Computing radiances, reflectance and albedo from DN's
(September 21, 2005)

1. Introduction:

In some cases, but not all, it is preferable to convert raw short wave satellite image data to physical quantities before using the data to interpret the landscape. Important physical quantities include radiance (at-ground or at-satellite), reflectance, or albedo. For example, it is the at-ground reflectance that is characteristic of a particular surface type, and independent of the illumination and atmospheric characteristics. In the sections below we discuss several approaches to the development of physical data layers.

2. Converting DN values to at-satellite radiance

With Landsat for example (see the online Landsat Science Data Users Handbook) the at-satellite radiance must be computed from the instrument calibration function

$$I_\lambda = aDN + b \tag{1}$$

where a and b are the gain and offset. Each spectral channel will have different gain and offset values. Usually the radiance given by such a formula will have units Watts per square meter per steradian per micron (i.e. $Wm^{-2}sr^{-1}\mu m^{-1}$).

3. Solar Illumination

In many situations, the incoming flux is dominated by a bright narrow beam of radiation coming directly from the sun. The strength of the solar beam at each wavelength is the "Solar Spectral Irradiance" (S_λ). For example, the value for band 1 wavelength for ETM is about $S_\lambda = 1969$ Watts per square meter per micron. Note that this "irradiance" is not angularly resolved (i.e. it is not "per radian"). The angular width of the beam is about 0.5244 degrees (about 31 minutes) of angle, but this width is not usually needed for the computations below. The solar irradiance value outside the earth's atmosphere changes a bit with season as the earth's orbit is slightly elliptical. The irradiance is inversely proportional to the square of the earth-sun distance. If the earth sun distance is increased by 1%, the irradiance decreases by 2%.

The illumination of the earth's horizontal surface will depend on the solar zenith angle (ϕ) according to

$$F_\lambda = S_\lambda \cos\phi. \tag{2}$$

As the sun sets lower in the sky, the illumination decreases, reaching zero at sunset. If the local surface is tilted, the illumination should be computed using not the "zenith angle" but rather the angle between the "surface normal vector" and the sun. Note that with a complex forest target, the illumination of particular leaves may be as great as S_λ or

as small as zero, but the average illumination is still given by (2). The illumination of a forest on a hillslope is computed from (2) using the normal vector of the hill surface.

4. Lambertian Surfaces
When this solar beam hits a complex surface, the reflected radiation must in general be described by a radiance field, that is, an angularly resolved field of radiation. It is not a narrow beam anymore. The general description of how a complex surface reflects radiation is the Bidirectional Reflectance Distribution Function (BRDF); the ratio of the reflected radiance to the incident irradiance.

$$R(\theta,\phi,\theta_F,\phi_F) = I_\lambda(\theta,\phi)/F_\lambda$$

As it is the ratio of a radiance to an irradiance, it has units of inverse steradians. In general, it will be a function of both the angle of the incident radiation and the angle at which one observes the reflected radiation. In some cases however, when the reflected radiation field is isotropic, the whole subject of reflection become much easier. According to the Lambertian (isotropic) assumption, the reflected radiation is both independent of the reflected angle and independent of the angle at which the object is illuminated. In the case of an isotropic distribution of radiation (over the upper hemisphere), the upward irradiance is related to the upward radiance by

$$F_\lambda = \int I_\lambda(\theta,\phi)\cos\phi\, d\Omega \tag{3}$$

where $d\Omega$ are the increments of sold angle covering the hemisphere. If the radiance is independent of zenith angle, the integral becomes

$$F_\lambda = I_\lambda \int \cos\phi\, d\Omega = \pi I_\lambda \tag{4}$$

so $R = \pi^{-1}$. This is a famous and widely used relationship. The factor of pi is essential. It becomes easy to remember if you think of pi as being a measure of solid angle (steradians), thus resolving the units difference between F and I. Using (4), the key relationship between the illuminating irradiance and the reflected radiance is

$$I_\lambda = \rho_\lambda F_\lambda / \pi \tag{5}$$

where rho is the spectral reflectance. Solving (5) for reflectance and using (2) gives

$$\rho_\lambda = \pi I_\lambda / F_\lambda = \pi I_\lambda / S_\lambda \cos\phi \tag{6}$$

This is a familiar formula seen in textbooks and in the Landsat Science Data Users Handbook. Sometimes the earth-sun distance correction is included. If we know the solar spectral irradiance and we measure the reflected radiance, (6) gives us the spectral reflectance.

