Measuring polarization with ISIS

Users' manual

Jaap Tinbergen, René Rutten

October 7, 1997

Contents

List of Figures

1 Introduction

The ISIS triple spectrograph, at the Cassegrain focus of the 4.2 m. William Herschel Telescope of the Observatorio del Roque de Los Muchachos, came into operation as a common-user instrument in the autumn of 1989. Although the basic spectrograph was finished, a number of additional features were still being developed. One of these features is the option to convert the spectrograph into a spectropolarimeter, capable of measuring linear and circular polarization. The polarimetric capability became available for testing in the spring of 1990, and as a common-user option (for linear polarization) by the end of that year. We have gained experience doing spectropolarimetry with ISIS during commissioning tests and during scheduled observing. The tests show that the system is performing well, and common users find that spectropolarimetry with ISIS is hardly more complicated than standard spectroscopy.

This is the first version of the polarimetry manual for common users of the WHT/ISIS/FOS/CCD system and an introduction to the different classes of polarimetric observations that are possible with that system. Both it and the observational resources on La Palma will continue to evolve. For details of the current state of affairs consult any of the persons listed in Appendix J.

Section 2 of this manual contains a short introduction to polarimetric techniques and a schematic description of the ISIS polarimetry unit. Section 3 describes standard (linear) spectropolarimetric measurement and is intended as a common-user guide, sufficient for most observers. Section 4 deals specifically with circular polarimetry. Section 5 is intended for specialists whose astronomical application requires some non-standard mode of operation. Appendices provide information on the optical components, results from the commissioning tests and lists of standard stars, references, contact persons, etc.

Array-detector polarimetry is a relatively new technique and we request feedback from the observers to improve the system. Please communicate your experience to any of those in the list of Appendix J.

We thank Dave Clarke, Dave Axon and Jim Hough for their contributions to this manual, during the commissioning and/or proof-reading stages.

2 Overview

2.1 Modern polarimetry

"Classical" polarimetry consists mainly of 2 classes: photographic imaging polarimetry of low precision (1 %) and modulator/photomultiplier polarimetry, capable of very high precision (better than 0.01 %). Both types of polarimetry have astrophysically relevant applications and there is a continuum of potential applications between these extremes, notably the fairly unexplored technique of spectropolarimetry with good resolution and nominally 0.1 % precision, to which the ISIS system is eminently suited. Because of the number of photons required, relatively little precision polarimetry exists, and what there is, is generally broadband. Array detectors can make an enormous impact on polarimetric practice, if they can be made to work at sufficiently high precision. The WHT, with several instruments in fully computerised systems, can make a very significant polarimetric contribution in many astrophysical areas. ISIS spectropolarimetry is now in operation, FOS has been tried and should serve well, while TAURUS and UES will follow in due course. For polarimetry, all 3 instruments will use CCD detectors, since IPCS has a maximum count rate which is crippling for polarimetry of even moderate precision.

The photographic imaging polarimeters have developed into electronographic and CCD equivalents which are very successful for relatively faint, highly polarized objects. The modulator/PMT polarimeters are found in many varieties, but are limited to only a few simultaneous channels. A very important achievement would be to devise a modulator/array-detector equivalent; rapid-readout CCDs may be the answer in the near future, but that time has not come yet. Of the LPO instruments, Peoples Photometer and Multi Purpose Fotometer have polarimetric facilities using modulators and are fully described in their User Manuals. See also Fig. 1.

The essential feature of modulator polarimeters is that they, in one way or another, allow measurement of the 2 orthogonally-polarized intensities with one and the same detector within a very short time interval, shorter than any of the time constants of system sensitivity variations; "system" here includes atmosphere, telescope, instrument optics and detector. Since detector gain is in general a function of

Figure 1: A polarization modulator.

polarization, one must stabilize the polarization of the light striking the detector; this is why the last element of a polarization modulator is always a polarizer (generally a linear polarizer; it is referred to as the "analyser"). To make the detector see, in light of *constant* polarization, alternately one and the other orthogonal vibration of the light *incident* on the polarimeter, waveplates of various kinds are used. Rotation or periodic modification of the retardation of such a waveplate converts incident polarization in a time-varying manner; the analyser converts this into an intensity modulation. Since only linear polarizers exist as single components, it is convenient if the polarization emerging from the modulating element is linear, rotating. Modulators for circular polarization therefore tend to employ quarterwave plates, those for linear polarization halfwave plates. The required modulation rate is dictated by the time constants of the gain variations, those of the atmosphere as seen by the telescope generally being the most important. For a 4-metre telescope, about 10 Hz is expected to be sufficient for all but the very highest precision. When a 2-beam analyser is used, atmospheric noise can be eliminated by a ratio measurement, the modulation speed becomes irrelevant and only discrete states of the modulator are needed; the modulator then becomes a polarization-switching device. For reliable measurements at the very highest accuracy, modulation *and* a 2-beam analyser are usually incorporated into a single instrument, both techniques contributing to the robustness of the instrument.

Since the modulator and analyser convert the incident polarization into an intensity modulation of light of constant polarization, the particular state of polarization at the detector is no longer of interest. See Fig. 2. The polarization effects of gratings, a well-known scourge of precision spectro*photometry*, are irrelevant in a modulation spectro*polarimeter*; they cause a wavelength dependence of system gain (different for the 2 orthogonally polarized spectra), which is of no interest, unless one also wishes to use the same data for spectrophotometry, in which case such phenomena as Wood's anomalies might become important.

This completes the thumbnail sketch of astronomical polarimetry. For more detail consult the references in Appendix I.

Figure 2: ISIS polarimeter schematic, with representative beam cross-sections and polarization ellipses.

