer is calibrated. Laboratory calibration consists of reading a target of known radiance characteristics as the calibration. However, in practice, calibration in a field setting is also usually needed as the object of the exercise is field measurement.

The reason that the laboratory source is not enough is that when instruments read in a broad band and over a finite Instantaneous Field of View (IFOV) the calibration depends on the wavelength distribution and heterogeneity of the incident source. Hence, calibration in the field setting allows the types of irradiance relevant to the application to be sampled as well as standard laboratory sources.

Irradiance is the total hemispherical radiant flux per unit area and for a radiance distribution ($L(\mu)$) at a specific wavelength irradiating a flat target surface, the resulting irradiance (E) is:

$$E = \int_{2\pi} L(\mu)\cos\theta \, d\omega$$

$$= \int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\mu)\cos\theta\sin\theta \, d\theta d\phi$$

Where:

(θ, ϕ) are the coordinates (zenith, azimuth) of the radiance;

μ is a symbol denoting the direction cosines of the direction vector;

ω is solid angle (steradians).

If the irradiance distribution (such as a sky distribution) were a constant radiance at all points of the hemisphere (L) independent of angle, it would follow that:

$$E = L\int_{2\pi} \cos\theta \, d\omega$$

$$= L\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \cos\theta\sin\theta \, d\theta d\phi$$

$$= \pi L$$

Later, another irradiance definition will be briefly mentioned. It is the scalar irradiance which measures the total incident radiant flux rather than the normal incident radiant flux. It will be denoted here as S and is:

$$S = \int_{2\pi} L(\mu) \, d\omega$$

$$= \int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\mu)\sin\theta \, d\theta d\phi$$

For a constant radiance distribution (L) it follows that:

$$S = L\int_{2\pi} d\omega$$

$$= L\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \sin\theta \, d\theta d\phi$$

$$= 2\pi L$$

The ratio of the normal irradiance to the scalar irradiance is a measure of the angular distribution of the radiance. It is sometimes called the ‘average cosine’ of the field.

$$\bar{\mu} = \frac{E}{S} = \frac{\int_{2\pi} L(\mu)\cos\theta\, d\omega}{\int_{2\pi} L(\mu)\, d\omega}$$

$$= \frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\mu)\cos\theta\sin\theta\, d\theta d\phi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} L(\mu)\sin\theta\, d\theta d\phi}$$

For a uniform distribution of radiance the value of $\bar{\mu}$ is 0.5.

3. REFLECTANCE

The reflectance factor we measure in the laboratory and field is generally one of two types.

There is the directional reflectance factor (ρ_t):

$$\rho_t = \frac{\pi\, L_t(\mu_r)}{E_d}$$

This measurement is the target radiance recorded by the observer in the 'reflected' direction (μ_r) multiplied by π and divided by the total irradiance on the target (E_d). The directional reflectance factor is the factor closest to what is normally produced by atmospheric correction of remotely sensed data and measured in the field with a narrow IFOV radiometer.

A second measured reflectance factor is the irradiance reflectance:

$$R = \frac{E_u}{E_d}$$

This is the ratio of upwelling irradiance to downwelling irradiance and it is the reflectance factor obtained with an integrating sphere or from the ratio of data taken by cosine collecting diffusers in field experiments. It is sometimes called the spectral 'albedo' (Strahler *et al.*, 1995) although the above definition is for a particular wavelength and the albedo of energy balance studies is the ratio of total irradiances over all (shortwave) bands. The irradiance reflectance is measured by a Licor instrument in water studies and by an integrating sphere in the laboratory.

There are two complications to be taken into account in practice which will be revisited later. The definitions so far relate to radiances in specific directions in elements of solid angle dω and at a single wavelength. All of the instruments we are concerned with measure over finite wavebands and over finite solid angles and the broader these bands and angles are, the further the resulting reflectance factors will diverge from the ones we have so far defined.