To judge for yourself the validity of the Lambertian assumption, place a piece of white paper on a table. Look at the paper from different angles. Does its apparent brightness change?

5. **Path Radiance**

The earth's atmosphere modifies the illuminating radiance on an object and it modifies the reflected radiance on the way to the satellite. A full treatment of these effects is given in textbooks on atmospheric radiation such as that by Liou (2002?). Standard software packages such as 6S provide good estimates of the scattering, absorption and emission of radiation by molecules and particles in the atmosphere.

In many situations, the dominant atmospheric effect on remote sensing is "path radiance"; the scattering of radiation from the sun's beam into the direction of the satellite by air molecules or by suspended particles. Here are the assumptions that we make when we focus only on path radiance.

   a) Neglect absorption and emission of radiation by gasses
   b) Neglect all effects on object illumination
   c) Neglect scattering of reflected radiation out of the sensor view
   d) Consider only scattering of the sun's radiation into the sensor view.

Consider for a moment, our reasoning with point c and d. If an object is bright (e.g. a snow field), the reflected radiation will be intense and scattering out of the path will exceed the scattering in. Conversely, if an object is dark (e.g. a forest), the reflected radiation will be weak and scattering in will exceed scattering out.

As it turns out, in the visible range where most scattering occurs, most earth objects are dark (e.g. soil, water, vegetation). The exceptions are snow (80%) and bright sand (50%). Furthermore, the haze that causes strong path radiance is highly variable from day to day. Thus, if not corrected for, it will degrade any change detection study.

Path radiance is familiar to us (see Figures 1,2,3). It prevents us from seeing distant objects on a hazy day. It gives distant mountains a pale blue appearance.

To a first approximation, Path Radiance is an "additive" effect. The radiance received at the satellite is given by the sum of the upward reflected radiance and the path radiance.

$$I_{sat} = I_{surf} + I_{PR} \qquad\qquad (7)$$

at each wavelength (subscript lambda deleted here). The path radiance will depend on the strength of the illumination and the density of scattering particles in the field of view. It will be a decreasing function of wavelength, because shorter waves are scattered more than long waves. Because of this trend, it can often be ignored in the near infrared, unless the haze is very thick with some particles as large as 1 micron.

As we will see below, path radiance can be estimated and removed using dark object subtraction (DOS), if the haze layer is uniform over the scene. This assumption is

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sometimes valid when a broad scale polluted airmass covers the region. Haze layers are often only 1km thick however, so a region of high terrain might penetrate up through it. This would cause an error in the path radiance removal.

Another source of path radiance is a layer of thin cirrus ice cloud in the upper troposphere. These layers are seldom very uniform however, so path radiance removal could be problematic.

6. The effect of illumination, gains, offsets and path radiance in remote sensing

It is sometimes supposed that sensor calibration aspects or path radiance will not cause a problem if we always use band ratios, contrast enhancement or classification methods. Let's investigate these claims (Song et al., 2001).

   a. NDVI

Consider a first a normalized quantity such as NDVI, expressed in terms of at-surface reflectance:

$$NDVI = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \tag{8}$$

Such a quantity could be determined using a portable spectrometer. Can this value be determined using satellite data? What quantities should be entered in the formula: DNs, at ground radiance, at-satellite radiance? If we use (1) and (6), canceling a pi everywhere

$$NDVI = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} = \frac{(a_2 DN_2 + b_2 + I_{PR2})/F_2 - (a_1 DN_1 + b_1 + I_{PR1})/F_1}{(a_2 DN_2 + b_2 + I_{PR2})/F_2 + (a_1 DN_1 + b_1 + I_{PR1})/F_1} \tag{9}$$

Using (9) we can identify the special circumstances in which DN values can be used to obtain quantitative NDVI values: no path radiance or offset and equal gains and illumination. Only in this unlikely case does NDVI from (8, 9) equal

$$NDVI = \frac{DN_2 - DN_1}{DN_2 + DN_1} \tag{10}$$

A less restrictive condition is that the NDVI of an identical surface should stay constant from date to date. Such a definition would at least allow NDVI change detection. If NDVI is defined in terms of calibrated at-satellite reflectivity (I_{sat}) using (7)

$$NDVI = \frac{(I_{surf2} + I_{PR2})/F_2 - (I_{surf1} + I_{PR1})/F_1}{(I_{surf2} + I_{PR2})/F_2 + (I_{surf1} + I_{PR1})/F_1} \tag{11}$$

