14 Surface Reflectivity

To this point, in all considerations of object/background presentations, it has been assumed, by implication, that whatever the surface luminance structure is, it is invariant with time during presentation. Now, if one considers the laws of reflection, this assumption must imply one of two things – either the viewing and illumination conditions are invariant or all surfaces in the viewed scene are diffuse reflectors*. In a practical situation it is relatively rare for one to be looking at something from an invariant angle and with invariant illumination. On the other hand it is convenient to assume that most natural objects and many man-made objects, seen from a distance, will approximate to diffuse reflectors for modelling purposes. Obvious exceptions are glass and water, which are partially reflecting mirrors and therefore have luminance which is very dependent on incident light distribution. It is the purpose of this chapter to show how real surfaces behave as reflectors and to review the methods available for specifying and measuring surface reflectance.

14.1 GENERAL REFLECTION CHARACTERISTICS

Before considering forms of reflectance and methods of measurement let us look at the reflection characteristics of some natural and man-made surfaces as a function of viewing angle and form of illumination. We shall restrict ourselves for the present to the two simplest forms of illumination – uniform distribution over a hemisphere and a collimated beam. Considerable data are available illustrating the reflection characteristics of many forms of surface for the latter of these conditions (e.g. Coulson *et al*[2,3], Brennan and Bandeen[4], Hodgson and Overton[5] and Crowther[6,7]) and the reflectance under uniform hemispherical illumination may be simply derived by integration. In addition considerable data also exist of reflection from various surfaces under natural hemispherical illumination as measured directly (e.g. Duntley *et al*[8], Boileau and Gordon[9] and Gordon and Church[10,11]).

14.1.1 Reflection from grass and similar vegetation

One very common natural background against which objects are viewed is grass and similar vegetation. It is easy to consider such surfaces to be entirely specified

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*A diffuse surface is one which appears of equal luminance from whatever direction it is viewed. In other words it obeys Lambert's cosine law[1]

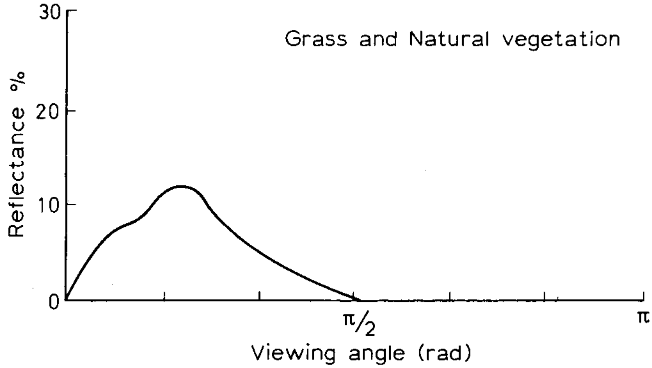

Fig. 14.1. Typical reflectance characteristic for grass. (Reproduced from Hodgson and Overton[5] by courtesy of the Directorate of Stores and Clothing Development).

in terms of mean diffuse reflectance, texture and colour. In practice there are severe changes in reflectance, and hence luminance, dependent on viewing direction. A little thought illustrates that this must be so, for how else can one explain the well known stripes produced on a lawn when it is mown by a roller-mower. The effect is, of course, produced by a layering of the individual grass blades such that their mean angle is other than vertical. This is turn must imply a directional reflectance effect, which is exactly what is recorded when reflectance is studied in detail (see Section 14.3.1). Fig. 14.1 shows a typical reflection characteristic for naturally growing grass as a function of direction of viewing. There is a region of peak reflectance at 0.5 rad viewing elevation, with lesser reflectance at both grazing angles and high elevations. This characteristic peak is due to statistical summation of a multitude of specular components of reflected light at various angles from the shiny surfaces of individual grass blades. Multiple reflections and diffuse reflectance of part of the incident light account for the regions of lower reflectance. It is the statistical summation of components of specular reflectance which is distorted in mean elevation angle by the action of a roller-mower.

14.1.2 Reflection from Foliage

Another major natural background component (or object of interest in some circumstances) is tree foliage. Again, as with grass, it is easy to think that the characteristics are specified by mean luminance, texture and colour, with the addition of broken outline in general. Once again, however, the sum total of reflectance is defined by a mixture of components due to shiny top surfaces and relatively diffuse under surfaces of individual leaves. Since there is a tendency for leaves to align themselves with shiny surfaces upwards, once again there is a predominent direction of peak reflectance defined by the statistical alignment of the leaves. Typical reflectance characteristics for foliage thus have strong similarities to those for grass in Fig. 14.1.

14.1.3 Reflection from soils and rocks

The third major natural background component is the group of surfaces comprising soils and rocks. For this class of surface it would seem, on the face of it, very reasonable to assume an approximately diffuse reflectance characteristic. However, although many soils and rocks do approximate to diffuse surfaces when dry and illuminated predominantly with light at normal incidence, there are marked deviations from the ideal diffuse characteristics for incident light other than near normal incidence. In addition the characteristics of reflectance change markedly when such surfaces are wet. This is due to the water acting as a partially reflecting mirror, with the result that strong lobes of local reflection are introduced, the strength and broadness of the lobes depending largely on the roughness and absorptivity of the surface. In general, the rougher and the more absorbent is the dry surface, the less severe and broader will be the additional reflectance due to the surface wetness.

14.1.4 Reflection from concrete and brickwork

We have just seen how most of the common natural surfaces deviate from being diffuse surfaces. What about man-made surfaces?

One of the commonest modern man-made surfaces encountered in outdoor

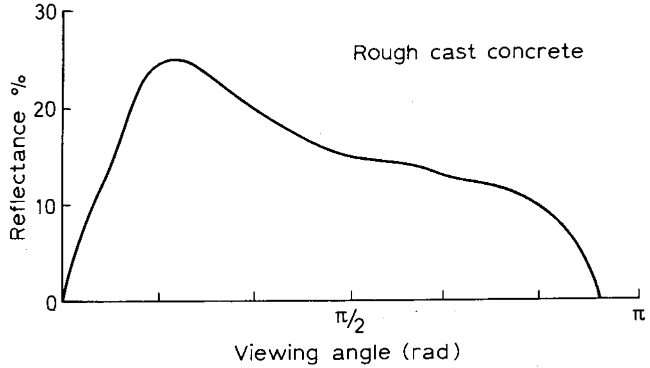

Fig. 14.2. Typical reflectance characteristic for dry concrete. (Reproduced from Hodgson and Overton[5] by courtesy of the Directorate of Stores and Clothing Development).

viewing is concrete. By its appearance one would think that concrete would behave reasonably like a diffuse surface (when dry). However, tests have shown that even here there is a significant departure from the ideal diffuse surface. A typical reflectance characteristic for dry concrete is shown in Fig. 14.2. Brickwork behaves in a similar manner when dry.

