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Polarized Light in Animal Vision

Polarization Patterns in Nature

With 127 Figures, 16 Plates in Colour

Springer

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Cover: **Background:** Pattern of the angle of linear polarization α of skylight and earthlight displayed on the surface of a *sphere* and measured by 180° field-of-view imaging polarimetry in the blue part (450 nm) of the spectrum from a hot air balloon at an altitude of 3500 m. The colour code of α is given in → colour Fig. 4.5. More details can be found in Chap. 4.2. **Foreground:** Collection of some representative polarization-sensitive animal species (dragonfly *Anax imperator*, house cricket *Acheta domesticus*, red-spotted newt *Notophthalmus viridescens*, spider *Pardosa lugubris* and rainbow trout *Oncorhynchus mykiss*), the polarization sensitivity of which is treated in Part III of this volume.

All figures in this volume were composed by Dr. Gábor Horváth

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Preface

The subject of this volume is two-fold. First, it gathers typical polarization patterns occurring in nature. Second, it surveys the polarization-sensitive animals, the physiological mechanisms and biological functions of polarization sensitivity as well as the polarization-guided behaviour in animals. The monograph is prepared for biologists, physicists and meteorologists, especially for experts of atmospheric optics and animal vision, who wish to understand and reveal the message hidden in polarization patterns of the optical environment not directly accessible to the human visual system, but measurable by polarimetry and perceived by many animals. Our volume is an attempt to build a bridge between these two physical and biological fields.

In Part I we introduce the reader to the elements of imaging polarimetry. This technique can be efficiently used, e.g. in atmospheric optics, remote sensing and biology.

In Part II we deal with typical polarization patterns of the natural optical environment. Sunrise/sunset, clear skies, cloudy skies, moonshine and total solar eclipses all mean quite different illumination conditions, which also affect the spatial distribution and strength of celestial polarization. We present the polarization patterns of the sky and its unpolarized (neutral) points under sunlit, moonlit, clear, cloudy and eclipsed conditions as a function of solar elevation. The polarization pattern of a rainbow is also shown. That part of the spectrum is derived in which perception of skylight polarization is optimal under partly cloudy skies. The reader becomes acquainted with the polarization of the solar corona and can follow how the polarization pattern of the sky changed during a total solar eclipse. We also treat the polarizational characteristics of water surfaces, mirages and the underwater light field. We explain why water insects are not attracted by mirages. Finally, the occurrence of circularly polarized light in nature is reviewed.

Part III is devoted to the description of the visual and behavioural mechanisms indicating how animals perceive and use natural polarization patterns. Surveying the literature, a detailed compendium of the sensory basis of polarization sensitivity in animals and humans is given. We also present several case studies of known behavioural patterns determined or influenced by polarization sensitivity. It is shown, for instance, how aerial, terrestrial and aquatic animals use celestial and underwater polarization for orientation. The role of the reflection-polarization pattern of water surfaces in water detection by insects is discussed. We illustrate how reflection-polarization patterns of anthropogeneous origin can deceive water-seeking polarotactic insects. The natural environment is more or less affected by human civilization and is overwhelmed by man-made objects, such as crude or waste oil surfaces, asphalt roads, glass surfaces, or plastic sheets used in agriculture, for instance. We explain why these surfaces are more attractive to water-seeking polarotactic insects than the water surface itself. We explain why mayflies or dragonflies lay their eggs *en masse* on dry asphalt roads or car-bodies. We show how dangerous open-air oil reservoirs can be for polarotactic insects and why oil surfaces function as insect traps. Some other possible biological functions of polarization sensitivity, such as contrast enhancement, intra- or interspecific visual communication and camouflage breaking are also discussed. Due to the interference of polarization and colour sensitivity, polarization-induced false colours could be perceived by polarization- and colour-sensitive visual systems. We calculate and visualize these false colours by means of a computer model of butterfly retinae, and investigate their chromatic diversity. Finally, a common methodological error is discussed, which is frequently committed in experiments studying animal polarization sensitivity.