2.2 Spectropolarimetry with ISIS

The following components comprise the ISIS/FOS polarization system, in the order the light traverses them (Fig. 3):

- Quarterwave plate (at present borrowed from the People's Photometer), effective over the wavelength range 300-1100 nm, which can be inserted/retracted and set to any position angle or rotated continuously at a speed of several Hz. The quarterwave plate converts circular into linear polarization, so that the calcite plate (linear beamsplitting polarizer) can detect its presence; rotating the quarterwave plate rotates the linear polarization striking the calcite plate.

- Halfwave plate, 40 mm diameter, mounted similarly to the quarterwave plate. Rotating the halfwave plate through n degrees results in a rotation of $2n$ degrees of the polarization vector of the light. Figure 4 shows an approximation to its polarimetric performance.

  NB The quarterwave and halfwave plates can be interchanged, to optimise a particular application; ISIS needs to come off the telescope for the interchange operation. With the present plates, halfwave last gives the best slit view and largest field for linear polarimetry, hence is recommended for general use.

- Standard ISIS slit unit with polarization Dekkers mounted. Comb-type Dekker masks are employed to avoid overlap between the two sets of spectra produced by the calcite slab analyser (see below).

- Choice of analyser:

  (i) calcite slab, 2 beams, 330-1100nm. (actually, a Savart plate, which equalizes focus for both polarizations and reduces polarization anomalies within ISIS). The calcite is located immediately below the slit and gives two beams which are both 100 % polarized, but orthogonally; the o- and e-beam. The relative intensity of these beams depends on the polarization vector (size and orientation) of the incoming beam.
  (ii) Polaroid (HNP'B; 300-800 nm approx.), for occasions when full spatial detail is mandatory, without interruptions by the Dekker structure.

- Standard ISIS/FOS.

- Standard CCDs, and Data Memory System.

- Polarimetric (as opposed to photometric) reduction of the spectra.

It is instructive to regard the ISIS system as a modulation polarimeter with a double-beam analyser (the calcite plate) and a rotating halfwave plate modulator. Since it takes many seconds to read out a CCD frame, the modulation frequency in a CCD polarimeter is necessarily a small fraction of a Hz. With such slow modulation, the polarization-derived sine modulation in a single spectrum is contaminated by extinction variations, scintillation, image motion and other seeing variations. Under such circumstances one needs the second spectrum (orthogonal polarization), in which all such extraneous noise is in-phase with the first, while the effects due to the polarization of the light source are inverted. Dividing one spectrum by the other removes the extraneous noise, but introduces pixel sensitivity noise, which must be removed by special flat-fielding, or by relating 2 exposures for which the polarization is equal and opposite, while the pixel sensitivities involved are the same.

A set of 4 exposures through a beamsplitting analyser, with 4 different position angles of the wave plate (for details, see Section 3), in fact contain enough information to determine the fractional amplitude of the sine modulation (degree of polarization) and its phase (polarization angle). These 4 exposures allow calibration of the instrumental gain, and render the polarization measurement independent of sky transparency and scintillation. This is the basis of the standard method recommended in the next section. Measurements carried out with ISIS show that a precision of 0.1 % is feasible. This implies that relative pixel sensitivities remain constant to that extent over at least the time taken to complete a full observation. This unique combination of stability, simultaneous recording of many image points and re-usability of the same detector makes CCDs ideal for a great variety of astronomical polarimetry.

Figure 3: ISIS polarization modulator and slit area.

Figure 4: Theoretical performance of superachromat halfwave. Actual as-made properties of ISIS superachromat can be measured in situ.

3 A standard recipe for linear polarimetry

3.1 Instrumental setup

The modulation principle described in the previous section boils down to a sequence of 4 exposures, differing only in the position angle of the halfwave plate, each exposure yielding two spectra on the detector. Since in the mode of observation described in this section the modulation is of a (very) slow kind we shall refer to it as the *staring mode*. A more complicated observing scheme, in more truly modulating mode, is described in Section 5 and is for special cases only.

Large CCDs should be in operation in both arms of ISIS. After setting up the spectrograph and acquiring the object, one only needs to move the halfwave plate into the beam at a specific angle, move the calcite slab into the beam, correct telescope and spectrograph focus and select the appropriate Dekker mask. At present, only one Dekker mask is available for spectropolarimetry; see Fig. 11. Special masks can be produced; see Appendix B).

For point sources a Dekker with three apertures, one for the source and two for the sky, could be used. In this setup the chip may be windowed to reduce the time taken by readout and data transfer. For extended sources a comb dekker with $4''.5$ apertures is available (Dekkers 4 and 5), covering a $2.6'$ field in 9 apertures. The currently available comb Dekker has a duty ratio of 1/4 and hence observation of the full slit requires 4 complete polarization measurements with the telescope at offset positions along the slit to allow different parts of the slit to be observed.

Note that the calcite slab affects the spectrograph focus; this is corrected by adding 9200 units to the standard collimator positions.

The slit-view TV camera looks through the halfwave plate, which also affects the TV focus. The optimal TV focus (at scale 5) is about 1500 units less than the standard setting without the halfwave plate. If your object is faint it will be necessary to remove the halfwave plates and the Dekker in order to put the object on the slit.

A standard sequence of exposures is:

exposure 1 with halfwave plate at 0.0 degrees
exposure 2 with halfwave plate at 45.0 degrees
exposure 3 with halfwave plate at 22.5 degrees
exposure 4 with halfwave plate at 67.5 degrees

Exposures 1 and 2 yield Stokes Q, and exposures 3 and 4 Stokes U. Q and U, hence also the polarization angle, are defined relative to some instrumental coordinate system. The orientation of this instrumental reference system relative to the N-S meridian must be defined *and recorded*. It is convenient to keep the orientation of the instrument fixed relative to the sky (set Cassegrain rotator tracking), but equally it is important to keep the relative orientations of the telescope and ISIS constant (this will mean there is only one global system to calibrate for polarization zero-point). Our compromise recommendation is to track in angle during the entire observation, but to aim at having the slit vertical halfway through the observation. Fig. 5 can help you to plan this; in future it may be an on-line facility. Be sure to record the position angle of the halfwave plate (for each exposure) and of the Cassegrain rotator, and to understand the exact definitions.