If the surface being viewed is wet then the water again acts as a partial reflecting mirror and introduces much stronger lobes of local reflection in the same manner as discussed for soils and rocks.

14.1.5 Reflection from painted and similar surfaces

Other common man-made surfaces are painted surfaces and various plastics. These two types of surfaces have in common a smooth surface with a limited opacity. The very smooth surface will always behave as a partial mirror, the difference between a matt and a gloss surface being largely the difference in degree of surface roughness. Underlying this will be the basic, largely diffuse, reflectance of the underlying opaque surface. Thus once again we have a total reflectance characteristic which contains potentially prominent lobes.

14.1.6 Reflection from glass and water

Both glass and water are characteristically surfaces whose reflectance is specular. Hence, with collimated light falling on a smooth glass or water surface there is a narrow reflection lobe obeying the basic laws of specular reflection from dielectrics (e.g. Born and Wolf[12]). Equally, for smooth surfaces and an absolutely uniform hemispherical illumination, there will be a uniform luminance at all viewing angles. This is fine as far as it goes, but one must remember that, in practice, conditions are often not as simple. For instance, in a typical outdoor situation the natural illumination is frequently far from uniform. Whilst, neglecting direct sunlight, natural non-uniformities in illumination have only small effects on surface reflection from many materials – due to the broad lobe reflection characteristics of partially diffuse random surfaces – with smooth glass and water the non-uniformities in illumination will *totally* define luminance. This can have major effects when glass or water are part of a background. Similarly, in other than natural illumination, unless great care is taken to exclude unwanted light, contributions of incident light from windows, etc., can produce major directional reflectance effects. Such effects are frequently experienced in viewing pictures, meters, etc. through a glass cover.

So far, under this heading, we have specifically considered *smooth* surfaces of glass and water. Now water, in particular, often has a rippled surface. Such a surface will exhibit broadened specular reflectance lobes much as the wet concrete, this broadness being dependent on the roughness of the water surface.

It is interesting to note that, whilst such effects are usually troublesome, they are sometimes useful. An example of this is the recent use of specular lobe broadness to estimate ocean roughness from satellite pictures[13] and other aerial photography (e.g. Cox and Munk[14]).

14.1.7 Polarisation Effects

When considering surface reflection, it is wise to remember that light reflected specularly is, to a greater or lesser extent, polarised[12]. This is particularly true for reflections from dielectrics such as glass and water, where the reflected light may be very highly polarised. Thus the diffuse and specular (or gloss) components of surface reflection can often be at least partially separated out. Where it is essential to minimise angular variations in reflectance the use of a viewing polariser can be very effective. This principle is, of course, used to great effect in polarised sunglasses. It must, however, be realised that, even with dielectric surfaces, total blocking of specular reflection is only achieved at a certain angle (the Brewster angle), some components of the specular reflection remaining unpolarised at other angles[12].

14.2 FORMS OF REFLECTANCE

Having discussed the practical variations of reflectance as a function of viewing angle, type of surface and illumination conditions it is time to consider into what forms reflectance can be broken down. We have already mentioned the two classical forms – specular and diffuse – but these are obviously inadequate as complete descriptors. We require descriptors which can be related to surfaces, illumination and viewing angles.

A common practice is to refer to the overall reflectance characteristics in terms of two components, the basic diffuse reflectance and a *gloss* component, this latter being a broad descriptor of the strength and broadness of any specular reflectance lobe additional to the diffuse reflection characteristic. However, whilst such a pair of components provide a *general* indication of the surface properties, they are still inadequate for rigorous description of surface luminance properties under complex illumination conditions.

A thorough treatment of the problem of specifying reflectance is that due to Nicodemus[15]. He derives an expression defining a fundamental property which he calls *bidirectional reflectance* and also illustrates its meaning.

Consider a small source of intensity I_i in the direction of a surface element Δa. The source subtends a solid angle

$$\Delta\Omega_i = \sin\psi_i \Delta\psi_i \Delta\theta_i$$

at Δa, where ψ is the angle from the surface normal and θ is the azimuth angle in

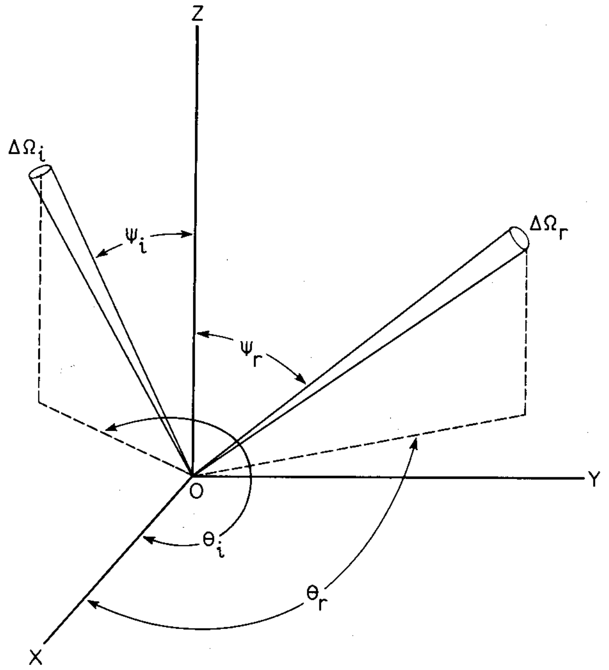

Fig. 14.3. Illustrating the geometry for reflection of elementary beams of light (from Crowther[6]).

the plane of the surface (see Fig. 14.3). The luminous flux incident on Δa is then

$$\Delta P_i = I_i \cos \theta_i \Delta a \Delta \Omega_i$$

or

$$\Delta P_i = I_i \Delta a \Delta \Omega_i' \tag{14.1}$$

where

$$\Delta \Omega_i' (\equiv \cos \psi_i \Delta \Omega_i \equiv \sin \psi_i \cos \psi_i \Delta \psi_i \Delta \theta_i)$$

is the 'projected' solid angle of the elementary incident beam.

Next consider the reflected light in a direction ψ_r, θ_r within a small element

$$\Delta \Omega_r = \sin \psi_r \Delta \psi_r \Delta \theta_r$$

The luminous power is then

$$\Delta P_r = \Delta I_r \Delta A \, \Delta \Omega_r' \tag{14.2}$$

where ΔI_r is the reflected light (due to the elementary source) in the direction ψ_r, θ_r and $\Delta\Omega_r' \equiv \cos\psi_r \Delta\Omega_r$.