4. BRDF AND REFLECTANCE FUNCTIONS

The BRDF, or Bidirectional Reflectance Distribution Function ($f(\mu_r, \mu_i)$) is not a reflectance but a ‘kernel’ or ‘phase function’ relating incoming and outgoing radiance. The (reflected) radiance observed in the observer direction ($L_r(\mu_r)$) is the composite of radiances derived from the incident (sky and sun for field measurements) radiance distribution ($L_i(\mu_i)$):

$$\begin{aligned} L_r(\mu_r) &= \int_{2\pi} f(\mu_r, \mu_i) L_i(\mu_i) \cos\theta_i \, d\omega_i \\ &= \int_0^{2\pi} \int_0^{\frac{\pi}{2}} f(\mu_r, \mu_i) \, L_i(\mu_i) \cos\theta_i \, \sin\theta_i \, d\theta_i d\phi_i \end{aligned}$$

The BRDF is generally taken as the material property on which the various reflectance factors and other measures can be based.

4.1 Directional Reflectance Factor

The reflectance measured as the directional reflectance factor (ρ_t) is therefore expressed in terms of the BRDF as:

$$\begin{aligned} \rho_t &= \frac{\pi \, L_r(\mu_r)}{E_d} \\ &= \pi \frac{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} f(\mu_r, \mu_i) \, L_i(\mu_i) \cos\theta_i \, \sin\theta_i \, d\theta_i d\phi_i}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} L_i(\mu_i) \cos\theta_i \, \sin\theta_i \, d\theta_i d\phi_i} \\ &= \pi \; \overline{f}(\mu_r; E_d) \end{aligned}$$

where *f* is the BRDF and $\overline{f}$ is an irradiance weighted average BRDF which depends on the irradiance angular distribution of Ed as well as the view direction.

For a uniform radiance distribution (L_i a constant for all directions) the measured reflectance factor would be:

$$\begin{aligned} \rho_t &= \pi \overline{f}(\mu_r, 2\pi) \\ &= \int_0^{2\pi} \int_0^{\pi/2} f(\mu_r, \mu_i) \cos\theta_i \sin\theta_i \, d\theta_i d\phi_i \\ &= \overline{\rho}(\mu_r, 2\pi) \end{aligned}$$

where $\overline{\rho}(\mu_r, 2\pi)$ is the directional reflectance factor for a uniform distribution and is a function of the material surface being measured.

For a direct beam irradiance from direction μ_s the measured reflectance factor would be:

$$\begin{aligned}\rho_t &= \pi \ f(\mu_r, \mu_s) \\ &= \overline{\rho}(\mu_r, \mu_s)\end{aligned}$$

where $\overline{\rho}(\mu_r, \mu_s)$ is often called the BRF or Bidirectional Reflectance Factor for direct beam irradiance. It is also a property of the material and is obviously the BRDF up to the factor π.

4.2 Irradiance Reflectance

The irradiance reflectance can also be expressed in terms of the BRDF as:

$$\begin{aligned}R_t &= \frac{E_u}{E_d} \\ &= \frac{\pi \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \overline{f}(2\pi, \mu_i) \ L(\mu_i) \cos\theta_i \ \sin\theta_i \ d\theta_i d\phi_i}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} L(\mu_i) \cos\theta_i \ \sin\theta_i \ d\theta_i d\phi_i} \\ &= \pi \ \overline{f}(2\pi, E_d) \\ &= \overline{\rho}(2\pi, E_d)\end{aligned}$$

where:

$$\begin{aligned}\overline{f}(2\pi, \mu) &= \frac{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} f(\mu_r, \mu) \cos\theta_r \ \sin\theta \ d\theta_r d\phi}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} \cos\theta_r \ \sin\theta_r \ d\theta d\phi_r} \\ &= \frac{1}{\pi} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} f(\mu_r, \mu) \cos\theta_r \ \sin\theta_r \ d\theta_r d\phi_r\end{aligned}$$

For a uniform irradiance, it follows that:

$$\begin{aligned}R_t &= \frac{\pi \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \overline{f}(2\pi; \mu_i) \ \cos\theta_i \ \sin\theta_i \ d\theta_i d\phi_i}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} \cos\theta_i \ \sin\theta_i \ d\theta_i d\phi_i} \\ &= \pi \ \overline{f}(2\pi, 2\pi) \\ &= \overline{\rho}(2\pi, 2\pi)\end{aligned}$$

This ‘Bi-hemispherical Reflectance Factor’ (Nicodemus *et al.*, 1977) is another material property directly derived from the BRDF. It is close to the measurement made in the laboratory with an integrating sphere.