Experiments with the dichroic beamsplitter in position showed reflected light from the rear of this component. Such light is displaced along the slit, partly into the spectrum of the other polarization; this spoils the polarimetry, so for the time being we must, reluctantly, advise against use of the dichroic (i.e. against *simultaneous* use of the ISIS red and blue arms; the blue folds – prism or mirror – are OK, you *can* alternate between red and blue in one run).

3.2 How to derive the Stokes parameters

The staring mode uses the calcite plate, which yields 2 spectra (of opposite polarization). The polarization information (one Stokes parameter per exposure) is contained in the ratio, at each wavelength, of the intensities in the 2 spectra but it is mixed up with the system gain ratio for the pixels concerned. The effect of the unknown gain is eliminated by inverting the sign of the polarization effects in a second exposure,

Figure 5: Planning aid to set slit vertical at mid-exposure; courtesy Robert Laing. The curve labels are declination values.

while leaving the gain ratios identical. Inversion of (linear) polarization effects and therefore of the Stokes parameters is accomplished by rotating the halfwave plate by 45 degrees; while the polarization effects are inverted, the system gains remain the same since these are determined by the built-in polarization of the o and e exit beams of the calcite plate. All instrumental conditions (grating parameters, filters, dichroics, Dekker, slit etc) must be the same in both exposures; image centering on the slit is the most difficult to control in this respect.

The derivation of Stokes parameters from the recorded spectra is presented below. We factorise the conversion 'constant' for input flux to detector signal into a polarization-dependent, time-independent part G and a time-dependent, polarization-independent part F:

$G_{\|}$ and $G_{\perp}$ refer to the o and e-spectra on a single frame; they include grating efficiencies and reflection coefficients of mirrors, and the sensitivity of the pixel considered to the polarized light striking it.
F_0 and F_{45} refer to the two separate frames (halfwave at 0 and 45 degrees) and include atmospheric transmission, seeing, image wander and variations in shutter timing.
I and Q refer to total and polarized flux input and the i refer to signals recorded by the detector.
$P_Q = Q/I$ is the Q-component of the degree of polarization.

In this notation, we obtain:

$$\begin{array}{lcllcllcl} i_{0,\|} & = & \frac{1}{2}(I+Q) & \cdot & G_{\|} & \cdot & F_0 \\ i_{0,\perp} & = & \frac{1}{2}(I-Q) & \cdot & G_{\perp} & \cdot & F_0 \\ \\ i_{45,\|} & = & \frac{1}{2}(I-Q) & \cdot & G_{\|} & \cdot & F_{45} \\ i_{45,\perp} & = & \frac{1}{2}(I+Q) & \cdot & G_{\perp} & \cdot & F_{45} \end{array}$$

To derive Stokes parameters from these spectra, first divide the o and e ray spectra in each frame to take out the scaling factors F. Dividing these ratios again cancels the G factors. The Q Stokes parameter, in degree-of-polarization scale, is:

$$P_Q = \frac{R-1}{R+1} \qquad \text{with} \qquad R^2 = \frac{i_{0,\|}/i_{0,\perp}}{i_{45,\|}/i_{45,\perp}}$$

Note that by multiplying the intermediate ratios, instead of dividing them, the G ratio (relative flat field) is obtained.

The other Stokes parameter, P_U, is obtained similarly from the pair of exposures with the halfwave plate at 22.5 and 67.5 degrees. The raw degree of polarization P and polarization angle θ, are then given by:

$$P = \sqrt{P_Q^2 + P_U^2} \qquad \text{and} \qquad \theta = 0.5 \arctan\left(P_U/P_Q\right)$$

Note that this schematic procedure neglects CCD bias, sky background and calibration for instrumental parameters. Bias may be subtracted from the data frames as a first step or be treated as part of the sky background; sky subtraction and calibration are treated in separate subsections below.

3.3 Sky subtraction

For faint objects sky polarization must be corrected for. Sky polarization can reach very high values compared to that of astronomical objects, so sky correction becomes important at brighter magnitudes than one may be used to from photometry.

The desired quantity is $P_{Q_\star}$ (and $P_{U_\star}$), the true degree of polarization of the light of the object. We express this in terms of the observables.

$$P_{Q_\star} = \frac{Q_\star}{I_\star} = \frac{Q_{obs} - Q_{sky}}{I_{obs} - I_{sky}} = \frac{I_{obs}}{I_{obs} - I_{sky}} \cdot \left(\frac{Q_{obs}}{I_{obs}} - \frac{Q_{sky}}{I_{sky}} \cdot \frac{I_{sky}}{I_{obs}} \right) \qquad [A]$$

$$\approx 1 \cdot \left(P_{Q_{obs}} - P_{Q_{sky}} \cdot \frac{i_{sky}}{i_{obs}} \right) \qquad [B]$$

where

Q = polarized flux (Q component), corrected for pixel gains etc.