The reflectance is then given as

$$\rho = \frac{\Delta P_r}{\Delta P_i} = \frac{\Delta I_r \Delta\Omega_r'}{I_i \Delta\Omega_i'} \tag{14.3}$$

If $\Delta\Omega_i$ is small, then ΔI_r is proportional to I_i and $\Delta\Omega_i'$, so ρ is invariant with respect to I_i and $\Delta\Omega_i'$. However, ρ is proportional to the solid angle of the receiver system, and a more appropriate measure would be

$$\rho' = \frac{\rho}{\Delta\Omega_r'} = \frac{\Delta I_r}{I_i \Delta\Omega_i'}$$

or

$$\rho'(\theta_i \psi_i \theta_r \psi_r) = \frac{\Delta I_r}{\Delta E_i} \tag{14.4}$$

where ΔE_i is the illuminance at Δa produced by the source. Strictly, the bidirectional reflectance should be written $\rho'(\theta_i \psi_i \theta_r \psi_r \lambda)$ to include the wavelength dependence. If the incident light is well-collimated within an element of solid angle $\Delta\Omega_i$, then the *total* reflectance from a surface, the directional-hemispherical reflectance ρ_{dh}, is given by

$$\rho_{dh}(\theta_i \psi_i) = \int_h \rho'(\theta_i \psi_i \theta_r \psi_r) d\Omega_r' \tag{14.5}$$

where the integration is carried out over the upward (or reflected) hemisphere.

In the special case of a perfectly diffuse reflector,

$$\rho_{dh} = \rho' \int_h d\Omega_r' = \pi\rho'$$

Therefore, because $\rho_{dh} = 100\%$, $\rho' = 31\%$. (Some authors in fact plot graphs of ρ' on a scale multiplied by a factor π).

Albedo, on the other hand, which should be termed the hemispheric-hemispheric reflectance since it is the proportion of incident illumination which is reflected, is the integration of ρ' over the downward (incident) and upward hemispheres.

Finally the reflectance in a given direction from a generally distributed incident light, the hemispherical-directional reflectance ρ_{hd} is the integration of ρ' over the downward hemisphere.

It can thus be seen that one may obtain any reflectance data from a knowledge of the bidirectional reflectance and the hemispherical distribution of incident illumination.

14.3 PRACTICAL REFLECTANCE DATA

14.3.1 Bidirectional Reflectance

The only reliable data available for bidirectional reflectance are a limited number derived from laboratory measurements, where incident and reflected directions are closely controlled. Only a few materials have been thoroughly studied in this way, these mainly comprising samples of soil, sand, grass and a few artificial surfaces.

Soils and rocks. The angular distribution of bidirectional reflectance for light of wavelength 0.643 μm incident on samples of sand and soil has been measured by Coulson[2,3]. None of the samples is perfectly diffuse, although for small

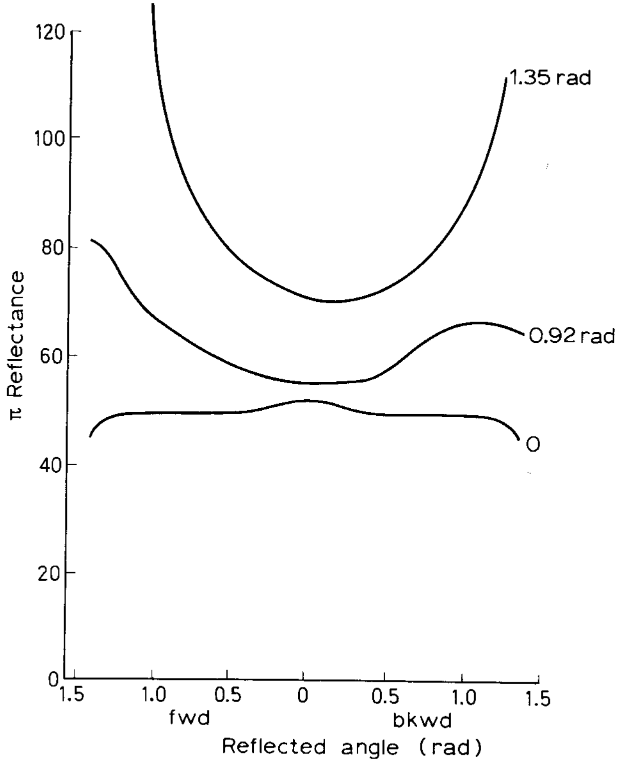

Fig. 14.4. ρ' for white quartz sand, as a function of reflectance angle, for various angles of incidence at a wavelength of 0.643 μm. (Reproduced from Coulson et al[3] *by permission. Copyright by the American Geophysical Union).*

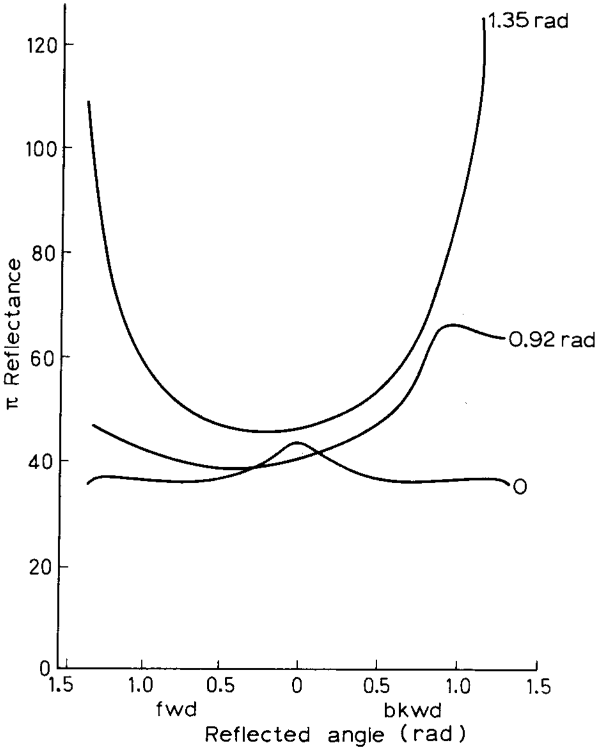

Fig. 14.5. ρ' for red clay soil, as a function of reflectance angle, for various angles of incidence at a wavelength of 0.643 μm. (Reproduced from Coulson et al[3] *by permission. Copyright by the American Geophysical Union).*

angles of incidence (relative to the surface normal) all samples approximate this ideal case. Each sample exhibits backscatter (also called back-gloss) of an amount which increases with incident angle, (see Figs. 14.4 and 14.5 for example). Forward scattering also develops with increasing incident angle, leaving a minimum reflectance in the normal direction. Generally, at any given viewing direction, the amount of reflected light increases with the incident angle. At the larger incidence angles (over about 0.7 rad) the characteristics of the samples begin to differ. Forward scattering becomes greater than backscatter for both sand samples (desert sand and white quartz sand), whereas the soils (red clay and black loam) exhibit the opposite trend. In fact for black loam the forward scattering is almost non-existent.