In addition, if the irradiance is beam irradiance from direction μ_s it follows that:

$$\bar{\rho}(2\pi, \mu_s) = \pi \ \bar{f}(2\pi, \mu_s)$$

Without pursuing the discussion here, the ‘reciprocity’ principle implies that:

$$\bar{f}(\mu, 2\pi) = \ \bar{f}(2\pi, \mu)$$

hence

$$\bar{\rho}(2\pi, \mu) = \bar{\rho}(\mu, 2\pi)$$

The objective of processing remotely sensed data to ‘reflectances’ and measuring ‘reflectances’ is to establish a property of the materials rather than the environmental conditions. The BRDF is not always only a property of the material but the assumption is normally made that it is ‘close’ to a material property independent of the radiation environment. The BRDF is also the source for the reciprocity relations. Moreover, the measurable reflectance factors have complex geometrical relationships and depend on the environmental conditions. That is, there can really be no ‘spectral library’ without a clear record of the measurement geometry, the environmental conditions and sensor all being specified. They are part of the spectrum and the only means by which the different measurements can eventually compared.

The laboratory based integrating sphere irradiance reflectance and the field directional reflectance factors are different measurements and they depend on the irradiating source and the measurement conditions. However, it is our objective to attempt to get standard measurements and material properties. One way towards this is to define a directional quantity:

$$\gamma(\mu_r, \mu_s) = \frac{\bar{\rho}(\mu_r, \mu_s)}{\bar{\rho}(2\pi, 2\pi)}$$

This quantity is a material property and contains essentially the directional behaviour.

4.3 Summary of Special Cases

The BRF is the reflectance measured by the radiance radiometer when there is only incident beam (eg sun) radiation. To summarise the factors arising from the uniform irradiance distribution case in terms of the BRF:

$$
\begin{aligned}
\bar{\rho}(\mu_r, 2\pi) &= \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2} \bar{\rho}(\mu_r, \mu_i)\cos\theta_i \sin\theta_i \; d\theta_i d\phi_i \\
\bar{\rho}(2\pi, \mu_i) &= \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2} \bar{\rho}(\mu_r, \mu_i)\cos\theta_r \sin\theta_r \; d\theta_r d\phi_r \\
&= \bar{\rho}(\mu_i, 2\pi) \\
\bar{\rho}(2\pi, 2\pi) &= \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2} \bar{\rho}(2\pi, \mu_i)\cos\theta_i \sin\theta_i \; d\theta_i d\phi_i \\
&= \frac{1}{\pi}\int_0^{2\pi}\int_0^{\pi/2} \bar{\rho}(\mu_r, 2\pi)\cos\theta_r \sin\theta_r \; d\theta_r d\phi_r
\end{aligned}
$$

In Strahler *et al.* (1995), $\bar{\rho}(2\pi, \mu_i)$ is called the 'Black Sky' Albedo and $\bar{\rho}(2\pi, 2\pi)$ is called the 'White Sky' Albedo. Estimates of these quantities will be standard products from MODIS expressed as polynomial functions. Some simplifications of these expressions is also possible if it is assumed the BRDF is symmetrical relative to the Principal Plane and the integrations with respect to ϕ changed to azimuthal difference.

5. NATURAL RADIATION MEASUREMENTS

The natural light irradiance that is measured by a well calibrated device with a good cosine response has a primary atmospheric component (E_d) that can be expressed as:

$$
\begin{aligned}
E_d &= E_0^{'} \cos\theta_s \; t_s + \int_0^{2\pi}\int_0^{\frac{\pi}{2}} L_{sky}(\mu_i)\cos\theta\sin\theta \; d\theta d\phi \\
&= E_{dir} + E_{diff}
\end{aligned}
$$

where:

$E_0^{'}$ is the exoatmospheric normal irradiance (corrected for sun-earth geometry);

t_s is the beam transmittance;

L_{sky} is the sky radiance distribution from the upper hemisphere;

E_{dir} is the direct irradiance and

E_{diff} is the diffuse irradiance.

