5 180^o Field-of-View Imaging Polarimetry

5.1 Simultaneous Full-Sky Imaging Polarimeter with a Spherical Convex Mirror

North and Duggin (1997) developed a practical method to obtain colour-coded maps of the partial Stokes vector (I,Q,U) of polarized light and its derivatives (p, α) across the whole sky. They used a four-lens camera (Nishika N8000, focal length = 30 mm) with negative colour roll films. The four apertures of the camera were covered by neutral density linearly polarizing filters (HN38, Polaroid), the transmission axes of which were oriented at 0^o, 45^o, 90^o and 135^o with respect to a given reference direction. Hence, all polarizational pictures of the sky were taken simultaneously, which is the main advantage of this simultaneous imaging polarimeter. The polarimeter was suspended 2.7 m over a spherical security convex mirror (46 cm diameter, back-surface aluminium coating on an acrylic matrix) by four thin rods. This height was required to mitigate the parallax effects created by the finite separation of the four lenses. Figure 5.1 illustrates the setup providing a circular image of the nearly complete skydome reflecting off the mirror and onto the focal planes of the four cameras. A 6 m air-driven shutter release was used to minimize obscuration by the photographer. Although the spherical mirror of this imaging polarimeter encompassed a field of view of almost 180^o, the instrument could not record data of the entire skydome, since the camera above the mirror and the tetrapod screened out certain areas of the firmament.

After taking the polarizational photographs of the mirror-reflected skydome, the developed film was converted by a standard photo-CD process to digital images of the sky. Although the aluminium coating on the mirror might induce a small amount of circular polarization, the fourth component V of the Stokes vector was assumed to be zero. This simplifying assumption allowed to obtain images of the partial Stokes vector (I,Q,U) by using only linear polarizers. The digitised images were then evaluated by a commercial image-processing software. The resulting spatial distributions of the partial Stokes vector components were obtained over the full sky in the red, green and blue part of the spectrum, where the colour film had its sensitivity maxima.

Since the polarimeter of North and Duggin (1997) was not calibrated, the Stokes vector $\underline{S}_{sky}$ of the incident skylight could not have been measured. With this system only the spatial distribution of the Stokes vector $\underline{S}_{image}$ of skylight reflected from the spherical mirror could be determined, which is the major disadvantage of this polarimeter. The underlying mathematics is described by Clarke and Grainger (1971). From the resulting partial Stokes vector $\underline{S}_{image}$ the radiance I_{image}, degree of linear polarization p_{image} and angle of polarization α_{image} were derived, which inform qualitatively about I, p and α of skylight. Thus, a controlled experiment remains to be executed to provide absolute polarimetric calibration, to obtain full polarimetric characterization of the optical system, and to invert $\underline{S}_{image}$ to derive $\underline{S}_{sky}$. This work has not been done until now. Furthermore, the equipment is voluminous and cumbersome (Fig. 5.1), which does not permit easy and rapid setting up, disassembly, transfer and transport. These may be the reasons why results on skylight polarization obtained with this mirror-based simultaneous imaging polarimeter have been never published. Nevertheless, an improved version of this polarimeter could be a next generation of the radiometric total sky imager (Fig. 2.7). Such a polarimetric total sky imager could monitor continuously the radiance, spectral and polarizational properties of the full sky.

5.2 Sequential Full-Sky Imaging Polarimeter with a Fisheye Lens and a CCD

To measure the polarized radiance distribution of skylight over the whole celestial hemisphere, Voss and Liu (1997) developed a sequential full-sky imaging polarimeter (Fig. 5.2). It is based on a 178° field-of-view fisheye camera lens, a cooled (–30 °C < T < –40 °C) CCD sensor controlled by a computer interface card and a remotely controlled filter changer. Typical integration times of the CCD are between 0.5 and 15 s. With the spectral filter changer, measurement in several spectral ranges can be performed. With linearly polarizing filters placed in one of the filter wheels the Mueller matrix of the instrument can be varied. The data process involves taking three polarizational images with different orientations of the transmission axes of the polarizers. The overall time period for one complete measurement is 1.5–2 minutes. After digitisation the images are stored in a hard drive of a personal computer. From these three images the components I, Q, U of the Stokes vector as well as the degree p and angle α of linear polarization of the incident light are computed, saved and displayed in image format. The accuracy of the polarization measurement is about 2%.