The relative magnitudes of the bidirectional reflectance of these four samples (for radiation 0.643 μm) can be illustrated by comparing the values found under normal incidence. The bidirectional reflectance is almost constant with viewing direction, except for a slight peak in the normal direction. The mean values for quartz sand, desert sand and red clay are about 16%, 10% and 13% respectively, whilst that for black loam is only 2%. It must be remembered that these figures should be compared with a value of $100/\pi = 31\%$ for a perfect white diffuser. The graphs in Figures 14.4 and 14.5 are plotted in terms of πx reflectance, on this scale the perfect diffuser having a reflectance of 100%.

Coulson has investigated the effects of moisture on the reflectance of soil[3]. A considerable change of angular dependence occurs as the surface becomes wetter. The forward reflection maximum of a clay surface is greatly increased by the surface moisture, while the relative importance of the backscattering peak is decreased.

Measurements made at SCRDE (Stores and Clothing Research and Development Establishment)[5,16] showed a similar effect. Both soil and sand exhibited increased forward reflection when wet, whilst the effect of surface moisture on rough concrete was to reduce the backward maximum to the level of forward scattering. The geometry of the SCRDE system is, however, not very closely defined and does not strictly measure bidirectional reflectance. In fact, measurements are made relative to an arbitrary standard and are intended only for comparative purposes, a single incident angle (1.05 rad) being used, and reflection measurements being confined to the plane of incidence, which is perpendicular to the surface (i.e. the principal plane).

Coulson[2] has measured the bidirectional reflectance of soil and sand outside

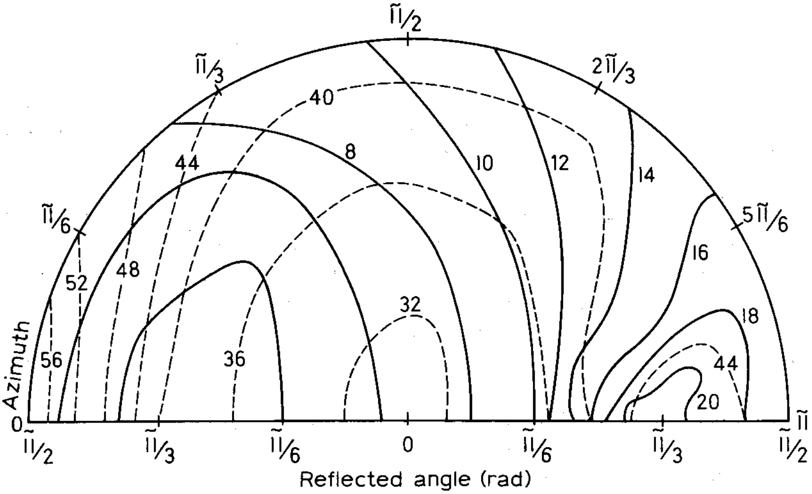

Fig. 14.6. Hemispheric bidirectional reflectance patterns of sand (dashed isopleths) and black loam soil (solid isopleths). Values shown are π x reflectance. Incidence angle 0.92 rads; $\lambda = 0.643$ µm. (Reproduced from Coulson[2] by courtesy of the Optical Society of America).

the plane of incidence. Radiation of wavelength 0.643 μm was incident at 0.92 rad. For this incidence condition, complete contour maps of bidirectional reflectance (isopleths) are available (see Fig. 14.6). The patterns of isopleths for both soil and sand samples are symmetrical about the plane of incidence, maxima and minima occuring in this plane. The curvatures of the isopleths reflect the relative forward and backward scattering properties of these two samples.

Vegetation. The bidirectional reflectance of grass has been measured for four incident wavelengths by Coulson[2]. The reflectance values are probably sensitive

TABLE 14.1. ρ' of turf: principal plane

Source elev.	Viewing elevation ϕ_r(rad)					
ϕ_i(rad)	0.07	0.105	0.14	0.175	0.21	0.245
0.26	0.0273	0.0264				
0.35			0.0255	0.0273		
0.435	0.0164	0.0182			0.0305	0.0296
0.52			0.0209	0.0228		
0.61	0.0100	0.0124			0.0236	0.0276
0.70			0.0157	0.0200		
0.785	0.0069	0.0091			0.0182	0.0240
0.87			0.0126	0.0173		
0.96	0.0047	0.0073			0.0149	0.0201
1.04			0.0113	0.0155		
1.13	0.0040	0.0066			0.0121	0.0175
1.21			0.0106	0.0142		
1.30	0.0035	0.0060			0.0102	0.0156
1.39			0.0096	0.0137		
1.48	0.0031	0.0047			0.0095	0.0140
1.56			0.0093	0.0124		
1.65	0.0034	0.0032			0.0104	0.0138
1.74			0.0109	0.0127		
1.83	0.0035	0.0032			0.0110	0.0154
1.92			0.0118	0.0135		
2.00	0.0040	0.0037			0.0138	0.0162
2.09			0.0126	0.0142		
2.18	0.0042	0.0047			0.0162	0.0169
2.26			0.0135	0.0147		
2.35	0.0055	0.0058			0.0197	0.0195
2.44			0.0158	0.0155		
2.53	0.0069	0.0064			0.0217	0.0219
2.61			0.0180	0.0167		
2.70	0.0104	0.0104			0.0236	0.0232
2.79			0.0175	0.0178		
2.88	0.0150	0.0158			0.0217	0.0219
2.96			0.0191	0.0191		
3.05	0.0177	0.0149			0.0134	0.0130