The ratio of the diffuse term E_{diff} to the total E_d is the fraction of diffuse radiation:

$$f_d = \frac{E_{diff}}{E_d}$$

Strictly, these expressions are for a “black” earth but in practice, there are interactions between the earth and sky which are greatest when the diffuse fraction is high. Radiation reflected back into the atmosphere from the earth is again reflected back to the surface by an atmospheric reflectance (s). This means that the measured irradiance can be expressed as:

$$E_d^* = \frac{E_d}{1 - s\rho^*}$$

where ρ^* is the local background reflectance near the target which is approximately an average over an area of about 200 metres radius under some conditions and s depends on the atmospheric turbidity. The effects due to s are smallest for clear skies (when the diffuse radiation is low) and highest when the atmospheric turbidity is high (when the diffuse radiation is high).

In practice, the increase in irradiance can be regarded as a component of the (even more diffuse) diffuse sky distribution.

$$\begin{aligned} E_d^* &= E_{dir} + E_{diff}^* \\ &= E_{dir} + \frac{s\rho^* \; E_{dir} + E_{diff}}{1 - s\rho^*} \end{aligned}$$

and

$$f_d^* = f_d + (1 - f_d)s\rho^*$$

It is important to recognise the presence of the background effect (which becomes most significant in atmospheric correction) by always assessing and (if possible) measuring the background as part of a target field survey. Because of this extra term, it is often not possible to neglect the effect of the diffuse fraction outlined here - especially in the near infra-red when the background is green.

If the irradiance distribution is modelled simply as a beam term (the direct radiation) and a uniformly diffuse irradiance term (assuming a uniform sky radiance distribution), it follows that the measured reflectance factors will be:

$$\begin{aligned} \rho_t &= (1 - f_d)\; \overline{\rho}(\mu_r, \mu_s) + f_d \; \overline{\rho}(\mu_r, 2\pi) \\ R_t &= (1 - f_d)\; \overline{\rho}(2\pi, \mu_s) + f_d \; \overline{\rho}(2\pi, 2\pi) \end{aligned}$$

In this expression there are the three special case material property measures and the fraction of diffuse radiation at the wavelength being measured. This gives a lead as to how field measurements may be done to estimate the BRDF. A range of measurements could taken under natural conditions (where diffuse and direct irradiance terms are measured) with (possibly) both directional and irradiance reflectances measured. If the BRDF is modelled with a parametric model, the parameters could be chosen to fit the data.

Using the directional term defined previously, these equations may be written:

$$\rho_t = \bar{\rho}(2\pi, 2\pi)\big((1 - f_d)\,\gamma(\mu_r, \mu_s) + f_d\,\gamma(\mu_r, 2\pi)\big)$$
$$R_t = \bar{\rho}(2\pi, 2\pi)\big((1 - f_d)\,\gamma(2\pi, \mu_s) + f_d\ \big)$$

It would be ideal if from such field data and other sources (such as airborne data) some relatively consistent γ functions were found for classes of land cover. It may be necessary to use different functions (ie ‘kernels’) for the different covers but the key is to have some consistency in the γ functions.

6. MEASURING REFLECTANCE IN THE FIELD

In principal, if a calibrated instrument measured the radiance and another the irradiance the reflectance could be computed simply as:

$$L_t = \frac{1}{\pi}\rho_t\, E_d^*$$
$$\rho_t = \frac{\pi L_t}{E_d^*}$$

This is the paired radiometer approach and the operation of atmospheric correction of remotely sensed data effectively works in this same way.

However, in the field there is an alternative and very convenient way to measure the reflectance without separately measuring the irradiance which uses a *reflectance standard*. It can easily be carried out with a single instrument plus a panel rather than two instruments.

A reflectance standard is a panel of known total and directional reflectance properties. If the target radiance (L_t) is measured by a radiance radiometer and the standard radiance (L_s) is also measured under the same geometrical and environmental conditions with the same instrument then, if ρ_s is the known reflectance of the standard it follows that:

$$\rho_t(\mu_r, E_d) = \frac{\pi\, L_t(\mu_r)}{E_d}$$

$$\rho_s(\mu_r, E_d) = \frac{\pi\, L_s(\mu_r)}{E_d}$$

$$\rho_t(\mu_r, E_d) = \rho_s(\mu_r, E_d)\,\frac{L_t(\mu_r)}{L_s(\mu_r)}$$

Moreover, suppose the calibration relation between volts measured by the instrument measuring the radiance (with dark current effect removed) and radiance is linear and can be written as:

$$L = c_L\, V$$

then it follows that the reflectance of the target (*t*) can be obtained without knowing c as:

$$\rho_t(\mu_r, E_d) = \rho_s(\mu_r, E_d)\,\frac{V_t}{V_s}$$

In this expression, only the properties of the standard must be known other than the uncalibrated target and standard readings.

