7 Polarizational Characteristics of the Sky

7.1 Skylight Polarization

7.1.1 The Importance of Skylight Polarization in Atmospheric Science

Solar radiation as a natural light source is unpolarized before entering the earth's atmosphere. The natural light field originating from the sky is partially linearly polarized through scattering interactions (Liou 1980; Hulst 1981) with the atmospheric constituents, such as the permanent gases (e.g. N_2, O_2), gases with variable concentration (e.g. O_3, SO_2) and various solid and liquid particles (aerosol particles, water droplets, ice crystals). The intensity and polarization of skylight have long been studied for many reasons. Early interest involved explaining natural phenomena such as the colour of the sky and rainbows (Young 1982; Coulson 1988). Since the discovery of skylight polarization by Arago in 1809, studies of the polarization of skylight and neutral points have been emphasized, as these can be used as indicators of atmospheric turbidity (Kimball 1913, Coulson 1980) and surface properties (Coulson 1974). The principal interest in measurements of skylight polarization is its sensitivity to dust, haze and pollution in the atmosphere (Sekera 1956; Bullrich 1964). The maximum degree of polarization, for example, is diminished by the effects of aerosol scattering, and at the same time the neutral points of skylight polarization are shifted from their normal positions.

The clear sky has a characteristic polarization pattern depending on the solar position, the distribution of various components of the atmosphere and the underlying surface properties (Coulson 1988). The polarization of skylight has been the subject of numerous theoretical and experimental investigations (e.g. Chandrasekhar 1950; Neuberger 1950; Hulst 1952; Sekera 1957a,b; Holzworth and Rao 1965; Bellver 1987; Coulson 1988; North and Duggin 1997; Voss and Liu 1997; Horváth et al. 1998b; Horváth and Wehner 1999). The principal features of the intensity and polarization of the sunlit sky can be explained in terms of Rayleigh scattering by molecules in the atmosphere (Coulson 1988). Modern radiative transfer theory in the investigation of polarization (Chandrasekhar 1950; Liou 1980; Hulst 1981) has been applied to studies on planetary atmospheres (e.g.

Coulson et al. 1960; Chamberlain 1978) as well as the earth-ocean system (e.g. Plass and Kattawar 1970; Kattawar et al. 1973; Kattawar and Adams 1989).

Understanding the intensity and polarization of light in the atmosphere is also important in atmospheric correction of remotely sensed data (e.g. Gordon 1978; Gordon and Wang 1992). Neglecting the polarization in radiance calculations in an atmosphere-ocean system can introduce errors as large as 30% (Adams and Kattawar 1993). Measurements of the total sky polarized radiance distribution can be used to test the validity of exact (vector) radiative transfer models. Through inversion techniques this distribution can also be used in the determination of physical and optical properties, such as the absorption and scattering phase function of aerosols (Wang and Gordon 1993), for instance.

7.1.2 Measuring Skylight Polarization

Early measurements of skylight polarization were made mainly by visual means. As the semiconductor technology advanced, new photodetectors in conjunction with computer technology made the automatic measurement of light and its polarization possible. A large number of optical systems have been developed for observations of skylight polarization. Coulson (1988) listed the various types of point-source polarimeters developed until 1988 for observations of the atmosphere and surface of the earth. Although photomultiplier tubes have been used as detectors for most of these systems, some devices use other detectors such as silicon cells or photographic films.

Most ground-based measurements of skylight polarization were performed by means of point-source polarimeters using narrow-band interference filters to determine the degree and angle of linear polarization for different wavelengths of light. As these polarimeters possess a very small aperture (ca. 1^o-5^o, in which the optical information are averaged), the polarizational characteristics of the sky can be analyzed by them only within very restricted fields of view. The spatial distribution of skylight polarization could be determined by scanning the firmament with such a point-source polarimeter, but this is a time-consuming task done rarely and only in special cases: Using a point-source polarimeter and making repeated scans along the solar-antisolar meridian and perpendicularly to the solar meridian, Shaw (1975) measured the skylight polarization at 400 nm during the total solar eclipse of 30 June 1973 in Kenya. Brines and Gould (1982) undertook similar measurements at several points of the firmament by means of a point-source scanning polarimeter. They could measure points at every 5^o of zenith angle and azimuth of a half hemisphere of the sky within 7-8 minutes, during which the sun moved about 2^o along its arc. Certain unavoidable errors were a consequence of their rapid measurement process, such as inaccuracies attendant upon setting the axes of the instrument. If one wished to enhance the spatial resolution of the samples by one or two orders to obtain a picture-like scan of the polarization of the entire sky, the measurements would require 70-80 or 700-800 minutes, a period during which the celestial polarization pattern would change considerably due to the rotation of the earth (it takes 80 minutes for the sun to move by 20°). It is clear that the polarization pattern of the entire firmament cannot reliably be measured by such a time-consuming method.