Our monograph is in close connection with the treatise about planets, stars and nebulae studied with photopolarimetry edited by T. Gehrels (1974), the volume on polarized light in nature by Günther P. Können (1985), and the monograph of Kinsell L. Coulson (1988) on polarization and intensity of light in the atmosphere. When these volumes were published, the technique of imaging polarimetry was not yet available, thus the polarizational characteristics of natural optical environments were presented in the form of graphs or pairs of photographs taken through linear polarizers with two orthogonal directions of their transmission axes.

Due to imaging polarimetry developed in the last decade, the polarization patterns are visualized in our volume as high resolution colour/grey-coded maps of the degree and angle of linear polarization. All colour figures are placed at the end of the book. They are cited in the text as e.g. → colour Fig. 1.1.

Considering various kinds of point-source non-imaging polarimeters, including radar polarimetry, the reader is referred to the monographs of Egan (1985), Kong (1990), Azzam and Bashara (1992), Boerner *et al.* (1992) and Collett (1994), for instance. All relevant details of the physics of light polarization can be found in the text-books of Shurcliff (1962), Clarke and Grainger (1971), Kliger *et al.* (1990), Born and Wolf (1999), for example. The early knowledge about the sensory basis of animal polarization sensitivity and its

biological functions was reviewed by Karl von Frisch (1967) and Talbot H. Waterman (1981). Rüdiger Wehner (1976, 1982, 1983, 1984, 1989, 1994, 2001) also wrote several important reviews and essays about this topic, especially on honeybees and desert ants. In addition to relying on our own contributions to the field, we have liberally quoted from the numerous publications of many other investigators with appropriate references given in each case. While the bibliography at the end of our book is not complete, it is fairly representative of the field.

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Gábor Horváth
Dezső Varjú

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The polarimetric measurements in Finland, in the Tunisian desert and in Switzerland were possible due to fruitful cooperation with Professors Viktor

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Many thanks to our wives, Heide Varjú and Zsuzsanna Horváth-Tatár who ensured the ideal and quiet familiar atmosphere, which was one of the most important prerequisites of our work. We dedicate this monograph to them.

Gábor Horváth is very grateful to Professor Rudolf Schwind, who introduced him into the wonderful world of polarized light and its role in animal vision during his one-year postdoctoral fellowship at the Institute of Zoology of the University of Regensburg in 1991–1992.

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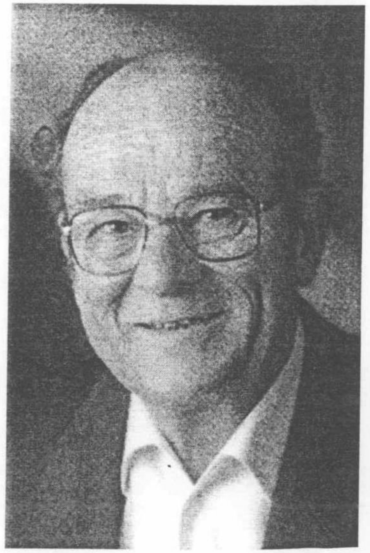
About the Authors

Gábor Horváth was born in 1963 in Kiskunhalas, Hungary. In 1987 he received his diploma in physics from the Loránd Eötvös University in Budapest. Then he was a research assistant at the Department of Low Temperature Physics of the same university, where he investigated electrical percolation processes in granular superconductors. In 1989 he received a doctoral fellowship in the Biophysics Group of the Central Research Institute for Physics of the Hungarian Academy of Sciences (Budapest), where he developed a mathematical description and computer modelling of retinal cometlike afterimages. He obtained his Ph.D. at the Eötvös University in 1991. His thesis in physiological optics is a computational study of the visual system