Note that in the case of the paired radiometers it follows that:

$$\rho_t = \frac{\pi c_L}{c_E}\frac{V_t}{V_d}$$

That is, the ratio of the instrument calibration factors must be known and be stable. However, for expensive instruments the use of paired radiometers is often not an option and only the panel method is feasible.

It is convenient to write the reflectance of the standard panel in the form:

$$\rho_s(\mu_r, E_d) = R_s\; K_s(\mu_r, \mu_s, f_d; \lambda)$$

where R_s is the Bi-hemispherical reflectance of the panel (as measured, for example by an integrating sphere) and K_s is the panel K-factor. It is shown as a function of observer position, sun position, fraction of diffuse irradiance and wavelength as all of these can affect it.

In terms of modelling the panel BRDF it is useful to consider the simplified irradiance model of direct plus uniform diffuse for which:

$$\begin{aligned}\rho_s(\mu_r, E_d) &= (1 - f_d)\ \bar{\rho}(\mu_r, \mu_s) + f_d\ \bar{\rho}(\mu_r, 2\pi) \\ &= \bar{\rho}(2\pi, 2\pi)\big((1 - f_d)\gamma(\mu_r, \mu_s) + f_d\ \gamma(\mu_r, 2\pi)\big) \\ &= R_s\ K_s(\mu_r, \mu_s, f_d; \lambda)\end{aligned}$$

That is, the panel could be characterised by its directional function and its Bi-hemispherical Reflectance Factor and K obviously depends on both the sun and observer positions as well as f_d in the field if there is a significant BRDF variation.

At this point, without going too far with the (very wide) discussion, it is necessary to remember that the panel method discussed here assumes that the panel essentially ‘replaces’ the target to get the reference measurement. If the target and standard are separated then the measured reflectance factor will be different again from the ones being considered. There are many cases where panel and target are in quite different situations. These provide us with equally different ‘reflectance’ measurements.

6.1 ESTABLISHING PANEL K-FACTORS

A considerable amount of attention is normally given to making a standard panel close to a ‘Lambertian’ target. A Lambertian target is perfectly diffusing and has uniform BRDF over the outgoing hemisphere. For a truly Lambertian panel, therefore K_s is 1.0 and only R_s needs to be known. Since a Lambertian panel is difficult to approximate, the panel K-factor must be carefully assessed. Low sun, specular panel effects and diffuse conditions will create problems if K_s is ignored.

Normally, considerable work is expended on a basic standard panel or money expended to buy a standard panel for the laboratory. These are often quite small and not field-robust. For field missions, the panels normally need to be large and robust as well as able to be cleaned. These requirements often mean they do not have ideal Lambertian behaviour and may change with use. Hence, establishing the panel K-factor and monitoring it is a basic step in field procedure.

The first factor needed is R_s which can be measured using an integrating sphere acting on a piece of the panel. This may only need to be done once - it is a normalising factor.

The panel directional factor could be established in the laboratory by physical measurement. Some investigations of this are needed for the larger field standards but this would be normally the way the ‘Lambertian’ panel is checked. In the past, people have also attempted to carry out some K-factor estimation of a field panel using the near ‘Lambertian’ panel and natural light as follows.

1. Assume that the Laboratory panel is Lambertian and has a spectral reflectance which is a constant R_s in the visible NIR range.
2. Monitor the radiance of the Laboratory standard and the field panel with a narrow FOV radiance sensor at the same time as monitoring the irradiance using a calibrated irradiance sensor with high spectral resolution.

3. Monitor the diffuse radiation well as total irradiance.
4. Collect the data over a number of days, with as wide a variation in sun positions and view angles as possible.

A set of measurements of this type can be used in a number of ways. One important use is to establish Calibration Consistency. That is, if the sensor being used is calibrated then the following equation needs to be consistent when the Laboratory standard is being measured:

$$L_s(\mu_r) = \frac{1}{\pi} R_s \, E_d$$

Since the Lambertian panel reflectance (R_s) is assumed known and E_d is measured, this provides a consistency check on the (inter-)calibrations over a wide range of conditions. Departures from a simple calibration can be expected and this will provide an average 'field' corrected calibration of considerable usefulness.