During the measurements a sun occulter blocks the direct solar radiation to avoid camera lens flaring and overexposure of the CCD. This occulter also blocks a rectangular portion of the sky, as a result, no data are available within a celestial area of about 20° around the sun ranging radially from the horizon almost up to the zenith. Due to the sun occulter this polarimeter cannot measure the part of the sky where the Babinet and Brewster neutral points occur. Calibrations of the system linearity, spectral and polarizational responses, camera system roll-off and absolute response of the instrument are described in detail by Voss and Liu (1997).

Using this polarimeter, Liu and Voss (1997) measured the polarized radiance distribution of skylight at different sites, under various atmospheric conditions, at different wavelengths, and studied the position of the Arago neutral point. Although the setting up of this polarimeter is much easier than that of the full-sky imaging polarimeter of North and Duggin (1997), this equipment is not portable either, because it needs a mains power supply and connection with a computer, furthermore its CCD has to be thermoelectrically cooled.

5.3 Portable 180° Field-of-View Sequential Rotating-Analyzer Imaging Photopolarimeter

Gál et al. (2001c) designed a portable, 180° field-of-view, sequential, rotating-analyzer imaging photopolarimeter, with which numerous successfull measurements have been performed in the field (e.g. Gál et al. 2001a,b,c; Pomozi et al. 2001a,b; Barta et al. 2003; Bernáth et al. 2003; Horváth et al. 2002b, 2003; Barta and Horváth 2003) due to the portability of the instrument and because it is easy to manage.

The setup of this polarimeter is shown in Fig. 5.3A-C. An angle of view of 180° is ensured by a Nikon-Nikkor fisheye lens (F-number = 2.8, focal length = 8 mm) including a built-in rotating filter wheel mounted with three neutral density linearly polarizing (HNP'B, Polaroid) filters with three different orientation (0°, 45° and 90° measured from the radius of the wheel) of their transmission axis, and the detector is a photoemulsion in a Nikon F801 photographic camera. Different types of colour reversal film is used; the maxima of their spectral sensitivity curves are usually at about 650 nm (red), 550 nm (green) and 450 nm (blue). In the calibration of the instrument the following are involved: the determination of the system Mueller matrix, which describes the influence of the fisheye objective on the optical parameters of the light passing through it, and the determination of the transfer function of the whole evaluation process, that is, the function between the real light intensity I fallen onto the photoemulsion and the digital value of the intensity taken from the digitisation process.

From a given sky three photographs are taken for the three different alignments of the transmission axis of the polarizers on the built-in filter wheel. In skylight measurements, the camera is set up on a tripod in such a way that its axis passing through the view-finder points northward (Fig. 5.3C) and the optical axis of the fisheye lens is vertical pointing towards the zenith (Figs. 5.3A,B). In order to eliminate distorting internal reflections of direct sunlight from the refracting surfaces of the fisheye lens, the sun is blocked by a sun occulter. Under normal illumination conditions of the sunlit sky, the overall time needed for one complete measurement is about 6-8 sec.

After chemical development of the colour reversal films, the framed colour dia slides are digitised with a scanner. The triplet of the digitised polarizational pictures of a given scene are then evaluated and the patterns of the intensity, degree and angle of linear polarization are visualized as high-resolution colour-coded two-dimensional circular maps in the red, green and blue spectral ranges, in which the three colour-sensitive layers of the photoemulsion have the maximal sensitivity. The calculation of the intensity, degree and angle of linear polarization of skylight is the same as in the case of video polarimetry (Horváth and Varjú 1997). In the case of skylight measurements, the three-dimensional celestial hemisphere (Fig. 5.3D) is represented in two dimensions by a polar-coordinate system, where the zenith angle θ and the azimuth angle φ from the solar meridian are measured radially and tangentially, respectively (Fig. 5.3E). In these circular images the centre is the zenith, the horizon is the perimeter, and the zenith angle θ is directly proportional to the radius from the centre. Modifying appropriately the design, this 1-lens 1-camera 180° field-of-view imaging polarimeter can be adapted to underwater measurements too, like the submersible video polarimeter designed by Shashar et al. (1995b).

5.4 Portable 3-Lens 3-Camera Full-Sky Simultaneous Imaging Photopolarimeter

The major shortcoming of the 180° field-of-view polarimeters described in the preceding two sections is their slowness due to they record the three polarizational pictures of the full sky sequentially. One cycle of three exposures and, in between, exchanging the polarizer may well take several seconds or minutes depending on the time of exposure. Thus, these instruments cannot be used if the cycle duration is comparable with the time, during which the optical characteristics of the sky change considerably. Such situations occur in the following cases:

- The sky is cloudy and the clouds move fast.
- Moving aerial objects (e.g. birds or airplanes) occur in the firmament.
- Immediately after sunset or prior to sunrise when the radiance of skylight changes rapidly and moreover the time of exposure increases considerably due to the relatively low radiance of skylight.
- The platform of the polarimeter, being on the board of a ship, for example, is moving or rocking.