Now if we assume that I_{surf} and I_{PR} are proportional to the illuminating irradiance, that is $I_{surf2} = \rho_2 F_2$ and $I_{PR2} = h_2 F_2$ etc., we obtain

$$NDVI = \frac{(\rho_2 + h_2) - (\rho_1 + h_1)}{(\rho_2 + h_2) + (\rho_1 + h_1)} \qquad (12)$$

where "h" is some measure of the haze density and scattering efficiency. According to (12) the definition of NDVI (11) gives invariant values under changing illumination but if "h" were to change, the NDVI value would change also. If the path radiance can be neglected (e.g. h = 0, a clear day) (12) returns to (8).

A special problem arises with clouds. In a cloud or mountain shadow for example, the NDVI may be shifted (reduced) because the skylight illuminating the pixel is richer in blue light, and very deficient in NIR.

b. Contrast stretch

Can a procedure of contrast stretch correct for unknown illumination, gain, offset and path radiance? Yes, in principle! Any linear transformation on radiance (such as adding path radiance (7)) or in converting DN to Radiance value (gain and offset (1)) can be easily undone by the appropriate linear contrast stretch. Thus, for example, an image taken in a hazy atmosphere can be restored by contrast stretching to appear like an image without haze. In making this claim, we assume that the radiometric resolution and saturation value of the sensor is sufficient to prevent permanent loss of information by the original transformation. Also, we usually adjust the contrast stretch by eye, instead of using the specific values that would compensate for environmental or instrument factors.

c. Classification

Now we consider the impact of a linear transformation on classification (Song et al., 2001). As a linear transformation will only shift and stretch the points on a scatter diagram, the results of many classification algorithms will not be thereby altered. As an example, consider a "maximum likelihood" algorithm. As it normalizes the Euclidean distance between pixels with the variances computed in the same Euclidean way, the result of the classification will not be altered by a linear transformation (i.e. shift or stretch).

7. The use of reference areas

When at-ground radiance or reflectance data are not available, references areas can sometimes be used to develop quantitative remote sensing results. For example:

- Dark object subtraction (DOS)

A "dark pixel" is defined as a pixel that has zero reflectance in one or in all bands (i.e. $I_{ref} = 0$). According to (7)

$$I_{sat} = I_{PR} \qquad (13)$$

for the dark pixel. Defining $I_{dark} = I_{sat}$ for that pixel, the other radiance values in the scene can be corrected using

$$I_{corr} = I_{sat} - I_{dark} \tag{14}$$

If the at-ground illumination could be estimated, the at-ground reflectance could be computed from (14) and (6). The best dark spots are clear deep water with no white caps, dense forest, cloud shadow and burned biomass. Even better would be a cloud shadow on clear deep water or a dark forest.

- Dark spot/white spot scaling to get reflectance

If perfect dark (DN_D) and white (DN_W) spots can be identified, the DN value for any other pixel can be converted to a reflectance value using

$$\rho_\lambda = \frac{DN - DN_D}{DN_W - DN_D} \tag{15}$$

To derive (15), use (1),(6) and (14) to write the reflectance for all three pixels

$$\rho = \frac{\pi I}{F} = \frac{\pi}{F}(aDN + b - I_{PR}) \quad \rho_D = \frac{\pi}{F}(aDN_D + b - I_{PR}) = 0 \quad \rho_W = \frac{\pi}{F}(aDN_W + b - I_{PR}) = 1$$

The second equation gives $b - I_{PR} = -aDN_D$. Subtracting the second and third equations gives $a(DN_W = DN_D) = F/\pi$. Applying these two expressions to the first equation gives (15). Note that if the two reference pixels were not perfectly black and white, but their reflectances were known, a similar formula to (15) could be found.

In practice, it is difficult to find a pixel with a perfect reflectance. The best choice in the visible range would be a deep dense cloud. Clean snow might work too. Its reflectance can exceed 90% in the visible, but it drops off quickly in the NIR. It's difficult to find any natural surface that has a reflectance exceeding 70% in the NIR, so (15) will probably work better in VIS than in NIR. A problem with Landsat (and sometimes MODIS) is that the sensor will saturate (e.g. DN=255) for highly reflective pixels. These pixels are too bright for the sensor. Thus no pixel with near perfect reflectance exists in the image.