$Q_\star$: star only

$Q_{\rm sky}$: sky aperture

$Q_{\rm obs}$: star aperture (star + sky)

I = total flux, corrected for pixel gains etc. $I_\star, I_{\rm sky}, I_{\rm obs}$ as above

P_Q = degree of polarization (Q component). $P_{Q_\star}, P_{Q_{\rm sky}}, P_{Q_{\rm obs}}$ as above

i = recorded intensity (= CCD pixel gain $\cdot$ I)

$i_{\rm sky}$: sky aperture

$i_{\rm obs}$: star aperture

Equation A is exact, while B contains 2 implicit approximations:

- $I_\star \gg I_{\rm sky}$, hence $I_{\rm obs}/(I_{\rm obs} - I_{\rm sky}) \approx 1$
- CCD pixel sensitivity is constant over the entire frame. Then $I = c \cdot i$, c being a function of wavelength only.

For a great deal of work, B will suffice. It does *not* require *any* flat-fielding, the spectra from the star and sky apertures can be reduced in the same way, with a final small correction depending only on the *recorded* intensities of star and sky spectra. Furthermore, for bright stars and/or dark sky, the entire correction is negligible.

When approximation B is not good enough (this is a question of scientific requirements), one uses A and will need to know *true* (but relative) star and sky fluxes, $I_{\rm obs}$ and $I_{\rm sky}$. For this one needs (relative) sensitivities (i.e. "system gain" including such things as grating used, its wavelength setting, any vignetting in the optical system) for the pixels recording the spectra (o and e-ray separately) from star and sky apertures. The best way to obtain these is to expose an *unpolarized* flat field through the polarimetric system. The best flat field is blue sky (necessarily with an ND filter, which may somewhat compromise the flatness; a filter far from the focal plane is best). To depolarize this flat field, use the halfwave plate in a continuously rotating mode, making sure there are many cycles within the exposure time. To transfer a blue-sky flat field to night-time observations, one could use a tungsten lamp (which probably does not produce a very flat field, since the specification was very slack), relying on constancy of the *pattern* of illumination by the lamp. Note that choice and setting of the grating - and any auxiliary anti-scattering filters - should be the same for programme and flat-field exposures. If one trusts CCD constancy more than constancy of the lamp illumination pattern, the lamp exposures are omitted.

Note that the sky region may be affected by scattered light from your object (Fig 6). One could take a second set of frames exposed on nearby clear sky to avoid confusion with scattered light from the object. Processing similar to that for the object spectra will yield the degree of polarization for the sky signal. Alternatively, one could take the sky regions symmetrically on either side of the object. This to first order eliminates the influence of scattered light from the determination of sky *polarized* flux; the *total* sky flux also contains a scattered component, to be removed in some other way (such as scattered-light modeling). For more detail on problems of scattered light, see Section 3.5.

To check on whatever method of sky subtraction one uses, take a few sky frames *exactly* as one takes star frames. Use the "stellar" spectrum in these frames to correct for sky in the observations proper.
NB. There seems to be no way to determine how the extinction varied between the 2 frames, one just waits for seemingly photometric conditions and keeps one's fingers crossed.

When only one sky aperture is available, a good approach to reducing errors is to take a second complete set of exposures, this time with the star in the "sky" aperture. As long as the errors involved are small, they should largely cancel in the average of the 2 sets.

3.4 Flat fields

As explained in the previous section on sky subtraction, flat field information is not required in staring mode when the correction for sky polarization need not be extremely accurate and an average instrumental gain correction suffices. In most applications this will be the case.

Figure 6: Scattered light causing false sky polarization. See text.

Flat-field information is needed in at least 2 applications. The most common is when one does not want to assume constant gain in correcting for sky polarization obtained from a different set of pixels than was used for the star. The other is in compressing a spectrum of finite width into a 1-dimensional array of numbers. The *average* gain of a row of pixels drops out in the course of polarimetric reduction, but if the star image did not expose exactly the same pixels in the 2 exposures for the 2 halfwave plate positions (e.g. no autoguiding), "average" does not refer to the same collection of pixels and one should refer the recorded intensities to one and the same standard pixel in both exposures. It is therefore advisable *always* to take flat fields, with the rotating halfwave plate in the beam.

Something to remember is **not to change any sensitivity parameters** of the system between programme exposure and calibration. This applies particularly to gratings, grating settings, and filters. The CCD frame contains a set of monochromatic images of the slit, for a range of wavelengths. Each monochromatic slit image in the CCD frame is a separate entity. Spectro*photometry* tries to relate the intensities in separate slit images to each other, but spectro*polarimetry* does not bother; we are only determining the state of polarization at each wavelength separately (by a proper observing schedule including standard stars one could use the same frame for spectrophotometry, but that does not concern us here). So the term "flat field" in the present context relates only to the relative system gains along a monochromatic image of the strip of sky isolated by the slit. As long as the grating remains put, pixel is synonymous with wavelength. When the relation is disturbed by moving the grating, we must realise that we are aiming to calibrate the *pixel* system gain, for light of a certain *wavelength*; since "system gain" includes the spectrograph optics, it will not always be true to say that a pixel calibration at one wavelength will be correct for a neighbouring wavelength; likewise, as long as CCDs are not very nearly uniform, a calibration for a certain wavelength at one pixel location will not necessarily be correct for a neighbouring pixel at the same wavelength. For the best spectropolarimetry it is a must to flat-field (whether explicitly or implicitly) at *precisely* the same grating setting as for the programme exposure; if the proper flat field has not been obtained, it is probably best, for the foreseeable future, to use the data for corresponding pixels, even if the calibration is at a slightly different wavelength (just beware of Wood's anomalies, which could now show up as false polarization; see ING La Palma Technical Note no 76).