TABLE 14.2. ρ' of turf: outside principal plane

Incident elevation ϕ_i(rad)	Azimuth difference θ(rad) 0	$\pi/6$	$\pi/3$	$\pi/2$	$2\pi/3$	$5\pi/6$	π
				ϕ_r = 0.07 rad			
$\pi/12$	0.0220	0.0190	0.0113	0.0085	0.0110	0.0130	0.0145
$\pi/6$	0.0140	0.0125	0.0088	0.0065	0.0070	0.0075	0.0076
$\pi/4$	0.0086	0.0077	0.0065	0.0045	0.0049	0.0051	0.0053
$\pi/3$	0.0074	0.0071	0.0055	0.0031	0.0034	0.0036	0.0038
$5\pi/12$	0.0057	0.0047	0.0037	0.0025	0.0033	0.0041	0.0053
$\pi/2$	0.0034						
				ϕ_r = 0.105 rad			
$\pi/12$	0.0264	0.0208	0.0119	0.0103	0.0121	0.0140	0.0158
$\pi/6$	0.0153	0.0130	0.0098	0.0075	0.0079	0.0082	0.0084
$\pi/4$	0.0091	0.0080	0.0068	0.0050	0.0052	0.0055	0.0058
$\pi/3$	0.0082	0.0076	0.0058	0.0035	0.0038	0.0040	0.0042
$5\pi/12$	0.0060	0.0051	0.0040	0.0030	0.0032	0.0039	0.0058
$\pi/2$	0.0039						
				ϕ_r = 0.14 rad			
$\pi/12$	0.0335	0.0264	0.0139	0.0125	0.0136	0.0146	0.0183
$\pi/6$	0.0209	0.0153	0.0132	0.0110	0.0128	0.0142	0.0180
$\pi/4$	0.0142	0.0100	0.0085	0.0075	0.0087	0.0103	0.0147
$\pi/3$	0.0113	0.0100	0.0092	0.0080	0.0098	0.0100	0.0126
$5\pi/12$	0.0101	0.0090	0.0074	0.0065	0.0079	0.0099	0.0114
$\pi/2$	0.0093						
				ϕ_r = 0.175 rad			
$\pi/12$	0.0355	0.0285	0.0183	0.0142	0.0168	0.0166	0.0185
$\pi/6$	0.0228	0.0180	0.0150	0.0135	0.0142	0.0157	0.0167
$\pi/4$	0.0187	0.0156	0.0138	0.0120	0.0128	0.0138	0.0151
$\pi/3$	0.0155	0.0138	0.0121	0.0111	0.0119	0.0132	0.0142
$5\pi/12$	0.0139	0.0121	0.0109	0.0098	0.0106	0.0121	0.0131
$\pi/2$	0.0124						
				ϕ_r = 0.21 rad			
$\pi/12$	0.0356	0.0290	0.0187	0.0155	0.0175	0.0185	0.0198
$\pi/6$	0.0260	0.0210	0.0175	0.0155	0.0170	0.0180	0.0200
$\pi/4$	0.0200	0.0185	0.0165	0.0134	0.0145	0.0170	0.0180
$\pi/3$	0.0160	0.0145	0.0130	0.0120	0.0128	0.0140	0.0152
$5\pi/12$	0.0133	0.0126	0.0113	0.0100	0.0113	0.0126	0.0132
$\pi/2$	0.0129						
				ϕ_r = 0.245 rad			
$\pi/12$	0.0360	0.0280	0.0200	0.0185	0.0192	0.0209	0.0213
$\pi/6$	0.0285	0.0240	0.0195	0.0175	0.0188	0.0207	0.0216
$\pi/4$	0.0214	0.0203	0.0183	0.0148	0.0162	0.0188	0.0197
$\pi/3$	0.0175	0.0162	0.0145	0.0134	0.0142	0.0156	0.0168
$5\pi/12$	0.0138	0.0132	0.0117	0.0105	0.0119	0.0131	0.0136
$\pi/2$	0.0135						

to the condition of the sample. Coulson's measurements on a thick grass sample with upright blades 4 or 5 cm long show that the bidirectional reflectance generally increases with incident angle, with the backscattering peak developing more quickly than that of forward scattering. The results are not greatly different from those of the desert sand. With a sample of a broad-leafed, rather waxy plant, however, some particularly strong changes with both incident and viewing angle were observed. A third sample of grass, measured by SCRDE[16], showed prominent backscattering but very little forward scattering. SCRDE also measured two types of leaves. These samples were found to be very similar to the grass, except that bidirectional reflectance at small reflected angles was a little higher.

All the foregoing data concerning vegetation refer to measurement in the plane of incidence. The general features are the pronounced backscattering and smaller amount of forward scattering, these peaks becoming more prominent with increased angle.

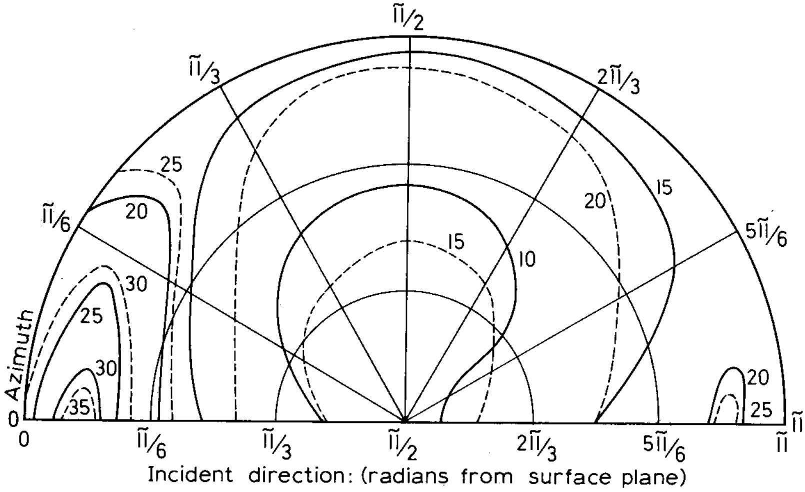

Fig. 14.7. Contours of bidirectional reflectance, (steradian)$^{-1}$ × 10^3, of turf as a function of incident and azimuth directions for two reflected angles – 0.14 rad (solid isopleths) and 0.245 rad (dashed isopleths), measured from the surface plane (from Crowther[6]).

Crowther[6] has measured the bidirectional reflectance of turf, both in the plane of incidence and outside it, for white light at a wide range of reflected angles. The results are given in Tables 14.1 and 14.2 for reflectance in the plane of incidence and outside it respectively. Typical isopleths are shown in Fig. 14.7. Field measurements[8,11], in which the sun defines the incident direction, exhibit similar features, but effects are softened due to skylight.

Snow and Ice. Middleton and Mungall[17] have measured the reflectance properties of several snow and ice surfaces. The types of snow may be listed in order of increasingly large specular component as follows: surface hoar, settling snow, new snow, rain crust, wind packed snow, glazed rain crust (ice). Apart from ice surfaces, for which virtually all the reflected light appears at the specular angle, diffuse reflection contributes significantly at small incidence angles. This is particularly so for the least compacted surfaces.

14.3.2 Spectral Characteristics

The dependence of bidirectional reflectance on the wavelength of the incident light has been determined for a few surfaces[2,3]. The measurements were confined to angles in the plane of incidence, and generally show an increase in bidirectional reflectance with wavelength through the visible spectrum.

For bare soil and sand surfaces, increasing the wavelength raises the bidirectional reflectance without appreciably altering the angular distribution. In the case of quartz sand it is essentially proportional to wavelength, the increase being about 16% between 0.492 and 0.643 μm and the same between 0.643 and 0.796 μm. This accounts for the yellow colour of sand. For red clay, under the same conditions (incident angle 0.92 rad), the change is of the order of a 25% increase from 0.492 to 0.643 μm, with a small decrease of about 5% from 0.643 to 0.796 μm. These properties give the clay its red colour. It is interesting that, with white light illuminating the clay surface, the colour of the reflected light would change with the angle of incidence. For instance, in the normal direction, the red light is reflected 2.5 times as strongly as the blue-green, whereas at 1.4 rad incident angle the ratio of bidirectional reflectances at the normal is only 1.8.