and optical environment of certain animals. In 1991 he was offered a one-year postdoctoral position in the Institute for Zoology of the University of Regensburg (Germany), where together with Professor Rudolf Schwind he started to study the polarization patterns of skylight reflected from water surfaces. Then he was a postdoctoral fellow at the Department for Biological Cybernetics of the University of Tübingen (Germany) for 1 year. Here, he investigated experimentally the polarization-sensitive optomotor reaction in water insects and natural polarization patterns together with Professor Dezső Varjú. In 1993 he finished his postdoctoral dissertation in computational visual optics to obtain the degree "Candidate for Biophysical Science" awarded by the Hungarian Academy of Sciences. For this treatise he won the first International Dennis Gabor Award. In 1993 together with Dezső Varjú, he won also the biomathematical Richard Bellman Prize from the journal of Mathematical Biosciences. He also received several best paper awards of different Hungarian popular-scientific journals. He won the first prize of the Hungarian Biophysical Society three times. In 1994 he received the *Pro Schola* award from the Áron Szilády secondary school, where he studied earlier. Presently he is an associate professor at the Department of Biological Physics of the Eötvös University and leader of the Biooptics Laboratory. He received the Hungarian István Széchenyi (3 years), Loránd Eötvös (9 months), János Bolyai (3 years), Zoltán Magyary (1 year) scholarships and the German Alexander von Humboldt fellowship (14 months). His main research interest is studying experimentally as well as theoretically the optics of animal eyes, polarization sensitivity of animals and the polarizational characteristics of the optical environment. He developed different kinds of imaging polarimetry, by which he records and visualizes the polarization patterns in nature. He conducted several expeditions and polarimetric measuring campaigns in Hungary, in the Tunisian desert as well as in the Finnish Lapland. His wife, Zsuzsanna Tatár-Horváth teaches mathematics and physics in a secondary school in Budapest. His sons, Loránd and Lénárd were born in 1991 and 1999, respectively.

Dezső Varjú was born in 1932 in Hungary. In 1956 he received his diploma in physics from the Loránd Eötvös University in Budapest. In the same year he left Hungary and joined as graduate student a group of biophysicists headed by the late Werner Reichardt at a Research Institute of the Max Planck Society in Göttingen, Germany. There he was involved in the investigation of movement perception in insects and of phototropic and light growth responses of the slime mold *Phycomyces*, on both experimental and theoretical levels. In 1958 he received his Ph.D. from the Georg August University in Göttingen. In the same year the group moved to the Research Institute for Biology of the Max Planck Society in Tübingen. In 1959 he obtained a one-year postdoctoral position at the California Institute of Technology in Pasadena with Max Delbrück, where he continued his investigations into the light and gravity responses of *Phycomyces*. Returning to Tübingen, he started to study nonlinear signal transformation and binocular interactions in the human pupillomotor pathway at the above-mentioned institution. Afterwards he examined frog retinal ganglion cells. Later, he frequently changed the objects of his investigations, because he was looking for biological problems, the mathematical modelling of which promised to be fruitful, and each new object gave him the opportunity to become acquainted with a new chapter in biology. In 1968 the Eberhard Karls University in Tübingen offered him a Chair for Zoology, which was soon renamed the Department for Biological Cybernetics. The general field of his research during the last 30 years was invertebrate behavioural neurobiology with a special interest for localization and orientation. In



1983 he organized the triannual conference of the German Association for Cybernetics on these topics. His activities included both experimental investigations and mathematical modelling. His experimental animals were the beetle *Tenebrio*, the stick insect *Carassius*, the crabs *Carcinus*, *Leptograpsus*, *Pachygrapsus*, the crayfish *Cherax*, the bugs *Triatoma*, *Gerris*, *Notonecta* and the hawk moth *Macroglossum*. From 1969 until 2001 he was member of the Editorial Board of Biological Cybernetics and since 1993 of the Advisory Board of the Journal of Comparative Physiology A. He spent his sabbaticals in the laboratories of friends in Canberra and Sydney (1980/81, 1986/87, 1991/92). In Tübingen he conducted research with guest scientists from Argentina, Canada, USA, and most frequently with Gábor Horváth from Hungary. Since October 1997 he is Professor Emeritus of the University of Tübingen.

Contents

Part III: Polarized Light in Animal Vision

Part I:
Imaging Polarimetry

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	UV IT	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
Barter *et al.* (2003)	SIM VID	CAMO + 4-way beam-splitting	CCD	36×36°	640× 480	VIS	Patterns of linear circular polarization of the optical environment at 60 Hz frame rate

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.