To obtain a genuinely unpolarized field, we employ the waveplates as depolarizers. Generally, only the halfwave is likely to be needed; it reverses any circular polarization that may be present, which will then be divided 50/50 by the calcite plate (as will unpolarized light). If you do wish to depolarize any circular polarization present, you could insert the quarterwave, behind the halfwave, rotating in the *opposite direction* at some other rate; focal-plane field is reduced in this case. Depolarization is only complete if the exposure contains an integral number of quarter-revolutions of the halfwave plate; it is safest to use exposure times long enough for any non-integral part of a revolution not to cause an unacceptable error: if flat-field source polarization = x %, desired error level y %, rotation rate z Hz, exposure time t seconds, then

$$t \approx x/(16 \cdot y \cdot z)$$

If one is only interested in flat-fielding the pixels one is using in programme observations, one uses the same Dekker. However, one could employ one of the comb-type Dekkers and flat-field a larger part of the CCD in one exposure; one just has to make sure that the comb Dekker includes the pixels of the Dekker one is interested in.

We have found that a convenient way to get a well-exposed flat-field frame quickly is to use blue sky when the Sun has an altitude of between 10 and 30 degrees. Experiment with slit width and ND filters to obtain a satisfactory signal level (close to CCD saturation). Since the rotating halfwave plate is a linear depolarizer, pre-slit filters are permitted even if they modify the polarization. We used exposures of 30 seconds or more, according to the formula above, the halfwave rotating at 1 Hz.

A completely different alternative would be to expose the entire CCD without any Dekker and with the halfwave out of the beam, but first through one of the A&G polaroid calibrators oriented to provide exactly the polarization of one of the 2 beams from the calcite plate, then through the other. Given a truly flat field of unpolarized illumination, this would yield 2 maps of the system gain, each for one polarization, both on the same scale. In practice one could probably obtain a truly flat field (see discussion above), but the light will be polarized to some extent (minor if one uses sky close to the Moon) and the scale for the 2 maps will not be the same. At any one wavelength, the relative intensities in each frame map the relative gains correctly; what is lacking is the relation between the 2 frames. This relation one may obtain by an exposure of the same field through the *rotating* halfwave plate, without the calibration polarizer, and with a comb-type Dekker; such an exposure yields relative system gains in 2 polarizations for the apertures in the comb Dekker. These data can be used to bring the 2 earlier single-polarization maps on to a common scale.

We stress that these procedures have not yet been tried extensively. Since much of what will be done with ISIS will not need explicit flat-fielding, such tests are not urgent. From the discussion it should be clear in which direction to experiment.

3.5 Scattered light

Light scattering within the spectrograph causes unwanted exchange of light between the o and e beams. This results in loss of contrast between the beams (i.e. scale error in degree of polarization) which must be corrected. As discussed in the section on sky subtraction, scattered light from the object also affects the light level in the adjacent sky apertures and the apparent sky polarization will be wrong.

Both sky and lamps flood the entire slit area and there could be excess scattered light (bypassing the slit area components), as a diffuse background overlying the whole frame, a stellar image causing less of such diffuse scattered light. This could upset the determination of pixel sensitivities. Our preliminary impression is that such diffuse scattering, though present, is negligible.

To measure cross talk between the o and e spectra for your specific instrumental setup, observe a star through a calibration polarizer with the halfwave plate set to such an angle that (almost) all the light gets into only one of the beams. The light detected between spectra must be due to scattered light from the illuminated parts of the slit and can be used to estimate the crosstalk level from one spectrum to another. Tests of this kind during commissioning showed a few tenths of a percent of the light in one beam was scattered into the adjacent beam (depending on wavelength).

It should be noted that scattered light from other parts of the spectra (other wavelengths) can have consequences, particularly if $P(\lambda)$ is structured.

Optimal solutions of the scattered-light problem will involve modeling ISIS' scattering properties (which will change with time and depend on incident spectrum and spectrograph settings). In due course, we shall be able to give more useful advice, at present the best we can do is alert you to the

Figure 7: Linear polarization as a vector quantity. In each case, the complete circle denotes the rms error, the circular arcs are loci of constant degree of polarization. See text.

problem. In many cases, the solutions suggested in this section and that on sky subtraction will suffice. Refer to Appendix C for more detail; as we gain experience, that appendix will evolve.

Recapitulating, for *point source* observations the following applies:

- Apparent modulation efficiency (degree-of-polarization scale) is reduced by scattered light. By observing a star (preferably your object itself, because that keeps the scattering from nearby other wavelengths roughly the same) through a calibration polarizer, all such reductions are estimated in one go and global correction for the sum total will usually suffice. If not, model scattered light intelligently first, then use the corrected calibration polarizer results to determine the true polarimetric modulation efficiency.

- Sky polarized and total flux are affected by scattered light from the much brighter star. An average of 2 symmetrically-placed sky spectra will eliminate the scattered-light component from the polarized flux; for the total flux, model the scattered-light component and subtract. See Fig. 6.

3.6 Calibration of linear polarimetry

After correction for scattered light and sky contribution (which can be done more or less without reference to other observations), the data consist of a raw measure of the (vector) polarization of the object itself, added to an instrumental zeropoint (vector) and in a Stokes parameter system with indeterminate scale (degree of polarization) and orientation (polarization angle). These quantities are all potentially wavelength-dependent and must be calibrated by observations of 'standards' of one kind or another *with the instrument set up exactly as for your programme.*

Which of the above properties is the most important in practice will be determined by the ratio of object polarization to instrumental zeropoint. Fig. 7a shows the general case. Note that while, for sufficient photons, P_Q and P_U are normally distributed, P and 2θ are not. In averaging equivalent observations, therefore, we should average P_Q, P_U and compute 'average' P and 2θ from them. For cases such as in Fig. 7b, exact knowledge of the zeropoint is most important, for Fig. 7c scale and orientation are much more significant uncertainties. Your scientific aims can be translated into required accuracy for each of these quantities. Depending on the required accuracies, calibration may be simple and straightforward or exceedingly complex and subtle. General guide lines are given for each quantity in turn; it is up to you to devise a satisfactory procedure for your particular problem.