In order to eliminate the major shortcoming of the mentioned polarimeters, Horváth et al. (2002a) designed a 3-lens 3-camera full-sky imaging polarimeter, which takes the 3 polarizational pictures of the entire sky simultaneously rather than sequentially. Thus, celestial polarization patterns can be recorded with this instrument even if rapid temporal changes occur in the sky. The ability of this polarimeter to provide full-sky polarization patterns without motion artefacts has great potential for application in atmospheric optics and radiative transfer problems in the earth-ocean system, because data can be collected simultaneously, thus changes in the atmosphere during measurement can be neglected.

The setup of the polarimeter of Horváth et al. (2002a) is shown in Fig. 5.4. The polarimeter is composed of three Nikon F801 roll-film photographic cameras (Fig.

5.4A), each of them equipped with a Sigma fisheye lens (Figs. 5.4B,C). The F-number of the lenses is 4, their focal length is 8 mm, and their field of view is 180°. The cameras are fixed on a tripod parallel to each other onto a horizontal guide pointing always northward during the measurements (Fig. 5.4D) with the optical axes of the fisheye lenses vertical, pointing towards the zenith. On one of the outside cameras the vertical direction of looking through the view-finder is turned to horizontal by means of a 90° angle-finder. The simultaneous triggering of all three cameras is mechanically ensured by synchronous pressing the buttons of the remote exposure cords. The same values of aperture and exposure are set manually on all three cameras, which are focussed to infinity.

Each Sigma fisheye lens (Fig. 5.4B) is composed of two lens groups with a circular filter mount in between (Fig. 5.4C). Into the mounts neutral density linearly polarizing filters (HNP'B, Polaroid) are inserted in such a way that the angles β between their transmission axes and the horizontal guide pointing northward are 0°, 60° and 120° in the first, second and third camera, respectively (Fig. 5.4D). The type and sensitivity of film material used as detector depends on the type of recording.

To minimize ghost effects due to internal reflections of direct sunlight from the refracting surfaces within the fisheye lenses and the blooming effect caused by the direct solar radiation and the limited dynamic range of the photoemulsion, the direct sunlight is blocked. A sun occulter is fixed to a rod held by an assistant (Figs. 5.4E,F) and positioned at a distance as great as possible from the polarimeter to minimize the area of its shadow on the picture of the skydome to be photographed. The evaluation of the three polarizational pictures taken with this 3-lens 3-camera full-sky imaging polarimeter is the same as in the case of the 1-lens 1-camera full-sky imaging polarimeter of Gál et al. (2001c). The calibration of both polarimeters was also the same.

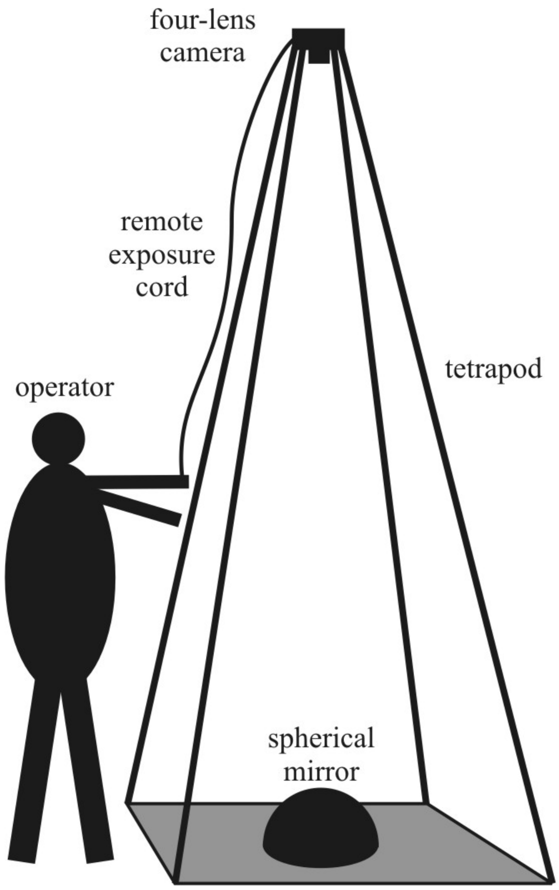

Fig. 5.1. Setup of the simultaneous full-sky imaging polarimeter of North and Duggin (1997, Fig. 2, p. 725).