Vegetative surfaces are rather different from soil and sand. At 0.4 μm the bidirectional reflectance is low, reaching a small maximum in the region 0.5 to 0.55 μm (accounting for the green appearance) followed by a minimum in the chlorophyll absorption band centred on 0.68 μm. There is a sudden and large increase at 0.7 μm to a level which is maintained into the infrared. The angular distribution of bidirectional reflectance is, unlike that for soil and sand, dependent on wavelength. At wavelengths greater than about 0.7 μm the forward and backward scattering maxima are greatly enhanced.

The wavelength dependence of bidirectional reflectance means that any light source for laboratory measurements should be chosen with care. In a laboratory simulation of natural reflectance properties the source of illumination should have approximately the same spectral composition as daylight. As the spectral content of skylight varies with position in the sky, weather conditions and time of day, this simulation is difficult to achieve.

14.3.3 Directional-Hemispherical Reflectance

If, for a particular incident angle, the bidirectional reflectance is integrated over the upward hemisphere, the directional-hemispherical reflectance is obtained. This parameter serves as a useful comparison between different surfaces.

Kondratyev[18] claims that the directional-hemispherical reflectance of soils varies between about 5% and 45%, compared with a value of 100% for a perfect diffuser. The higher values are found for sands and dry soils, whilst the dark, heavier soils have the lower reflectances. In general, the smoother the surface (on the large scale) the higher the total reflectance. For example, a flat field reflects more than does a ploughed one. The directional-hemispherical reflectance of vegetation lies roughly between 10 and 25%, a smaller range than that of soil. The directional-hemispherical reflectances of all these surfaces increase with the angle of incidence. It should be noted that the term albedo strictly refers to the proportion of the total incident illumination which is reflected, and is derived from ρ' by integration over both downward and upward hemispheres. It is not very useful for comparative purposes because some distribution of illumination is implied.

14.3.4 Polarisation

For completeness, it is interesting to look briefly at the polarisation of reflected light. Natural surfaces exhibit their own characteristic polarisation effects. Coulson[3] summarises the data existing in 1965. More recent work is that of Chen and Rao[19]. The highest values of polarisation (70% to 95%) have been found for dark mineral surfaces. High values (65% to 70%) have also been observed for wet clay surfaces, whilst most dry soils and fine-grained materials exhibit low polarisation ($< 10\%$) at most angles. Black loam soil (up to 20%) is rather an exception. The behaviour of apparently smooth water surfaces can only be described as scattering by an 'optically rough, locally smooth' surface, according to Chen and Rao. In the light of the above, measured contrast when viewed by a polarisation sensitive 'receiver' will certainly be dependent on the plane of polarisation to which the 'receiver' is sensitive, a fact which may have important implications on acquisition tasks in the field.

14.3.5 Symmetry

Coulson[3] found the patterns of bidirectional reflectance of desert sand and black loam to be symmetrical about the plane of incidence. It seems likely that this is true of flat, amorphous surfaces in general. The data for grass have a larger scatter, although Coulson does not note any asymmetry. If the vegetation

TABLE 14.3. Summary of terrain reflectance

Surface	Bidirectional reflectance	Spectral characteristics	Total reflectance
Soils, sand, etc.	Back and forward scattering	Increasing to 1 μm	5% to 45%
	Sand has larger forward scattering	Decreasing above 2 μm	Moisture decreases reflectance by 5% to 20%
	Loam has small forward scattering		Smoother surfaces have higher reflectances
	Moisture increases forward and reduces backscattering		
Vegetation	Backscattering	Small below 0.5 μm	5% to 25%
	Small forward scattering	Peak at 0.5 to 0.55 μm	Diurnal effects; max. reflectance at large angles (from normal)
		Chlorophyll absorption at 0.68 μm	
		Sharp increase at 0.7 μm	Marked annual variation
		Decrease above 2 μm	
		Variation with growing season	
Water	Back and forward scattering, large at large angles (from normal)	Maximum at 0.5 to 0.7 μm	Small reflectance
			Maximum at grazing angles
		Dependent on turbidity	Dependent on turbitidy
Snow and Ice	Diffuse component plus specular component	Decreases slightly with increasing wavelength	Variable, 25%–100%
	Specular component increases with incidence angle	Large variability depending on purity, wetness and physical condition	

(leaves, grass blades, etc.) is randomly oriented, the average bidirectional reflectance, measured over a large enough area, should be symmetrical. If the distribution is not random, for example crops leaning in the wind, there will probably be some asymmetry about the incident plane. The striped effect of recently mown grass previously mentioned is a good illustration.

A further symmetry consideration arises from the reciprocity theorem[2]. If this theorem applies, then a reversal of incident and reflected directions leaves the bidirectional reflectance unchanged. The surfaces for which this theorem is valid are not known at present, though it probably does not hold for many natural surfaces.

A summary of the reflectance properties of the main surfaces for which data are available is to be found in Table 14.3.

14.4 MEASUREMENT OF REFLECTANCE

The method of measurement of reflectance employed must depend on the use to which the measurements are to be put. If a practical measurement of reflectance for normal viewing in a stable environment is required, then it may be simplest to measure the hemispherical-directional reflectance as a function of viewing angle, with the integrated light appropriate to the situation. If, however, the incident light conditions are not stable, it is necessary to measure the bidirectional reflectance as a function of angle of incident light. Then, knowing or estimating the distribution of incident light, the hemispherical-directional reflectance may, in theory, be computed for any given condition.

14.4.1 Reference Surfaces

In any method of reflectance measurements, one of the prime requisites is a standard reference surface. Ideally such a surface should be completely diffuse and should reflect 100% of the incident light. In practice there are no such surfaces. The closest approach is possibly a sublimation of magnesium oxide, but such a surface is very easily damaged and deteriorates quickly. Considerable efforts have been made to produce durable reference surfaces with not very great success. The nearest to a standard reference for everyday use is a ceramic tile of defined surface properties which can be calibrated at some Standards Bureau (such as the National Physical Laboratory in the UK or the National Bureau of Standards in the USA) (e.g. Crowther[6]). Such standard tiles can now be obtained in white or several standard colours.

14.4.2 Measurement of Bidirectional Reflectance

In order to measure bidirectional reflectance of a surface, it is necessary to have control of the direction of incident light and, ideally, the incident light should be collimated. It is thus hardly feasible to measure bidirectional reflectance out of doors. Even indoors the requirements are sufficiently complex for it to be uneconomic to try to make *ad hoc* measurements. A much more satisfactory approach is to construct a facility with the required degrees of freedom and bring samples to it. This is, in fact, what has been done at BAC (GW), amongst a small number of other establishments.

