Literature Review on the optical properties of cloudless skies

Understanding the optical properties of the sky is important for many practical purposes. Much work on this area has been done for the solar power industry, who are interested in the type and distribution of the irradiance on solar panels. From the point of view of remote sensing, understanding the optical properties of the sky is essential to be able to atmospherically correct images from both satellite and airborne sensors. Data about the optical properties of the atmosphere can also be used to measure atmospheric pollutants, and to calculate pollen indices (Winch, 2008).

The sun provides a huge amount of energy to the earth, and this energy controls the physical and biological processes which take place on the Earth's surface. The amount of energy received from the sun at the top of the atmosphere (TOA) is known as the *solar constant*, although this is a misnomer as it varies due to changes in the sun and changes in the distance of the Earth from the sun. The solar constant at present is around 1373 W m^{-2} and is decreasing at around 0.02% per year (Hickey et al., 1982). The amount of solar radiation reaching the surface of the Earth is not the same as the solar constant, due to the effects of the atmosphere. These effects can be split into scattering and absorption, and will be discussed later.

The solar radiation reaching the Earth's surface can be split into two parts: direct and diffuse. The direct portion is that which reaches the Earth from the direction of the solar disc, and the diffuse portion is that which comes from the rest of the sky, due to the scattering of the solar radiation in the atmosphere. The sum of these components is known as the global solar irradiance. Direct solar irradiance rarely exceeds 75% of the solar constant because of scattering from the atmosphere (Monteith and Unsworth, 1990). The solar irradiance can be measured in various wavebands; one of the most common is the region of Photosynthetically Active Radiation (PAR) which is roughly equivalent to visible light (400-700nm).

At this point, a distinction must be made between radiance, and luminance, as there has been much work in this area based on both types of measurement. Radiance is measured in SI units and refers to the amount of light reaching the detector. Luminance, however, is related to human perception of light, and is therefore only measured over the wavelength range that the human eye recognises. Luminance measurements have been used when work has been done for the benefit of architects and others interested in the human perception of light incident upon structures on the Earth, but they are not appropriate for use in remote sensing work.

The passage of solar radiation through the atmosphere has a large effect on the properties of the light once it reaches the ground, and on the optical properties of the sky itself. The two main processes involved are scattering and absorption. Scattering is of two main types: Raleigh and Mie. Rayleigh scattering occurs when the diameter of the scattering particle is much smaller than the wavelength of the radiation. As such, shorter wavelength radiation is scattered far more than longer wavelength radiation (for example blue light is scattered around nine times more than red light). Mie scattering occurs when the diameter of the scattering particle is around the same as the wavelength of the radiation, and is often caused by aerosols in the atmosphere.

The second important process is absorption by ozone, water vapour, CO_2 and oxygen. This causes more of a problem in the infra-red part of the spectrum, and therefore measuring the water and ozone content of the atmosphere is important for correcting data obtained from the infra-red bands.

The amount of absorption and scattering depends on two main factors: the path-length of the radiation passing through the atmosphere and the amount of scattering or absorbing constituents. The former is normally measured as the *air mass* number which is the length of the path relative to the depth of the atmosphere, and the latter by the *Aerosol Optical Thickness* for scattering and the amount of *precipitable water* for absorption. Values for these measures can be obtained by use of instruments such as sun photometers.

The distribution of irradiance across the sky (the *sky radiance distribution*) is irregular, and variable in both time and space. Brunger and Hooper (1993) stated that the "one overwhelming characteristic of sky radiance is its variability". Various mathematical models of this distribution have been proposed. The sky condition is very important in determining which model to use and what parameters to put into the model. Early models assumed an isotropic distribution of sky irradiance for an overcast sky, known as a *Uniform Overcast Sky* (UOS). Although this is relatively accurate under completely overcast conditions, it performs poorly under varying sky conditions. For example Garnier and Ohmura (1970) found that it disagreed with measured values by as much as 56% based on measurements from Quebec.

A more realistic model of an overcast sky is the *Standard Overcast Sky* (SOC) which is described by the following formula:

$$N(\Psi) = N(0)(1 + b\cos\Psi)/(1 + b)$$

Where Ψ is the sun zenith and *(1 + b)* is the ratio of the radiance at the zenith to the radiance at the horizon, typically in the range 2.1-2.4 (Steven and Unsworth, 1979). This heliocentric term allows for the brightening at the zenith compared to the horizons, providing a more accurate representation of reality.

A Standard Clear Sky has also been described (Kittler et al., 1997), and this, along with the Standard Overcast Sky and the Uniform Overcast Sky have been adopted as official models of the *Commission Internationale de l'Eclairage* (CIE). Images of the distribution of radiance across these skies are shown in Figure 1.