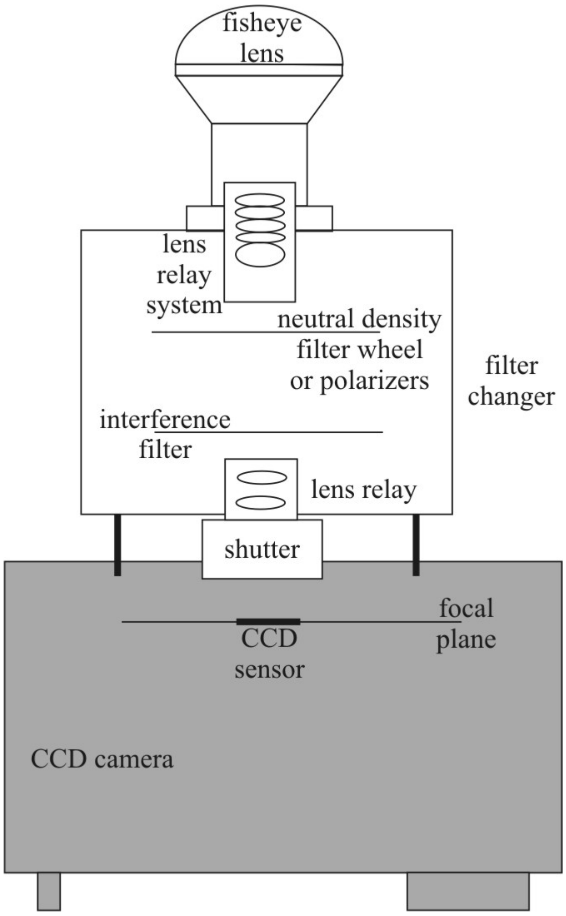

Fig. 5.2. Block diagram of the sequential full-sky imaging polarimeter of Voss and Liu (1997, Fig. 1, p. 6086).