Having elected to use *spectro*polarimetry as your preferred scientific method, it is likely that you will be able to do at least part of your calibration in a spectrally differential way. When using 'standard stars', be aware of the difference between classical polarimetry and what you are attempting. Certified standards for broadband work may not be suitable now; you need to devise your own consistency checks. You should also realise that, at levels below 0.1% and 1 degree, many stars have variable polarization (i.e. broadband, it may be worse spectrally). The dilemma is that bright polarized stars are generally distant supergiants with unstable atmospheres, but at the highest accuracy every star is in fact suspect (as are terrestrial sources; more so than stars, in fact).

3.6.1 Degree-of-polarization scale

Imperfections in the system result in a small loss of modulated (i.e. polarization) signal. A correction for this modulation inefficiency is obtained by measuring the polarization of any star through a polarizing filter (located in the A&G main filter slide). In restricted wavelength ranges the Polaroid polarization filters produce a 99.99 % polarized beam and any deviation from that must be attributed to system inefficiencies (or to errors in the correction for scattered light !).

Two types of Polaroid filter are (or will be) in use: a UV-type 99.99 % effective from 320 to 780 nm, and a visual type from about 420 to 810 nm. Check with your support astronomer which filters are available. For the full wavelength range there is a calcite plate but this only works for point sources and in good seeing (not fully tested); one would like to have a twin-tilted-plate polarizer to produce about 5 % polarization on unpolarized stars, but this is only in the preliminary planning stage. Whatever polarizer you use for calibration of modulation efficiency, use exactly the same ISIS configuration as for your observations and correct the polarization of programme objects for the inefficiencies. Fig. 8 shows the data for a laboratory superachromatic halfwave plate; the ISIS component is similar (though not identical).

3.6.2 Polarization angle

The effect of the halfwave plate on the polarization angle of the beam is a function of wavelength. This causes the instrumental frame for measuring the direction of polarization to exhibit dispersion. The necessary correction can again be obtained by measuring any star through the 100 % polarizer. The polarization angle obtained from such a polarized source should be independent of wavelength and any deviation from that situation is due to the halfwave plate. The inverse should be applied as a correction to the other observations; you may choose any wavelength as your reference at this point. Fig. 9 shows laboratory data of the ISIS halfwave, Fig. 12 a sample observation.

At this point, the data are defined relative to some instrumental reference frame (which may have changed since you last used the ISIS system; too many steps are involved, both hardware and software, to make an attempt at fixing the system once for all). You must therefore measure the polarization of

Figure 8: Actual performance of a halfwave plate similar to that of ISIS.

Figure 9: Wavelength-dependence of the apparent polarization angle. This is a direct consequence of specifying super-achromatism of the retardation; observations need to be corrected for this effect.

at least one polarization standard star to calibrate the instrumental zero-angle (also useful for verifying degree-of-polarization scale and reduction procedures). References to appropriate standard stars are given in Appendix H; see Bastien et al. for a recent report on variability of 'standards'.

To determine the polarization angle from scratch, several methods are available, not all equally convenient. One good possibility is to observe a low-albedo asteroid at a phase angle which yields appreciable polarization. For the polarization to have reasonable values, the phase angle of the asteroid needs to be in the range 10 to 20 degrees, or above 30 degrees. In the former case, the polarization vibration will be parallel to the Sun-Asteroid-Earth plane and in the latter case it will be normal to this scattering plane. Preparations for such observations must be done beforehand, so that the coordinates and the phase angle of the asteroid are known; careful tracking will be required.

Another promising method is to observe blue sky in the zenith (or close to the zenith at anti-solar azimuth if the zenith itself cannot be reached). By symmetry (but: waves on the sea, structure in cirrus clouds, how perfect is the symmetry?), any remaining linear polarization in the multiple scattering should on La Palma closely average out to zero, while the polarization angle of the singly-scattered component is determined by the Sun's azimuth. This method needs to be verified, but could be very convenient; together with flat fields, it could in future make up the afternoon run of the seasoned observer.

An old and tried method is due to Gehrels and Teska and is also described in Serkowski (p. 411); it involves reversing a Polaroid suspended in front of a horizontal telescope. Bring your own Polaroid and enquire in good time what it takes to make WHT observe horizontally. An alternative 'mechanical' method is described in Dolan & Tapia (see Appendix H on standard stars); for this method to be used operationally, the exact orientation of the polarization of the analyser beams will have to be determined with respect to the slit, after which drift of a star along the slit can be used for routine verification.

3.6.3 Instrumental polarization zeropoint

Measure the polarization of at least one zero-polarization star to establish the system polarization zero. Remember that both the telescope and the A&G + ISIS contribute to the zero-point polarization, so decide in advance how you are going to use the instrument rotator: keeping the slit and instrumental coordinate frame approximately (or even exactly) vertical during your observation, or alternatively with the instrument aligned with the equatorial system. In the latter case, for the telescope's contribution to instrumental polarization, you must allow for relative rotator angle when correcting other observations later. For short observations, the best solution is probably to set the slit just one side of vertical and to let it track during the complete observation, the median slit orientation being vertical (use Fig. 5 for planning this); your coordinate frame then has a fully defined relation to the astronomical frame, while the fact that telescope polarization rotates slightly in the course of the observation does not matter as long as it is small enough.

To 'depolarize' a zero-polarization star completely, observe it twice, with a difference of about 90 degrees in parallactic angle (Fig. 5). In the Alt-Az frame, the average of the two observations represents pure instrumental zeropoint (exercise for the reader, including the inherent assumptions). The converse holds for a representation in the equatorial coordinate frame: the average is purely the stellar polarization. A reference to zero-polarization stars is given in Appendix H. Remember the cautions about stability and spectral dependence of stellar polarization.