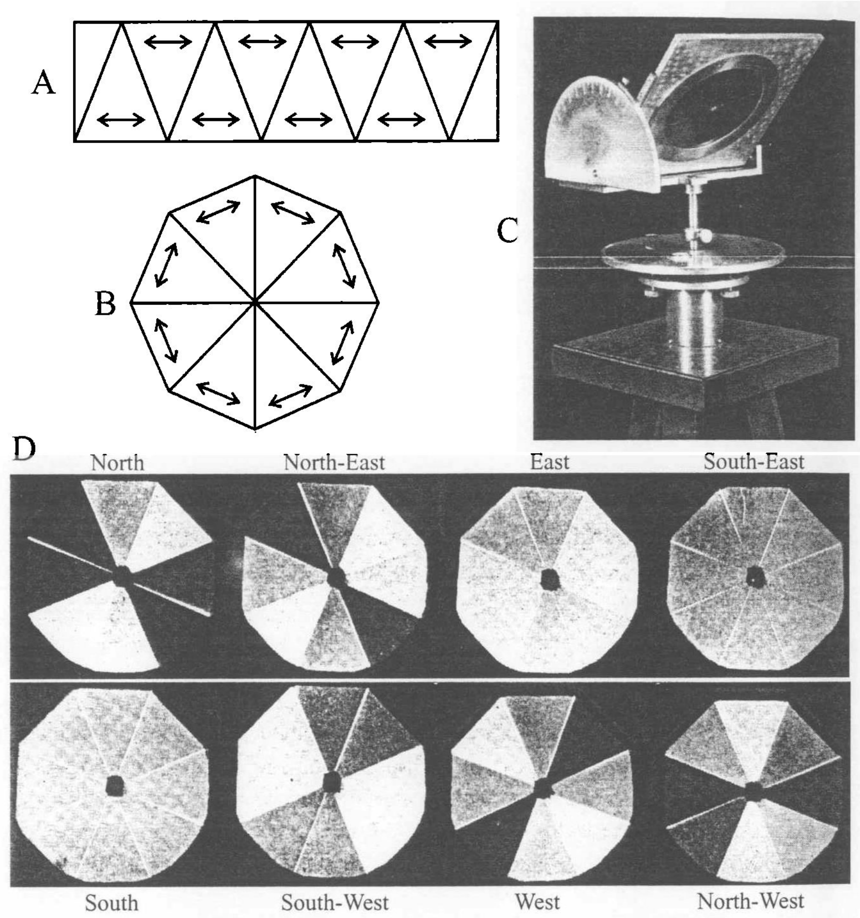


Fig. 1.3. **A** Schematic drawing of a sheet of linearly polarizing filter with cut pattern to construct the "Sternfolie" ("star foil") used to demonstrate the gross distribution of linear polarization of skylight by Karl von Frisch (1953, 1967). The orientation of the transmission axis is shown by *double-headed 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).

1.2 Elements of the Stokes and Mueller Formalism of Polarization

Polarized light can be decomposed into two components vibrating coherently (that is, with a constant phase difference) and perpendicularly to each other. The state of polarization of transversal electromagnetic waves (e.g. light) is usually described by a four-element vector known as Stokes vector $\underline{S}$, first introduced by Stokes (1852) with the following components:

$$\underline{S} = (I, Q, U, V), \quad I = I_r + I_p = I_{45} + I_{135} = I_{rc} + I_{lc},$$
$$Q = I_r - I_p = I \cdot p \cdot \cos(2\varepsilon) \cdot \cos(2\alpha), \quad U = I_{45} - I_{135} = I \cdot p \cdot \cos(2\varepsilon) \cdot \sin(2\alpha),$$
$$V = I_{rc} - I_{lc} = I \cdot p \cdot \sin(2\varepsilon) \tag{1.1}$$

where I is the total intensity of light, I_r and I_p are the intensities of the light components polarized totally linearly in a reference plane and perpendicularly to it, I_{45} and I_{135} are the intensities of the components polarized totally linearly in planes 45 and 135° to the reference plane, I_{rc} and I_{lc} are the intensities of the components polarized circularly right- and left-handed, p is the degree of linear polarization, ε is the ellipticity of polarization, and α is the angle of polarization, which is the angle of the direction of oscillation from a given plane. Q quantifies the fraction of linear polarization parallel to the reference plane, U gives the proportion of linear polarization at 45° with respect to the reference plane, and V quantifies the fraction of right-handed circular polarization. The degree of polarization P, the degree of linear polarization p, the angle of polarization α and the ellipticity ε can be expressed by the components of the Stokes vector as follows (Shurcliff 1962):

$$P = (Q^2 + U^2 + V^2)^{1/2}/I, \quad p = (Q^2 + U^2)^{1/2}/I, \quad 0 \le P, p \le 1,$$
$$\alpha = 0.5 \cdot \arctan(U/Q), \quad \varepsilon = 0.5 \cdot \arcsin[V/(Q^2+U^2+V^2)^{1/2}]. \tag{1.2}$$