14.4.3 The BAC Polar Reflectometer

The BAC Reflectometer[6] is shown schematically in Fig. 14.8. It comprises a specimen table, adjustable in azimuth and elevation, a source mirror which can

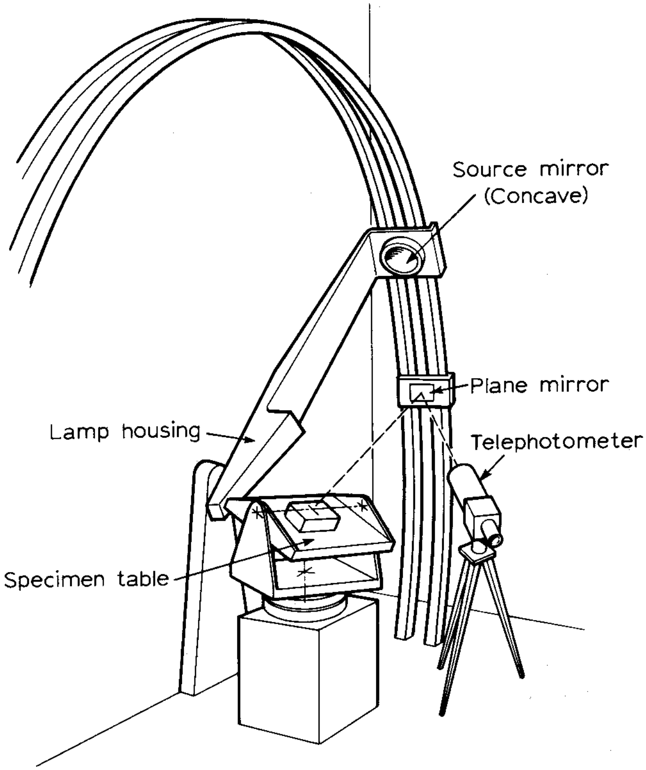

Fig. 14.8. Schematic representation of the B.A.C. (GW) Polar Reflectometer.

be moved in a fixed vertical arc (4 m diameter) centred on the sample, and a receiver mirror also constrained to move in the same arc. The specimen table has a continuous adjustment and can be set with an accuracy of 1 or 2 mrad. The receiver elevation can be similarly adjusted, whilst the elevation of the source mirror is limited to intervals of 87 mrad.

The source is a quartz iodine lamp having a colour temperature around 3400°K. Provision is made for filtering the incident beam (with, for example, polarising or colour temperature correction filters). The specimen table is illuminated with a parallel beam of light by locating the source in the focal plane of a 20 cm diameter concave mirror positioned on the vertical arc. A telephotometer is used to collect the reflected light after further reflection at a plane front-silvered mirror, which is also mounted on the arc.

Incident and reflected angles can be varied independently over a wide range of angles above the surface, provided the sample is of solid material. For loose samples, such as sand, the range of angles is limited by the amount of tilt permitted, and for liquids the plane of incidence and reflectance can only lie perpendicular to the surface.

In a typical measurement program the light source is filtered so that the colour temperature is about 5500°K, which corresponds approximately to mean natural daylight illumination. The receiver system is also filtered so that its response is photopic.

The field of view of the telephotometer can be varied to suit the nature of the sample. For homogeneous surfaces a probe with an acceptance angle of 1.75 mrad is generally used, whereas samples which have larger scale surface irregularities, such as grass, require a 17.5 mrad probe. This does not affect the measured value of ρ', providing it is constant over the 17.5 mrad range. A standard tile must, of course, be measured with the corresponding probe to maintain the correct calibration factor. Calibration checks are, in fact, frequently carried out throughout the measurement program.

14.4.4 Computation of Reflectance in Field Conditions

It is all well and good to have reliable data for the distributed bidirectional reflectance of various surfaces but, unless we know what forms of hemispherical illumination distribution typically exist in a field situation, and can compute intereactions with the surface reflectances, the data are of very limited practical use. In an effort to rectify the situation, BAC (GW) have undertaken large scale statistical measurements of sky luminance distributions as a function of time of day, time of year and weather[20,21]. This work has provided a large data bank for statistical prediction of the hemispherical incident illumination distribution. At the same time a computer program, 'Polar Bear', has been written which takes statistical sky luminance data and bidirectional reflectance data and computes hemispherical-directional reflectances for all viewing angles[6].

14.5 IMPLICATIONS ON MODELLING

The important conclusion from the results of studies reported in this chapter is that, in any visual viewing situation where incident lighting and viewing angle are not absolutely stable, there is no such thing as basic local scene luminance. Each local portion of the scene – object of interest and background – will have its own characteristic law of luminance variation with time as the viewing conditions change. We at BAC (GW) have found to our cost that such local temporal luminance signatures upset markedly the modelling of threshold trends as a function of range, since they can and do interact strongly with known range dependent factors such as size and atmospheric effects (see particularly Chapter 15). They also interfere with attempted photometry to establish atmospheric conditions.

TABLE 14.4. Model clear sky luminance distribution (cd/m^2) for a solar elevation $\pi/4$ rads, azimuth 0 rads

	Elevation (rad)						
Azimuth (rad)	0	$\pi/12$	$\pi/6$	$\pi/4$	$\pi/3$	$5\pi/12$	$\pi/2$
0	16 580	13 840	18 980	12 000	5 890	3 347	2 145
$\pi/4$, $7\pi/4$	9 250	6 990	5 824	5 070	3 940	2 994	–
$\pi/2$, $3\pi/2$	5 000	3 238	2 415	2 107	2 035	2 151	–
$3\pi/4$, $5\pi/4$	4 385	2 597	1 658	1 357	1 364	1 597	–
π	4 728	2 665	1 569	1 213	1 179	1 466	–

An example of the effects of polar luminance variations when viewing the ground obliquely from a low flying aircraft has been studied by Crowther[6] using the 'Polar Bear' computer program. The necessary input for this exercise comprised the set of bidirectional reflectance data for turf given in Tables 14.1 and 14.2 and a sky luminance distribution. Two different sky types have been used; a clear sky, with the sun at $\pi/4$ rads elevation, and a complete overcast. The clear sky model was based on the measurements of Jones and Condit[22] and the sky luminance values are set out in Table 14.4. Direct sunlight adds 58 850 lm/m^2 to the ground plane illumination. The overcast sky was modelled on Moon and Spencer's formula[23]

$$B_\phi = B_h(1 + 2\sin\phi)$$

in which B_ϕ is the sky luminance at elevation angle ϕ. The scaling factor B_h, which equals the horizon sky luminance, was given the value 1000 cd/m^2.

TABLE 14.5. Reflected luminance of turf as a function of viewing direction under clear and overcast sky models.