3.7 Reduction; some suggestions

Reducing the four frames, with two object spectra and two sky spectra each, to a polarization spectrum is a fairly simple matter. However, be aware of the fact that you are generally trying to obtain information on a small fraction of a large signal. The difficult steps will be sky subtraction and correction for scattered light. Experiment with your data to find the procedure which best suits your requirements.

Since polarimetric analysis uses relative photometry of two spectra (the o and e-ray), it is essential to avoid unintentional loss of photons along the way. You will probably collapse the spectrum of the o and e-ray in the spatial direction; make sure you get all the counts in your extracted spectra, even if the star moved or the seeing changed during your observation. If the boundaries of your collapsing operation coincide with strong gradients in the spatial direction (collapse region too narrow, but possibly of use for maximising object/sky contrast), you may find some false polarization, since the o an e images will not be sampled identically by the CCD pixel structure and this mismatch may vary from one exposure to another. However, such false polarization will not be a fast function of wavelength and may not matter in your application; if you cannot live with it, you must widen the collapse region or correct your data for individual pixel gains first, as discussed in the section on Flat Fields.

The basic reduction steps leading to the Q and U spectrum (i.e. cosmic ray removal, extraction of object and sky spectra, sky subtraction, dividing spectra as outlined in Section 3.2 and 3.3) can all be done within FIGARO. However, there are software packages which make data reduction and assessment of the results much easier and faster as well. These software packages handle 1-dimensional spectra and are therefore not appropiate for pixel-by-pixel analysis of the data. Firstly there is the STARLINK software package *Time Series Polarimetry* (TSP, by J. Bailey). Secondly there is a set of FIGARO-based routines available written by J. Walsh. We have gained experience with the latter package and found it very easy to use, easy to install and adapt if necessary. Both packages are available on the La Palma data-reduction VAX. Before using these packages make sure you understand and agree with the way Q, U, P and θ are derived and handled.

Slightly modified versions of the above Walsh routines have now been installed on the La Palma IRAF system and we consider this the most convenient of the on-site alternatives. A description will be issued as a La Palma Technical Note soon; in case of doubt, contact A410RGMR@HASARA11.

Note : an easy mistake to make is to average the degree of polarization P (e.g. co-adding polarization spectra or binning up a polarization spectrum). Remember that P is the modulus of a vector, and that adding moduli is not equivalent to true vector addition. Always use Stokes Q and U or P_Q and P_U to do arithmetic. Finally, re-compute P and θ.

3.8 Noise and statistics in polarimetry

3.8.1 Photon noise calculation

It is notoriously difficult to get the photon noise calculation right for polarimetry. We therefore include a reasoned example which we believe to be correct.

In the standard staring mode of measuring linear polarization, one Stokes parameter is derived from four spectra, recorded in two CCD images, for halfwave plate position angles differing by 45 degrees. Let $N_{0,\|}, N_{0,\perp}, N_{45,\|}, N_{45,\perp}$ be the number of photons detected per spectral resolution element in the o and e spectra for the two CCD exposures. The Stokes parameter, for example P_Q, is then given by the formula in Section 3.2.

When integration times for both exposures are the same and the level of polarization is small, $N_{0,\|} \sim N_{0,\perp} \sim N_{45,\|} \sim N_{45,\perp} \sim N_{total}/4$, where N_{total} is the total number of photons (per spectral resolution element) in the two exposures of the two spectra. In that case $R \sim 1$ and $Q \sim 0$.

Photon statistics gives an uncertainty of $\sqrt{N}$ for each of the N. The *fractional* error in each N is therefore $1/\sqrt{N}$. For multiplication and division, the *fractional* errors add in quadrature, hence the *fractional* error in R^2 is $2/\sqrt{N}$, the *fractional* error in R is $1/\sqrt{N} = 2/\sqrt{N_{total}}$. Since $R \sim 1$, the *absolute* error in $R-1$ is also $2/\sqrt{N_{total}}$. Since $R+1 \gg R-1$, the *fractional* error in P_Q is dominated by that in $R-1$, which is $2/(\sqrt{N_{total}} \cdot (R-1))$. Finally, this makes the *absolute* error in P_Q:

$$2/(\sqrt{N_{total}} \cdot (R+1)) \sim 1/\sqrt{N_{total}}.$$

For example, in order to determine one Stokes parameter to a degree-of-polarization accuracy of 0.005 (e.g. $P_Q = 2.5 \pm 0.5$ % or $P_U = 1.0 \pm 0.5$ % or $P_V = 0.1 \pm 0.5$ %), $4{\cdot}10^4$ photons per resolution element are required. To obtain both linear Stokes parameters with that accuracy, we need two such observations. With the present La Palma CCDs, maximum recorded output, which is close to saturation charge, is of order $6{\cdot}10^4$ electrons per pixel. It is advisable to stay somewhat below this in single exposures, and to average over pixels and/or repeated observations as necessary for the desired accuracy.