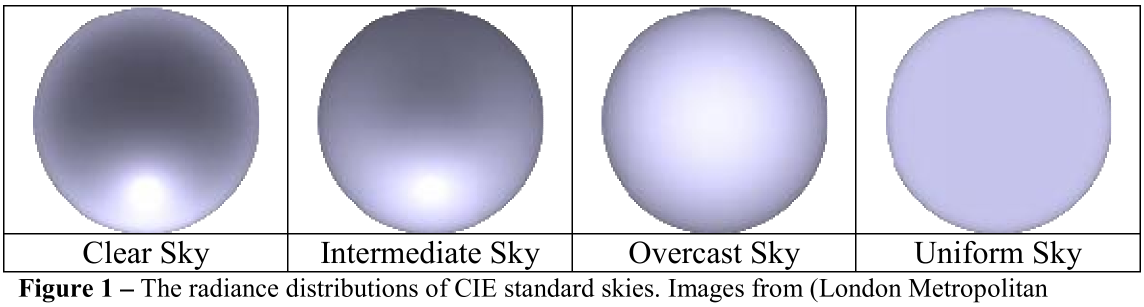

Figure 1 – The radiance distributions of CIE standard skies. Images from (London Metropolitan University (2009)

Igawa et al. (2004) compared the results from many sky radiance models with measured values from Japan, and found that the most representative models were the

All-Weather model (Perez et al., 1993), the Three-Component Continuous Distribution model (Hooper and Brunger, 1980, Brunger and Hooper, 1993) and the All Sky Model-R (Igawa et al., 2004). These will be examined below.

These complex models all follow the same structure, consisting of three main parts: the model mathematical framework, the input quantities and the method of relating these inputs to the coefficients which control the model. Two of the models below are based on a very similar mathematical framework (the CIE Standard Clear Sky) but use different inputs and parameterisation processes. In fact, the parameterisation has been highlighted as the most important part of the modelling process, and the part which can lead to the most uncertainty (Brunger and Hooper, 1993).

The All-weather model (Perez et al., 1993) is designed to work from inputs of global and direct irradiance, and is based upon the CIE Clear Sky distribution (Kittler et al., 1997). It has five coefficients which control five elements of the distribution: darkening or brightening of the horizon, luminance gradient near the horizon, relative intensity of the circumsolar region, width of the circumsolar region and relative intensity of the backscattering of light. The values of these parameters were calculated from the inputs by using the least-squares method to fit the model to over three million data points from measurements taken in Berkley, California. This model is actually a model for sky luminance distribution, but the model does not appear to be specifically tailored to luminance. It has therefore been suggested (Milton, 2009, personal communication) that this model may perform equally well with radiance values as input, and this is backed up by other research which shows that luminance and radiance can be modelled using the same formula (Igawa et al., 2004).

Hooper and Brunger (1980) proposed the *Three-Component Continuous Distribution* (TCCD) model which is based on the superposition of three distributions: isotropic, heliocentric and horizon brightening, as shown in the diagram below.

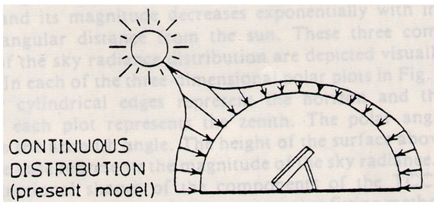

Figure 2 - Diagram of the distribution produced by the Three-Component Continuous Distribution model (diagram taken from Hooper and Brunger (1980))

The model has three parameters (a_0, a_1 and a_2) which allow the contribution from each of the three distributions to be varied, thus allowing the shape of sky conditions ranging from overcast to a clear blue sky to be modelled. This model describes the heliocentric irradiance distribution as decreasing exponentially with increasing angular distance from the sun, and the horizon brightening term as increasing parabolically from zero at the zenith to a maximum at the horizon. The main advantage of this model is that it is able to represent a wide range of sky conditions: Hooper and Brunger (1980) found that the RMS errors associated with the fitting of their model to five different sky conditions were less than 36%.

This model was further developed by its authors to improve the parameterisation and to change the mathematical distributions modelled to make them more accurate

(Brunger and Hooper, 1993). This version of the model allows the sky radiance to be calculated as a function of the following variables:

- The position of the sun in the sky
- *k,* the ratio of diffuse irradiance on a horizontal surface to the global irradiance on a horizontal surface
- k_t, the atmospheric clearness index, defined as the ratio of the global irradiance on a horizontal surface at the Earth's surface to the global irradiance on a horizontal surface at TOA

The variables k and k_t are used to calculate the a_0, a_1, a_2 and a_3 parameters, using tables provided by the authors. It should be noted that the horizon brightening effect is modelled with a cosine function in this version of the model, as opposed to the parabolic function used in the previous version.

The All Sky Model-R (Igawa et al., 2004) produces a sky radiance distribution for all sky conditions from clear to overcast, based on the *clear sky index* and the *cloudless index*. Although other studies have shown that luminance and irradiance distributions are quite different, Igawa et al. found that they could be modelled using the same equation. The model is based on the CIE Clear Sky model (Kittler et al., 1997), with gradation and scattering functions based on coefficients. These coefficients are calculated from the *sky index* (the sum of the clear sky index and the root of the cloudiness index). Validation of the model with measured data taken in Japan shows a good fit, with low RMSEs, and for most of the sky conditions tested the model outperformed the other models on test (including the TCCD model and the All-Weather model).

In summary, the optical properties of the sky are complex and both temporally and spatially variable. Solar radiation reaching the earth is absorbed and scattered by the atmosphere, making the total irradiance at the Earth's surface consist of both direct and diffuse parts. There are many models of the sky radiance distribution, ranging from simple but relatively unrealistic models such as the Uniform Overcast Sky to complex models consisting of many distributions overlain on top of each other (such as the TCCM model (Brunger and Hooper, 1993) or the All-weather model (Perez et al., 1993).

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