A change in the state of polarization of light produced by an optical system, i.e. a transformation of the Stokes vector $\underline{S}_0 = (I_0, Q_0, U_0, V_0)$ of the incident light into a new Stokes vector $\underline{S} = (I, Q, U, V)$ by an optical process (e.g. reflection, refraction, scattering, diffraction, birefringence, optical activity) can be expressed as a linear transformation in a four-dimensional space:

$$\underline{S} = M \cdot \underline{S}_0, \tag{1.3}$$

where M is a four-by-four matrix called "Mueller matrix" with real elements M_{ij} (i,j=0,1,2,3) containing information on all polarizational properties of light. The 16 elements of the Mueller matrix of a given optical system can be obtained by 16 measurements with independent combinations of states of

polarization (degrees and angles of linear and circular polarization) of the incident light.

1.3 Polarimetry of Circularly Unpolarized Light by Means of Intensity Detectors

Light in the natural optical environment is usually not circularly polarized. The few known exceptions are listed and discussed in Chap. 15. Skylight polarization, for instance, is predominantly linear and the component of circular polarization of skylight can be neglected (Hannemann and Raschke 1974). Thus, the contribution of the Stokes parameter V characterizing circular polarization to the total intensity is negligible in comparison with that of the linearly polarized component. The remaining Stokes vector components I, Q and U can be determined from three intensity measurements, using a rotating linear polarizer in front of a radiometer, for instance. If these three measurements occur at angles of orientation β = 0, 60 and 120° of the transmission axis of a perfect polarizer (with t = 1 and τ = 0, where t and τ are the transmittances of the polarizer along the transmission axis and perpendicularly to it), for example, and the state of polarization of light is not changed by other components of the polarimeter, then the transmitted intensities I are (Prosch *et al.* 1983):

$$I(\beta=0°) \equiv I_0 = I_i \cdot [1 + p \cdot \cos(2\alpha)]/2,$$
$$I(\beta=60°) \equiv I_{60} = I_i \cdot [1 - 0.5 \cdot p \cdot \cos(2\alpha) + 0.5 \cdot p \cdot 3^{1/2} \cdot \sin(2\alpha)]/2,$$
$$I(\beta=120°) \equiv I_{120} = I_i \cdot [1 - 0.5 \cdot p \cdot \cos(2\alpha) - 0.5 \cdot p \cdot 3^{1/2} \cdot \sin(2\alpha)]/2, \tag{1.4}$$

where I_i is the intensity of incident light. The components Q_i and U_i of the incident Stokes vector are:

$$Q_i = 2(2I_0 - I_{60} - I_{120})/3, \quad U_i = -2(I_{120} - I_{60}) \cdot 3^{-1/2}. \tag{1.5}$$

Finally, the intensity I_i, degree of linear polarization p and angle of polarization α of incident light can be calculated as follows:

$$I_i = 2(I_0 + I_{60} + I_{120})/3, \quad p = (Q_i^2+U_i^2)^{1/2}/I_i, \quad \alpha = 0.5 \cdot \arctan(U_i/Q_i). \tag{1.6}$$

1.4 Point-Source, Scanning and Imaging Polarimetry

The major aim of polarimetry is to measure the four components *I*, *Q*, *U* and *V* of the Stokes vector $\underline{S}$, from which further quantities of the incident light can be derived, according to Eqn (1.2). These measurements can be done either by a point-source polarimeter or by an imaging one. The only principal difference between them is that the former performs measurements in a given direction representing a very narrow field of view within which the optical variables *I*, *Q*, *U* and *V* are averaged, while the latter measures the polarization simultaneously in many directions in a wide field of view (→ colour Fig. 1.4). A further development of the latter technique is the stereo video polarimetry (Mizera *et al.* 2001) which visualizes the polarization patterns in three dimensions (→ colour Fig. 1.5). There is an intermediate technique, the scanning point-source polarimetry between these two extremities. Such a polarimeter scans a given area of the optical environment and measures sequentially the polarization in many directions. However, scanning a greater area of the optical environment with a point-source polarimeter is a troublesome and time-consuming task. Using imaging polarimetry, the spatial distribution of polarization can be easily and quickly determined.