		Luminance (cd/m^2)					
			Clear (azimuth indicated)				
Reflected angle (rad)	Range (km)	Overcast	0	$\pi/4$, $7\pi/4$	$\pi/2$, $3\pi/2$	$3\pi/4$, $5\pi/4$	π
0.070	8.7	47.7	619	519	350	379	398
0.087	7.0	49.7	639	533	370	393	417
0.105	5.8	51.7	659	546	389	408	436
0.122	5.0	66.6	834	622	485	557	730
0.140	4.3	81.4	1009	698	581	705	1023
0.156	3.85	91.7	1159	877	730	831	1046
0.174	3.5	101.9	1309	1055	879	958	1068
0.192	3.15	107.2	1357	1147	930	1040	1165
0.210	2.90	112.5	1405	1240	980	1121	1261
0.227	2.63	117.9	1455	1302	1031	1183	1320
0.244	2.45	123.4	1506	1365	1082	1245	1380

Table 14.5 contains all the computed luminance values under both clear and overcast skies as a function of the viewing direction. This direction has also been converted into effective slant range for an aircraft flying at 600 m. The luminances due to a clear sky are dependent on azimuth differences between the sun and the viewing direction. Therefore, values have been computed for a variety of azimuth directions relative to the sun. The underlying reflectance characteristics are clearly evident: backscatter is somewhat greater than forward scatter with a minimum at right angles to the sun's direction.

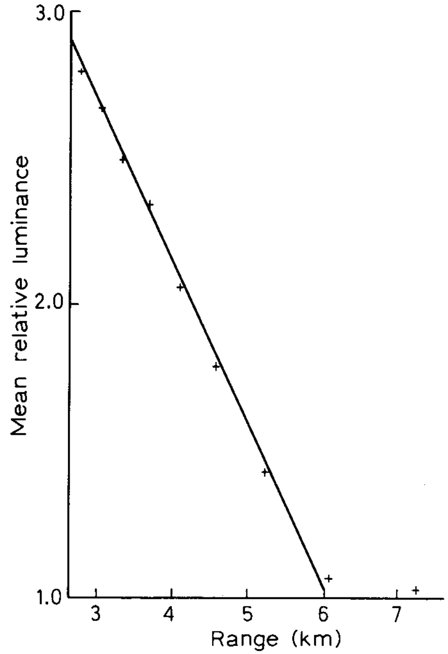

Fig. 14.9. Mean relative luminance of turf as a function of viewing range (From Crowther[6]).

If a mean relative luminance against viewing angle is determined then the result, on plotting against range, is as shown in Fig. 14.9. Between 2.5 and 5.5 km the relative luminance can be seen to be approximated by a straight line.

This graph is of course *only* applicable to the sample of turf measured, but does serve to illustrate how markedly the intrinsic luminance of turf is dependent on viewing range when viewed from an aircraft at constant altitude. In practice this intrinsic luminance will itself be modified as a range function due to the effects of atmospheric attenuation to be discussed in the next chapter.

REFERENCES

1. Born, M. and Wolf, E. (1964). *Principles of Optics*, Chap. 4.8. Pergamon Press
2. Coulson, K. L. (1966). 'Effects of Reflection Properties of Natural Surfaces in Aerial Reconnaissance', *Applied Optics*, 5, 905
3. Coulson, K. L., Bouricius, G. M and Gray, E. L. (1965). 'Optical Reflection Properties of Natural Surfaces', *J. of Geophys. Res.*, 70, 4601
4. Brennan, B. and Bandeen, W. R. (1970). 'Anisotropic Reflectance Characterisitics of Natural Earth Surfaces', *Applied Optics*, 9, 405
5. Hodgson, E. W. and Overton, T. K. W. (1965). 'Texture and its Significance in Camouflage', Directorate of Stores and Clothing Development, MOD
6. Crowther, A. G. (1972). 'Polar Luminance and Contrast', Annex A of *Final Report of Third Visual Studies Contract*, BAC (GW) Ref. L50/196/1535
7. Crowther, A. G. (1971). 'A note on Comparative Measurement of the Bidirectional Reflectance of Black Nylon Velvet and Matt Black Paint' BAC (GW) Tech. Memo. No. 7, Ref. L50/249
8. Duntley, S. Q., Gordon, J. I., Taylor, J. H., White, C. T., Boileau, A. R., Tyler, J. E., Austin, R. W. and Harris, J. L. (1964). 'Visibility', *Applied Optics*, 3, 556
9. Boileau, A. R. and Gordon, J. I. (1966). 'Atmospheric Properties and Reflectances of Ocean Water and Other Surfaces for a Low Sun', *Applied Optics*, 5, 803
10. Gordon, J. I. and Church, P. V. (1966). 'Overcast Sky Luminances and Directional Luminous Reflectances of Objects and Backgrounds under Overcast Skies', *Applied Optics.*, 5, 919
11. Gordon, J. I. and Church, P. V. (1966). 'Sky Luminances and Directional Luminous Reflectances of Objects and Backgrounds for a Moderately High Sun', *Applied Optics*, 5, 793
12. Born, M. and Wolf, E. (1964). *Principles of Optics*, Chap. 1.5, Pergamon Press, London
13. Webber, D. S. (1971). 'Surface Winds from Sun-glitter Measurements from a Spacecraft', in *Proceedings of SPIE, Vol. 27, Remote Sensing*, 93
14. Cox, C. and Munk, W. (1954). 'Measurement of the Roughness of the Sea Surface from Photographs of Sun's Glitter', *J. Opt. Soc. Am.*, 44, 838
15. Nicodemus, F. E. (1965). 'Directional Reflectance and Emissivity of an Opaque Surface', *Applied Optics*, 4, 767
16. Littlefield, T. A. 'Distribution of Light due to Texture', Ministry of Home Security – Research and Experimental Dept., Rep. REN 477
17. Middleton, W. E. K. and Mungall, A. G. (1952). 'The Luminous Directional Reflectance of Snow', *J. Opt. Soc. Am.*, 42, 572
18. Kondratyev, K. (1965). 'Actinometry', NASA TTF–9712, Washington DC, November
19. Chen, H. and Rao, C. R. N. (1968). 'Polarisation of Light on Reflection by some Natural Surfaces', *Brit. J. Appl. Phys. D.*, 1, 1191
20. Brown, M. B. (1971). 'The Measurement of Sky Brightness – Final Report', BAC (GW) Ref. L50/22/PHY/114/1296, February
21. Brown, M. B. (1974). 'The Measurement of Sky Radiance – Final Report', BAC (GW) Ref. ST11930
22. Jones, L. A. and Condit, H. R. (1948). 'Sunlight and Skylight as Determinants of Photographic Exposure', *J. Opt. Soc. Am.*, 38, 123
23. Moon, P. and Spencer, D. E. (1942). 'Illumination from a Non-uniform Sky', *Illum. Eng. (NY)*, 37, 707