1 Polarimetry: From Point-Source to Imaging Polarimeters

Biologists dealing with polarization sensitivity of animals, or engineers designing robots using polarization-sensitive imaging detectors, for example, need a technique to measure the spatial distribution of polarization in the optical environment. In the 1980s, 1990s and early 2000s, different kinds of imaging polarimetry have been developed to measure the polarization patterns of objects and natural scenes in a wide field of view. The conventional non-imaging point-source polarimeters average polarization over an area of a few degrees only. The conception of "polarization imagery" or "imaging polarimetry" was introduced by Walraven (1981) to obtain high-resolution information about the polarized components of the skylight radiance. Table 1.1 summarizes the most important properties of various imaging polarimeters.

1.1 Qualitative Demonstration of Linear Polarization in the Optical Environment

The presence of linearly polarized light (the most common type of polarization in nature) in the optical environment can be qualitatively demonstrated by the use of a linear polarizer. Looking through such a filter and rotating it in front of our eyes, the change of intensity of light coming from certain directions may be observed. This intensity change is an unambiguous sign of the polarization of light. If we take colour photographs from a scene through linear polarizers with differently oriented transmission axes and compare them, striking intensity and colour differences may occur in those regions, from which highly polarized light originates, furthermore the brightness and colour contrasts may change drastically between different parts of the scene (→ colour Figs. 1.1 and 1.2).

Using triangles cut from a sheet of linearly polarizing filter, Karl von Frisch (1953) constructed a simple device, the so-called Sternfolie (star foil), with which the gross distribution of linear polarization of skylight could be

Table 1.1. The most important properties of some imaging polarimeters designed by different authors and used for various purposes. Since all instruments contain linearly polarizing filter(s) of different types, the polarizers are not mentioned and specified in the column "imaging optics" (IO).

Author(s)	Type	IO	DET	FOV	RES	SR	Application
Gerharz (1976)	FIP	CAMO + Savart filter + CF	PP	12×15°	–	535	Polarization distribution of the circumsolar scatter field during a total solar eclipse
Dürst (1982)	SEQ PHO	CAMO + 6 NF + 1 CF	PE	8×10°	50×50	600	Polarization pattern of the solar corona during a total solar eclipse
Prosch *et al.* (1983)	SIM VID	3 lens systems	IT	25×25°	36×36	VIS	Ground- and airborne remote sensing of landscape features
Sivaraman *et al.* (1984)	SIM PHO	four–lens CAMO	PE	3×3°	32×32	WL	*p*-pattern of the solar corona during a total solar eclipse
Fitch *et al.* (1984)	POR SEQ PHO	CAMO	PE	30×40°	512×512	VIS	Polarization pattern of light reflected from grain crops during the heading growth stage
POLDER (1994–1997) Deschamps *et al.* (1994)	SEQ VID	wide field-of-view optics + filter wheel	CCD	114×114°	242×274	443, 670, 865	Space-borne measurement of the polarizational characteristics of earthlight
Wolff (1993), Cronin *et al.* (1994), Shashar *et al.* (1995a, 1996)	SEQ VID SUB	CAMO + 2 TNLC	CCD	30×40°	165×192 (D) 240×320 (V)	VIS	Polarization patterns of objects and biotopes
Wolff (1994), Wolff & Andreou (1995)	SEQ VID	2 CAMO + PPBS + TNLC	CCD	20×20°	165×192	VIS	Polarization patterns of objects for robot vision
Wolff & Andreou (1995)	1D SIM PCC	lens system	PSC	–	3×128	VIS	Prototype of future 2D polarization camera chips
Povel (1995)	SIM STO	telescope + PEMs	CCD	0.42'× 0.83'	288×385	VIS	Observation of solar magnetic fields
Pezzaniti & Chipman (1995)	MMI SEQ	lens system + retarders + laser	CCD	42×42°	512×512	VIS IR	Polarizational properties of static optical systems and samples

Table 1.1. (*Continued*)

Author(s)	Type	IO	DET	FOV	RES	SR	Application
North & Duggin (1997)	SIM PHO	four–lens CAMO + spherical mirror	PE	180° CIR	300×300	VIS	Ground-borne measurement of skylight polarization
Voss & Liu (1997)	SEQ VID	FEL	CCD	178° CIR	528×528 (B)	VIS	Ground-borne measurement of skylight polarization
Horváth & Varjú (1997)	POR SEQ VID	CAMO	CCD	50×40°	736×560	VIS	Polarization patterns of sky, objects and biotopes
Lee (1998)	POR SEQ PHO	CAMO	PE	36×24°	550×370	VIS	Polarization patterns of clear skies
Horváth & Wehner (1999)	POR SEQ VID	CAMO IT	UV	20×15°	736×560	UV+ VIS	Polarization patterns of sky, objects and biotopes
Bueno & Artal (1999), Bueno (2000)	SEQ MMI	CAMO + 2 TNL + 2 quarter-wave plate + laser	CCD	1×1°	60×60	630	Polarizational properties of static optical systems and samples (e.g. human eye)
Hanlon *et al.* (1999)	SIM VID	3-tube CAMO + prismatic beam-splitter	IT	20×30°	512×384	VIS	Polarization patterns of moving animals
Mizera *et al.* (2001)	POR SEQ STE VID	CAMO	CCD	50×40°	736×560	VIS	Polarization patterns of objects and biotopes
Gál *et al.* (2001 c)	POR SEQ PHO	FEL + filter wheel	PE	180° CIR	670×670	VIS	Ground- and airborne measurements of polarization patterns of the atmosphere, objects and biotopes
Shashar *et al.* (2001)	SEQ VID	microscope	CCD	5×5°	512×384	VIS	Polarization patterns of microscopic targets
Horváth *et al.* (2002a)	POR SIM PHO	3 FEL	PE	180° CIR	670×670	VIS	Ground-borne measurements of skylight polarization