The field (or 'alternate') panel K-factors can be estimated from the data (assuming the Laboratory panel's K-factor is known and the alternate panel Bi-hemispherical Reflectance Factor has been measured using an integrating sphere) by:

$$\begin{aligned} K_{alt}(\mu_r, \mu_s, f_d; \lambda) &= \frac{\rho_s}{R_{alt}} \frac{V_{alt}}{V_s} \\ &= \frac{R_s}{R_{alt}} \frac{V_{alt}}{V_s} K_s(\mu_r, \mu_s, f_d; \lambda) \end{aligned}$$

In this way, the estimated K_{alt} will be measured over many conditions of sun and observer position and environmental conditions if K_s is known. It is very important to measure the azimuthal variation fully to establish specular effects.

However, even with considerable work, the range of measurements is likely to be limited and not cover the range expected in the field. To overcome this, the best strategy would seem to be to fit the K-factor by a parametric function (which is likely to be much simpler for a panel than a natural surface!). For example, a good candidate might be the 'Walthall model' (Walthall *et al.*, 1985; Strahler *et al.*, 1995):

$$\overline{\rho}(\mu_r, \mu_i) = p_0 \, (\theta_r^2 + \theta_i^2) + p_1 \, \theta_r^2 \theta_i^2 + p_2 \, \theta_r \theta_i \, \cos\phi + p_3$$

The simplifying assumption of uniformly diffuse sky radiation can additionally be used to provide the model for K (since the γ functions will be computable as rational functions of the parameters):

$$K_s(\mu_r, \mu_s, f_d; \lambda) = (1 - f_d)\gamma(\mu_r, \mu_s) + f_d \, \gamma(\mu_r, 2\pi)$$

In this way, a fairly robust panel ‘calibration’ would be available that can be used under a wide range of conditions.

If such K-factors are established for the panels and tested relative to good laboratory standards then they can then also provide field checks of radiometer calibration against field robust but accurately calibrated irradiance devices. That is if the panel is read and converted to radiance and the irradiance taken at the same time, the following consistency equation should hold:

$$L_s(\mu_r) = \frac{1}{\pi} R_s \, K_s(\mu_r, \mu_s, f_d; \lambda) \, E_d$$

Readings under a number of conditions with panel radiance, total irradiance and diffuse irradiance measured can supply a constant check of instrument and/or panel behaviour.

In the field, if a panel model of this kind has been developed, the sun and view positions as well as the fraction of diffuse at the wavelengths used are necessary data in the measurement set as well as the two target and panel readings and data on sky conditions, surrounding area reflectance ideally should be recorded as well.

6.1.1 Measuring diffuse radiation

Separating diffuse and direct components of the irradiance is essential in most modelling. At very least, the fraction of diffuse should be established when BRDF effects are strong. Diffuse radiation is generated by many sources. Scattering by air and aerosols is a primary source but high objects on the land surface and clouds generate scattered radiation as well and the sky re-reflects radiation leaving the land back into the diffuse term. Clouds are an especially difficult source to model and take into account in corrections.

Therefore, diffuse radiation measurements should be accompanied by descriptions of the site (trees, buildings etc) and the sky (cloud type and amount) for reference. Given such data, the field crew could obtain diffuse data from two setups:

1. Shadow band instrument; and
2. A sun disk shading a LiCor irradiance sensor or a Spectron with diffuser.

To get diffuse readings using a sun disk, the procedure is as follows:

1. Have a sun disk 10cm diameter and blackened on a thin stick about 50cm length.
2. Person using disk should stand on the opposite side of the instrument from the sun and hold the disk 1 metre from the sensor head with the shadow centred on the sensor.
3. Take four readings (the Qin Yi method). One reading with no disk and no person, one reading with person in place but disk not used, one reading with person in place and shading the

sensor head and lastly one with no person and no disk to see that there has not been significant change.

The person shading the sensor should wear matt clothes which are not too reflective. Note, denim is bright in the near infrared!