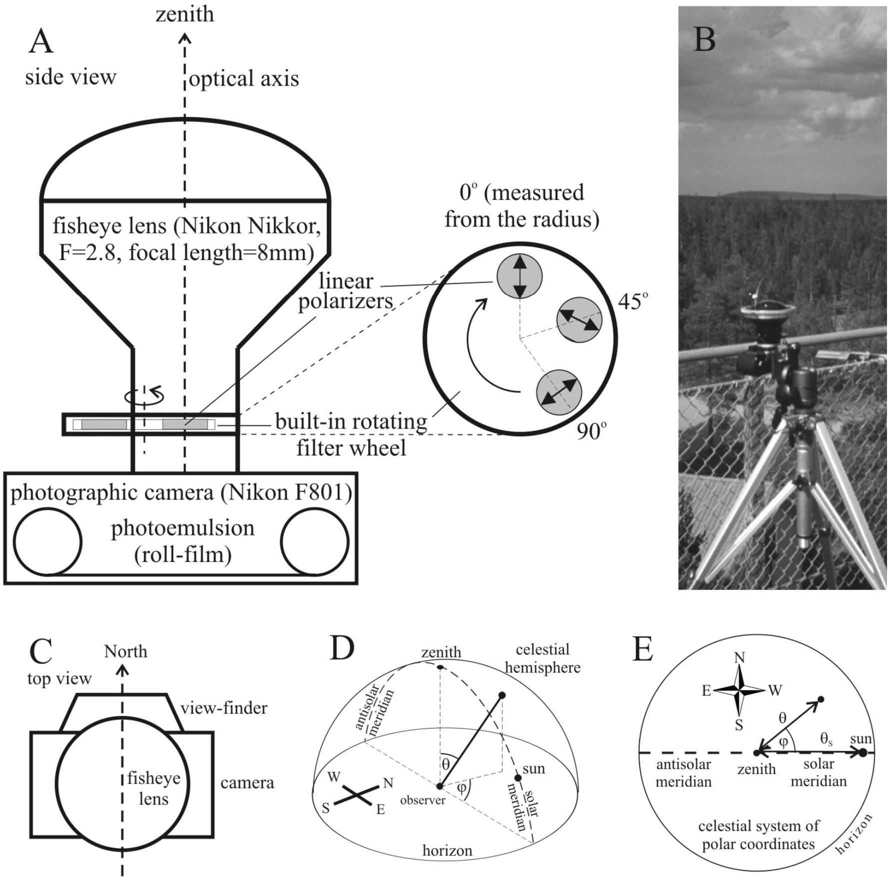

Fig. 5.3. A, C: Schematic representation of the portable, 180° field-of-view, sequential, rotating-analyzer imaging photopolarimeter of Gál et al. (2001c). The orientation of the transmission axis of the linearly polarizing filters is indicated by double-headed arrows. B: In-field setup of the polarimeter. D: Three-dimensional celestial polar coordinate system. E: Two-dimensional celestial system of polar coordinates used in the representation of the polarization patterns of the full sky measured by the instrument. East is on the left (rather than on the right) of the compass rose because we are looking up through the celestial dome rather than down onto a map. (After Fig. 1 of Gál et al. 2001c, p. 1388).

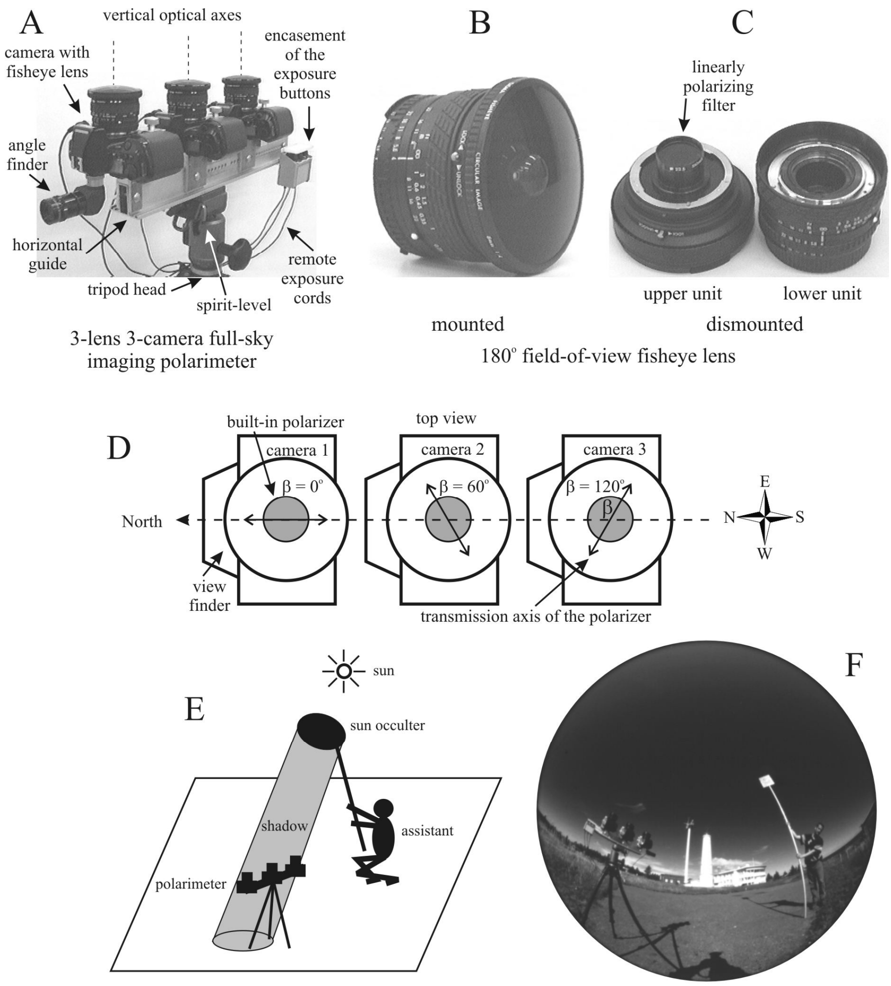

Fig. 5.4. The setup of the 3-lens 3-camera full-sky (180° field-of-view) imaging polarimeter of Horváth et al. (2002a). A: Photograph of the polarimeter. B, C: Photographs of the Sigma fisheye lens in mounted and dismounted state. D: Direction of the transmission axis of the built-in linearly polarizing filters indicated by double-headed arrows. E: Blocking the direct solar radiation by a sun occulter held by an assistant to eliminate multiple internal reflections at the refracting surfaces within the fisheye lenses. F: 180° field-of-view photograph showing the in-field setup of the polarimeter and an assistant with the sun occulter. (After Figs. 1-4 of Horváth et al. 2002a, p. 544, 545).