Table 1.1. (*Continued*)

Author(s)	Type	IO	DET	FOV	RES	SR	Application
Pomozi (2002), Pomozi *et al.* (2003),Garab *et al.* (2003)	DPL SM	Laser scanning microscope	CCD	256×256 μm	1024× 1024	VIS	Study of the anisotropic architecture of microscopic samples and the interaction of the sample with polarized light

1D one-dimensional (linear). *B* binned. *CAMO* camera optics. *CCD* charge-coupled device. *CF* colour filter. *CIR* circular. *D* digital. *DET* detector. *DPLSM* differential polarization laser scanning microscopy. *FEL* fisheye lens. *FIP* forerunner of imaging polarimetry. *FOV* field of view. *IR* infrared ($\lambda > 750$ nm). *IT* imaging tube. *MMI* Mueller matrix imaging polarimeter. *NF* neutral density filter. *PCC* polarization camera chip. *PE* photoemulsion. *PEM* piezoelastic modulator. *PHO* photopolarimeter. *POR* portable. *PP* photographic plate. *PPBS* polarizing plate beam-splitter. *PSC* polarization-sensitive chip. *RES* spatial resolution (pixel × pixel). *SEQ* sequential. *SIM* simultaneous. *SR* spectral region (nm). *STE* stereo. *STO* imaging Stokes polarimeter. *SUB* submersible. *TNLC* twisted-nematic liquid crystal. *UV* ultraviolet. *V* video. *VID* video polarimeter. *VIS* visible (400–750 nm). *WL* white light.

demonstrated (Fig. 1.3). This pioneering instrument was used by Frisch to investigate qualitatively the degree and angle of polarization of skylight, which was important to interpret the results of his behavioural experiments with honeybees.

What could be demonstrated only qualitatively by Frisch (1953) with his “Sternfolie”, nowadays can already be measured quantitatively by different kinds of full-sky imaging polarimeters (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; Barta *et al.* 2003). Figure 1.3 and → colour Figs. 1.4 and 1.5 (see also colour Figs. 4.3–4.5) demonstrate well the advance of imaging polarimetry in the last 50 years.

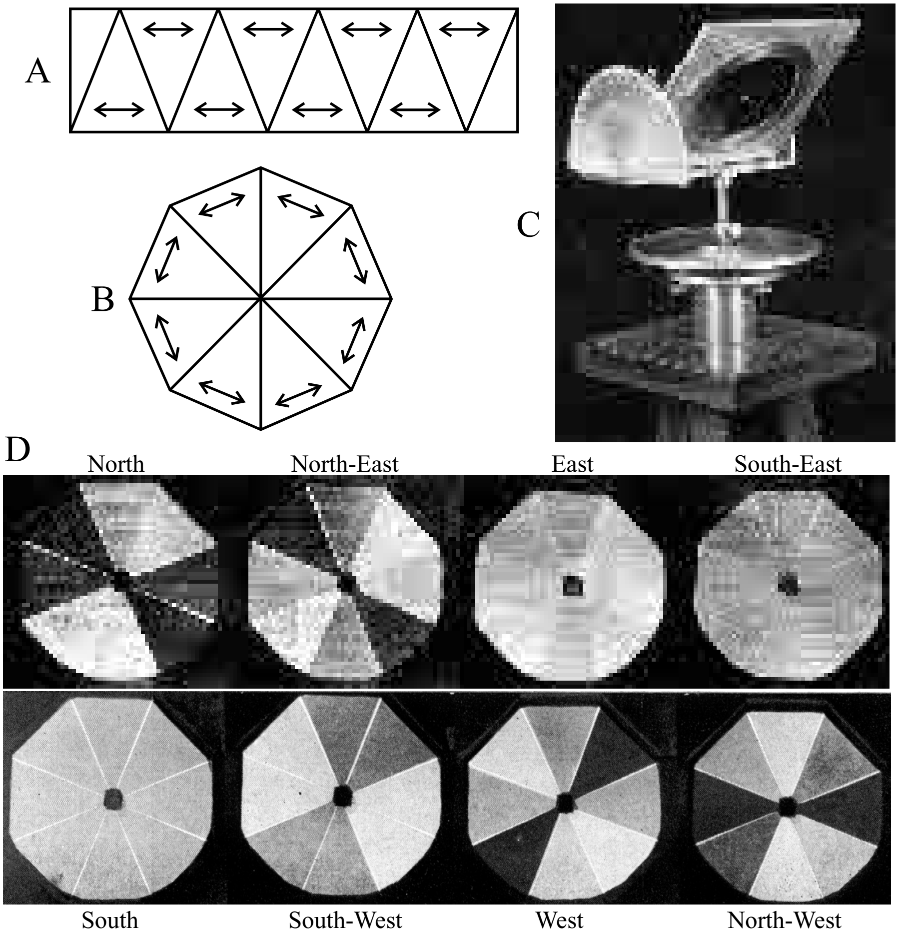

Fig. 1.3. **A** Schematic drawing of a sheet of linearly polarizing filter with cut pattern to construct the "Sternfolie" ("star foil") used to demonstrate the gross distribution of linear polarization of skylight by Karl von Frisch (1953, 1967). The orientation of the transmission axis is shown by *double-headed arrows*. **B** The geometry of the "Sternfolie". **C** Simple instrument – a "Sternfolie" mounted onto a metal holder in such a way that both the elevation and azimuth of the viewing direction through the foil can be changed, – with which Frisch (1953, 1967) investigated qualitatively the polarization of skylight. **D** View through the "Sternfolie" in eight different directions in the sky with an angle of elevation of 45°. (After Frisch 1953).