The development of full-sky imaging polarimetry (North and Duggin 1997; Voss and Liu 1997; Gál et al. 2001a,b,c; Pomozi et al. 2001a,b; Horváth et al. 2002a,b, 2003) offered new methods for observing the distribution of skylight polarization over the whole celestial hemisphere in several ranges of the spectrum quickly and accurately. Although various aspects of the intensity and polarization in the sunlit atmosphere have been studied in the past (reviewed by Coulson 1988), rapid measurements of the polarization distribution over the entire sky were not possible before the development of these different types of full-sky imaging polarimetry. The ability of these imaging polarimeters to provide polarization distribution over the full sky has great potential for application in studies of atmospheric aerosols as well as radiative transfer problems in the earth-ocean system, because data can be collected in a short time; thus changes in the atmosphere during measurement can be avoided or minimized. With these polarimeters neutral points can also be easily detected (Liu and Voss 1997; Gál et al. 2001a,b,c; Pomozi et al. 2001a,b; Horváth et al. 2002a,b, 2003).

7.2 Celestial Polarization Measured by Video Polarimetry in the Tunisian Desert in the UV and Green Spectral Ranges

In his seminal paper on skylight navigation in insects, especially in ants, Santschi (1923) wondered why certain genera and species used the sun as a compass, while others relied predominantly on the sun-free parts of the sky. In his lifetime, it was not known yet that the decisive aspect of light perceived by insects in the sky was the distribution of E-vectors of linearly polarized light – later discovered in bees (Frisch 1949), and now extensively studied in desert ants of the genus *Cataglyphis* (Wehner 1994a). The differences, however, that Santschi had observed among different genera and species are still a riddle. Are they really due to differences among different taxonomic groups of ants, or are they caused by characteristics of the habitats occupied by the different species? As the habitats of the *Aphenogaster*, *Messor*, *Monomorium* and *Cataglyphis* species are rather varied and include desert regions in mountains, sand-dune areas, salt pans or coastal inundation plains, several parameters such as water content, haze, frequency of clouds and the turbidity of the atmosphere vary accordingly. All these factors have strong influences on various optical aspects of scattered skylight (Coulson 1988, p. 350, 423).

One can imagine, for example, that due to the lower level of aerosols and haze in totally arid, vegetation-free desert mountain areas, the degree of skylight polarization p is higher there than in coastal regions, where haze commonly occurs. The atmosphere above salt pans, even if covered by hard, dried-out soil, can contain large amounts of water vapour due to the evaporation of water from the moist underground. How much do these differences in the structure of the ants' habitats affect *p*? This is an important question, because *p* largely influences the accuracy of navigation (Wehner 1982, Edrich and Helversen 1987). Furthermore, to what extent does *p* depend on the spectral composition of skylight? The *Cataglyphis* retina is equipped with UV and green photoreceptors, but only the former are used in E-vector navigation. Do the atmospheric factors mentioned above influence *p* of skylight more strongly in the UV than in the green, or *vice versa*?

In order to answer these questions, Horváth and Wehner (1999) measured the degree of linear polarization *p* and angle of polarization α of skylight in the UV and green by an UV-sensitive video polarimeter in three different North African habitats. The geometry of the celestial windows from which the measurements were taken is shown in Fig. 7.2.1. No recordings were taken of the celestial windows, in which the sun appeared at a particular time of day. Due to the low levels of radiance at sunrise and sunset and because of the low UV transmittance of the polarizers and UV filters, UV recordings could not be taken when the sun was at the horizon. Measurements were taken under clear-sky conditions in three Tunisian habitats occupied by different species of desert ants (genera *Cataglyphis, Messor, Aphenogaster, Monomorium*):

1. within the vast expanses of salt-pan area of the Chott el Djerid (site "Tozeur", east of El Mahassen; 33.9°N, 8.5°E)
2. in the extremely arid and vegetation-free highland area of the south-eastern parts of the North African Dorsale (close to the Tunisian/Algerian border; site "Metlaoui", halfway between Metlaoui and Moulares; 34.3°N, 8.2°E)
3. in the coastal inundation plains of the Tunisian Sahel zone (site "Maharés", 34.6°N, 10.5°E)