- Dual reference areas for change detection

When comparing two images taken on different dates, the path radiance may be different due to haze. In addition, the illumination may be different because of a different sun angle. These differences would introduce errors in some change detection techniques. These differences can be removed if two invariant regions can be identified in the scene. We might choose a lake, a coniferous forest or a dry gravel field. To avoid numerical errors, the two reference areas should be as spectrally distinct as possible (yet still invariant).

If we define the two invariant DN values as DN1 and DN2, then a scaled DN value is

$$DN_{scaled} = \frac{DN - DN1}{DN2 - DN1} \tag{16}$$

If DN2>DN1, a pixel brighter than pixel 2, will have a scaled DN value greater one. A pixel darker than pixel 1, will have a scaled DN less than zero. When the layer of scaled DN values is computed for each scene, they can be compared to detect change. Because of our method, the scaled DN values at the two reference pixels will be unchanged between the two dates (0 and 1 respectively).

Additional methods for change detection are given by Song et al., 2001.

8. Albedo
The albedo is an important quantity in climate theory. It is defined as the ratio of the total reflected irradiance to the incident irradiance

$$\text{Albedo = total reflected/ total incident.} \tag{17}$$

An accurate measurement of albedo in the field would require two "hemispheric receivers", collecting from all angles and at all wavelengths. The total downward or upward irradiance (incident or reflected) can be computed from the corresponding radiance by integrating over a hemisphere.

$$F = \iint I_\lambda \cos\phi d\Omega d\lambda \tag{18}$$

For climate applications, we would like to determine the global patterns of albedo using satellite data. This is difficult for two reasons (Liang and Strahler, 1999). First, satellites only measure reflectance in a few narrow spectral bands. For albedo, we need the reflectance at all wavelengths where the sun shines. Second, satellites usually measure reflectance at one angle incidence only, and at one reflected angle only. If the surface were Lambertian, this one angle would be sufficient. The assumption of a Lambertian surface is not sufficiently accurate for some albedo computations however.

A third problem can arise in relation to angle. In the real world, the angular nature of illumination can vary from hour to hour. If the sky is clear, the incident radiation hitting the earth's surface will be the sun's direct narrow beam. If the sky is cloudy, the incident radiation will be diffuse, almost isotropic. In this latter case, satellite can never be used to observe the reflective process.

All is not lost however. The Bi-directional Reflection Distribution Function (BRDF) that describes the reflectance as a function of incident and reflection angle, is a constant property of the local land surface. It is invariant under changes in lighting conditions. If it can be deduced from multi-angle satellite measurements during clear sky days, the total albedo can be computed for any angular distribution of incident radiation. For archiving purposes, it has been found useful to define to special albedos.

- Dark sky albedo: The albedo of a surface under conditions of direct solar illumination
- White sky albedo: The albedo of a surface under conditions of diffuse isotropic illumination

If these two albedo fields are known globally, the actual albedo for any meteorological situation can be determined by interpolating between them (Schaaf et al., 2002).

9. References

Liang, S., A.H. Strahler, C. Waltall, 1999, Retrieval of Land Surface Albedo from Satellite Observations: A simulation study, J. Appl. Met., 38, 713-725

Rees, W.G., 2001, Physical principles of remote sensing, Cambridge, 343p

Schaaf. C.B. et al., 2002, First operational BRDF, albedo nadir reflectance products from MODIS, Remote, Sens. Envir., 83, 135-148

Song, C., et al., 2001, Classification and change detection using Landsat TM data: When and How to correct atmospheric effects, Remote Sensing of Environment, 75, 230-244

10. Figures

Figure 1: A typical summer afternoon in northern Maine (August 2005). Note the two mountains in the distance. Why are the mountains lighter and bluer than the trees on the shoreline?

Figure 2: View of distant glaciers in Antarctica (January 2005: Orion). Why is the distant glacier darker and redder than the closer glacier?

Figure 3: A small cloud and its shadow in Arizona, as seen from an aircraft. Give two or three radiative processes that produce some radiance (to the observer) in the shadow.