1.5 Sequential and Simultaneous Polarimetry

If the (at least necessary) three intensity measurements with different orientations of the transmission axis of the polarizer are performed one after the other, we speak about "sequential polarimetry". When all these measurements happen at the same time, it is called "simultaneous polarimetry". For the latter at least three separate polarimeters are needed. The advantage of simultaneous polarimetry is that temporally changing radiation fields (e.g. light from cloudy skies with rapidly moving clouds, or skylight after sunset or prior to sunrise, or measurements from a moving platform) can also be measured with it, if the time needed is not longer than the characteristic period during which considerable changes occur in the radiation field. Its disadvantage is that at least three polarimeters have to be handled simultaneously, which is not a simple task. Furthermore, such a group of polarimeters is heavy, voluminous, its setting up, dismounting and transferring is difficult and time-consuming. These disadvantages frequently make the use of simultaneous polarimetry in the field impossible. The disadvantage of sequential polarimetry is that temporally changing radiation fields cannot be measured with it. Its advantage is that only one polarimeter has to be handled, the setting up, dismounting and transferring of which is much easier and quicker.

1.6 Colour Coding and Visualization of Polarization Patterns

On the basis of the functional similarity between polarization vision and colour vision, Bernard and Wehner (1977) suggested a hue-saturation-brightness visualization method for partially linearly polarized light. This "composite visualization" scheme was used by Wolff and collaborators (e.g. Wolff 1993; Shashar *et al.* 1995a), for example, who coded the angle of polarization α, degree of linear polarization p and intensity I of partially linearly polarized light by the hue, saturation and brightness, respectively. In their polarization maps, unpolarized light appears achromatic, strongly polarized regions show up chromatically saturated, and the intensity of light is the brightness regardless of colour. The advantage of this visualization lies in its compactness: it displays the distribution of all three optical parameters (I, p, α) in a single, false-coloured picture. The disadvantage of this coding is that it is difficult to decompose, since in a complex false-coloured picture it is not easy to separate and decode the values of I, p and α from each other. Changes in hue (coding α) appear to the human visual system more strikingly than changes in saturation (coding p). Furthermore, the perception of the hue-saturation-brightness scale is very non-linear (Shashar *et al.* 1995a).

These problems do not occur if the distributions of I, p and α are displayed in three separate patterns with arbitrary unambiguous colour coding (→ colour Figs. 1.4 and 1.5). This "separate visualization" of the I-, p- and α-patterns is preferred by Horváth and collaborators (e.g. Horváth and Varjú 1997; Horváth and Wehner 1999; Gál *et al.* 2001c; Pomozi *et al.* 2001b; Bernáth *et al.* 2002, Barta *et al.* 2003), for instance.

Other authors (e.g. Dürst 1982; Sivaraman *et al.* 1984) display the I-, p- or α-patterns measured by imaging polarimetry in the form of the conventional contour plots used frequently in the cartography, for example. Although this "contour plot visualization" is the most traditional, it can hardly reproduce the image feature of the spatial distribution of polarization, which is the most important characteristic of the visualization of data gained by imaging polarimetry.

1.7 Field of View of Imaging Polarimetry

The field of view of an imaging polarimeter is limited by that of the imaging optics used. In the case of common photographic and video cameras, the field of view of the lens system is about 30–50° (horizontal) × 20–40° (vertical) depending on the focal length and the aperture (→ colour Figs. 1.1, 1.4 and 1.5). This common field of view can be extended e.g. by decreasing the focal length. A fisheye lens with 8 mm focal length mounted onto a normal photographic camera is an extremum, ensuring a hemispherical field of view with