In Tables 7.2.1 and 7.2.2 *p* is given in the green (550 nm) and UV (360 nm) range of the spectrum for two different solar elevations (θ_s = 35° and θ_s = 70°) at the above three different types of habitat. None of the three study sites exhibited significantly higher or lower *p*-values than any of the other sites. Whenever two measurements have been performed at the same site on two subsequent days, *p* differed, sometimes remarkably, from one day to another. For example, at the *Maharés* site at 550 nm in celestial window AS-20 *p* exhibited values of 20.1% and 29.9% on August 8 and 10, 1996, respectively, even though the human observer could not detect any obvious differences in the appearance of the sky. The same statistically significant differences hold for all measurements made on two separate days in the same region of the sky; with the only exception of celestial window Z, at Maharés, for θ_s = 70^o (Table 7.2.2). In conclusion, the temporal (day-to-day) variations at one particular site always exceeded the variations that are due to the spatial (geographical) location of that site. In all celestial windows *p* was always higher in the green than in the UV. This is in accord with what one would expect to occur in the normal atmosphere (Coulson 1988). Even in the cloudless sky vaulting a subtropical desert landscape *p* within medium-sized (20°×15°) celestial windows never exceeded mean values of 60%, and 75% in individual celestial directions.

The starting point of the investigation of Horváth and Wehner (1999) was the question whether different types of habitat occupied by different insect navigators varied in one or another optical aspect of skylight polarization. Such conjectures are not unwarranted. Water vapour and aerosols, which cause absorption and multiple scattering events, might occur in the atmosphere more frequently above one type of habitat than above another. Furthermore, differential reflections from the ground are known to influence the optical properties of skylight patterns as well.

The general result emerging from the measurements of Horváth and Wehner (1999) is that the question posed above cannot be answered in the affirmative. p, which is much more affected by atmospheric disturbances and surface reflections than is α, does not vary systematically among the different types of desert habitat. The day-to-day fluctuations of p are much larger than the habitat-based variations. Hence, Santschi's (1923) early observation that for navigation some ant species inhabiting particular geographical regions relied more on scattered skylight than direct sunlight, cannot be explained on the basis of the distinctness of skylight cues available to the ants in these different habitats. Instead, the interspecific and intergeneric differences must be caused by peculiarities of the ants' species-specific navigational systems.

Tables

Table 7.2.1. Degree of linear polarization *p* of skylight measured by video polarimetry in the ultraviolet (UV, 360 nm) and green (G, 450 nm) spectral range (window size: $20^o \times 15^o$) at three different Tunisian study sites (Tozeur: salt pan, 04.08.1996; Metlaoui: mountains, 05.08.1996 and 06.08.1996; Maharés: coastal area, 08.08.1996 and 10.08.1996). Solar elevation: $\theta_s = 35^o$, local time 16:30 (= UTC+1). Mean values ± standard deviations. For conventions of direction of view see Fig. 7.2.1.

degree of linear polarization *p* (%) for solar elevation $\theta_s = 35^o$				
direction of view	**spectral range**	**Tozeur (salt pan)**	**Metlaoui (mountains)**	**Maharés (coast)**
AS-20	UV	8.2 ± 3.9	11.6 ± 4.3 10.3 ± 4.3	10.9 ± 3.2
AS-20	G	13.1 ± 5.9	16.1 ± 6.6 14.2 ± 6.0	14.9 ± 6.3
AS-55	UV	17.3 ± 5.1	14.4 ± 4.7 18.7 ± 5.2	20.3 ± 3.8
AS-55	G	30.4 ± 6.2	36.7 ± 5.7 32.7 ± 6.0	38.9 ± 7.1
Z	UV	11.4 ± 3.9	10.6 ± 4.2 12.3 ± 4.4	13.0 ± 3.3
Z	G	24.2 ± 6.9	26.2 ± 7.9 24.8 ± 7.6	29.8 ± 9.0
Z-OFF	UV	16.9 ± 3.9	17.8 ± 3.9 17.3 ± 3.5	19.9 ± 2.6
Z-OFF	G	27.9 ± 6.2	29.0 ± 6.9 27.9 ± 6.5	34.0 ± 7.2
S-55	UV	3.8 ± 2.1	5.1 ± 3.1	4.8 ± 2.4
S-55	G	6.0 ± 4.1	6.3 ± 3.5	7.5 ± 4.2