If the four readings in 3. above are denoted $[E_1, E_2, E_3, E_4]$ then the quantities needed are derived as:

$$\begin{aligned} E_d^* &= E_1 \\ E_{dir} &= E_2 - E_3 \\ E_{diff}^* &= E_d^* - E_{dir} \\ E_4 &\approx E_1 \end{aligned}$$

The shadow band method is automatic and much better in principle than the sun disk. However, the current YES MFR instrument that CL&W and CAR use only records in a relatively few (6) bands and does not therefore provide a complete irradiance description. It may be possible to fit an atmospheric model to the MFR data and predict the irradiance and the fraction of diffuse for the full spectrum. This needs some testing.

To provide some measure of the uniformity of the sky distribution, it may be useful to consider the benefit of taking scalar irradiance data (S) as well as cosine irradiance data (E). If the sun disk is used so that the diffuse and direct fraction are know it follows that the average cosine of the complete sun and sky distribution would be:

$$\bar{\mu} = \frac{E}{S}$$

$$\text{For no diffuse irradiance:}$$

$$\bar{\mu} = \cos\theta_S$$

If there is significant diffuse radiation but not completely diffuse conditions, a sun-corrected average cosine for the sky distribution would be:

$$\begin{aligned} \bar{\mu}_{diff} &= \frac{E_{diff}}{S_{diff}} \\ &= \frac{E - E_{dir}}{S - E_{dir}/\cos\theta_s} \\ &= \frac{f_d \bar{\mu}}{1 - (1 - f_d)\bar{\mu}\cos\theta_s} \end{aligned}$$

This can be used to assess the usefulness of the simplified irradiance assumption (that diffuse irradiance is uniform) and also provides useful (phase) data for an atmospheric model when conditions are relatively clear.

7. SUMMARY

This brief outline of the issues needing to be addressed in measurement and modelling of image 'reflectance' given the fact of BRDF and the variety of possible choices for reflectance factors has assumed a single wavelength and that the radiance measurements are done with a narrow Field of View instrument. If either of these assumptions is changed the nature of the measurement also changes.

Provided, however, that the BRDF characteristics of targets or panels are relatively the same over the wavebands of interest and that the targets are relatively homogeneous over the FOV (which should at least be less than or equal to 5° in field measurements) the method and ideas discussed here can be retained. However, any data taken must be augmented with waveband and FOV information.

Given this, the main outcome of the discussion is to suggest that field panels need to be modelled and their K-factors assessed regularly. This is as important as cross calibrating instruments. In addition, if no account is taken of BRDF then there will be wide variations between field and image estimates of reflectance. Spectral libraries may not be possible. Even if very standard viewing geometry is used, the variation of the data with sun position may be very large.

The issues discussed have ramifications for correction for BRDF in both Atmospheric Correction and field studies. A possible option is to use the simple model:

$$\begin{aligned}\rho_t &= \bar{\rho}(2\pi, 2\pi)\big((1-f_d)\,\gamma(\mu_r, \mu_s) + f_d\,\gamma(\mu_r, 2\pi)\big)\\ &= \bar{\rho}(2\pi, 2\pi)\,\Gamma(\mu_r, \mu_s, f_d)\end{aligned}$$

Since, if a simple parametric form is available for the BRDF and the diffuse fraction is known it follows that Γ is known and it could be proposed that all measurements be normalised to an apparent Bi-hemispherical Reflectance Factor:

$$\bar{\rho}(2\pi, 2\pi) = \frac{\rho_t}{\Gamma(\mu_r, \mu_s, f_d)}$$

If the BRDF directional behaviour parameters are defined for a given land cover it may be possible, provided f_d is measured or modelled, to normalise reflectances to the Bi-hemispherical Reflectance Factor in both field situations and in atmospheric correction.

Following from this is a specification for the structure of an adequate Spectral Library. A 'library' entry would include:

1. Waveband and FOV
2. ρ_t (the actual data)
3. $\bar{\rho}(2\pi, 2\pi)$

4. $\gamma(\mu_r, \mu_s)$ as a parametric function or land cover 'type'
5. μ_r, μ_s, f_d at the time of the measurement
6. Panel/Target geometry
7. ρ^* and other environmental information

Since this allows the original data to be reconstructed, the entry should also include the error of re-construction via the model.

8. REFERENCES

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