Table 7.2.2: As Table 7.2.1 for solar elevation θ_s = 70° at local summer time 14:00 (= UTC+1).

degree of linear polarization *p* (%) for solar elevation θ_s = 70°				
direction of view	**spectral range**	**Tozeur (salt pan)**	**Metlaoui (mountains)**	**Maharés (coast)**
AS-20	UV	20.4 ± 3.6	22.0 ± 4.1 22.4 ± 4.1	19.1 ± 3.2 23.8 ± 3.5
AS-20	G	26.2 ± 4.5	28.6 ± 3.4 25.1 ± 3.7	20.1 ± 5.1 29.9 ± 7.6
AS-55	UV	16.5 ± 3.6	16.5 ± 3.7 16.5 ± 4.2	17.5 ± 2.9 19.1 ± 3.2
AS-55	G	24.1 ± 4.6	25.4 ± 5.7 23.7 ± 5.3	23.5 ± 3.9 31.5 ± 6.8
Z	UV	4.9 ± 2.5	5.1 ± 2.9 5.1 ± 2.9	4.8 ± 2.1 4.8 ± 2.1
Z	G	8.1 ± 3.9	7.5 ± 3.9 7.7 ± 4.0	7.6 ± 3.7 9.5 ± 4.8
Z-OFF	UV	13.2 ± 3.7	14.2 ± 4.7 13.3 ± 4.4	14.9 ± 6.3 17.1 ± 3.2
Z-OFF	G	18.2 ± 6.5	16.0 ± 6.9 16.3 ± 6.6	24.3 ± 3.2 22.2 ± 8.8

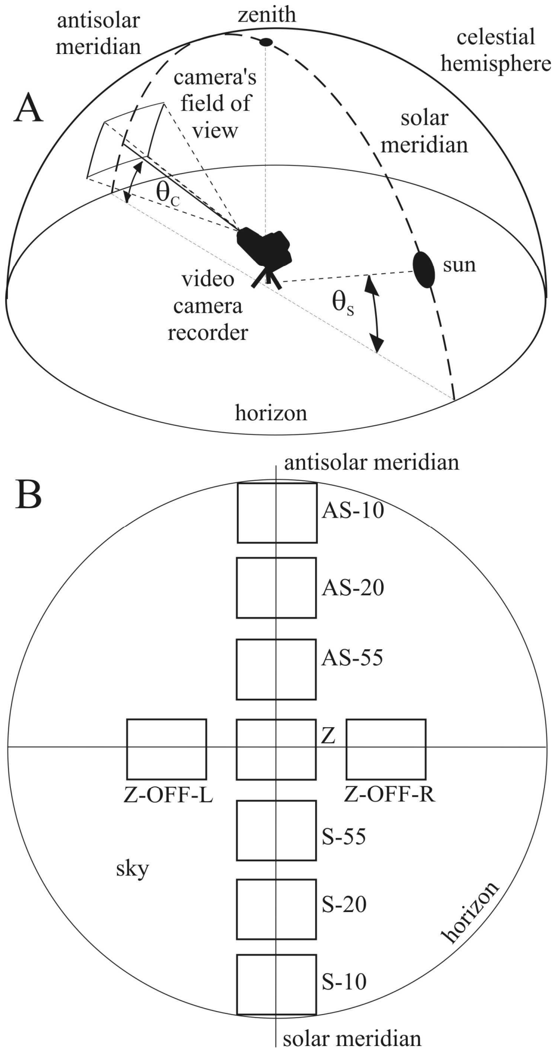

Fig. 7.2.1. A: Geometry of the video-polarimetric recording of skylight polarization taken by Horváth and Wehner (1999). The elevation of the video camera and the sun is θ_c and θ_s, respectively. B: The positions of the celestial windows within which video-polarimetric data were obtained. When the camera was oriented towards the antisolar and solar meridian, the rectangular window representing the field of view of the camera is designated by "AS-" and "S-", respectively. The numbers following these designations indicate the elevation θ_c of the camera in degrees. Window "Z" means that the camera recorded the region around the zenith. In case of window "Z-OFF" the camera was first rotated by 90^o from the solar meridian then elevated by 45^o in the plane perpendicular to the solar meridian (R: right, L: left). The field of view of the camera, i.e. the size of the celestial windows, is $20^o \times 15^o$ (horizontal and vertical extent, respectively). (After Fig. 1 of Horváth and Wehner 1999, p. 2).