3.8.2 Statistics

A normalized Stokes parameter (P_Q etc) is 'the difference between 2 intensity values, divided by their sum' and, since this quotient comprises parameters which are not statistically independent, repeated measurements do not yield a Gaussian distribution. The non-normality becomes apparent at small numbers of detected photons, a situation one might easily encounter in CCD polarimetry. Other non-Gaussian distributions are sent to plague us, notably those of degree of polarization and polarization angle in situations of low signal to noise. Clarke and Stewart (reference in Appendix I) treat these questions in detail; careful interpretation of data is especially required in low signal-to-noise situations. Whether full statistical treatment is required as a result of non-normality can be judged from the following rules of thumb:

- When the number of detected photons per elementary detector (i.e. after on-chip binning, but before software binning) is less than about 1000, the distribution of the normalized Stokes parameters is noticeably skew and this must be allowed for in proper binning or averaging procedures.
- Degree of polarization is always positive. When P is less than about 5 times the standard error of the normalized Stokes parameters, straightforward averaging of P produces biased results.
- Confidence intervals, for estimates of P from a sample of observations, are asymmetric in the domain $P/\sigma < 5$.
- Although the determined values of polarization angle are unbiased, their symmetric distribution about the mean is kurtose and confidence intervals do not correspond to those for a normal distribution. Attention to this detail is only warranted in the domain $P/\sigma < 5$.
- When σ_{P_Q} is not equal to σ_{P_U} (as may be the case when the ISIS standard recipe is used under conditions of varying extinction or pressure of time near sunrise), σ_P and confidence intervals of degree and angle of polarization will depend on the relative values of P_Q and P_U (in other words on what the polarization angle happens to be).
- A prescription for a (statistically) maximally effective observing campaign is given by Clarke and Stewart in their last section; however, add your own considerations of what fraction of time to spend on calibration of zeropoint, angle and degree of polarization.

3.9 Nuggets and wrinkles

3.9.1 Daytime use of WHT

Flat fields and zenith calibration of polarization angle require the installation to be available to astronomers during the afternoon. Normal LP practice is for handover at 1600 hours, after a series of technical checks. This will have to be moved to about 1400 hours, which is possible but not trivial.

If your programme requires afternoon observing, be sure to make the arrangements well in advance (a month, nominally), as it may involve rescheduling staff. Your support astronomer is the person to ask; failing that, the LPO polarization expert (see appendix J).

3.9.2 Cosmic rays

Cosmic rays may give spurious results in the polarization spectrum. The four exposures normally taken contain some redundancy which you may use for a consistency check (e.g. by deriving the gain ratio or the total-flux spectrum routinely). If you spot a spike in your polarization or gain ratio spectrum which you do not trust, go back to the raw data and compare each of the 2 exposures taken at the halfwave plate angles differing by 45 degrees with the *average* of the 2 exposures taken for the other Stokes parameter (this average represents total flux). If the spike is due to spectral-line polarized light from your source, it should be present in both exposures, in opposite senses; it should also be at least as wide as the instrumental p.s.f.

Cosmic ray problems are not peculiar to polarimetry. The best source of superior cleansing algorithms will probably be the Hubble Space Telescope WFPC community.

3.9.3 Variable sources

A full polarization measurement takes four exposures. If the source is variable (in polarization) within the time it takes to complete one full polarization measurement, the results will come out wrong. If, however, the instrumental gain ratio $G_{\|}/G_{\perp}$ is known and stable in time (see Section 3.2), two exposures (with the halfwave plate at 0 and 22.5 degrees) are sufficient to derive the polarization vector. The gain ratio can be readily derived from a full polarization measurement (i.e. four settings of the halfwave plate) of a constant source. Tests have shown that this gain ratio (averaged over the full Dekker aperture) was stable to within 1 % during a night, except in the cutoff region of the dichroic. Do not expect the gain ratio to be the same after moving any of the optics, since the throughput of many of the optical components depends strongly on polarization and the beams within the spectrograph are highly polarized.

3.9.4 Dekker masks

The currently available Dekkers are not polished and aluminized, and very little light is reflected off the surface. To find your target, set the Dekker slide to a clear position, center your target on the slit and move the Dekker in again. Better Dekkers will be produced in the near future.

3.9.5 "Data Lost"

Occasionally, pixels get lost while the data are being transferred to the DMS. When this occurs, the correspondence between counts and pixel number is lost and spectra will appear to have shifted in the spatial direction. Pixel-to-pixel sensitivity variations can then not be flat-fielded out. The latest folklore is that this problem disappears when a window is defined for readout; even if you need the entire CCD, it might pay you to formally window it.

4 Circular polarimetry

Circular polarimetry is similar to linear polarimetry. Instead of the halfwave plate one uses the quarterwave plate, to convert circularly polarized light of the incoming beam into linearly polarized light. This again enters the spectrograph and is separated into an o- and e-beam on passing the calcite slab. The position angle of the linear polarized vector is defined by the position angle of the quarterwave plate and by the sense of rotation (left or right) of the incoming circularly polarized beam.

Because of its limited diameter, the currently available quarterwave plate (a spare for the Peoples Photometer) allows one to observe point sources only. Two of the apertures in the comb Dekkers just fit into the unobstructed field.

Another complication is that the TV camera cannot see the slit through the quarterwave at all, which hampers acquisition of the target on the slit. Acquire the target with the quarterwave plate out the beam, find a star to guide on (or trust the tracking), and move the quarterwave plate back into the beam. Remember to adjust focus.

Because the quarterwave plate is not exactly quarterwave for all wavelengths, the circular polarimeter is partly sensitive to linear polarization, which in the astronomical context generally vastly exceeds the circular polarization one is trying to measure. If you suspect linear polarization in your source, you can depolarize it by inserting the halfwave plate ahead of the quarterwave plate and setting it into continuous rotation; this should eliminate systematic errors due to linear polarization, and invert but leave otherwise intact, the true circular polarization. *Note that the normal setup is with the halfwave* **after** *the quarterwave and a request to invert the order must be made when applying for telescope time; the inverse order makes TV slit viewing difficult even when just the halfwave is in the beam, e.g. for linear polarimetry.*

A full circular polarization measurement consists of:

exposure 1 with quarterwave plate at 0 degrees
exposure 2 with quarterwave plate at 90 degrees
exposure 3 with quarterwave plate at 45 degrees
exposure 4 with quarterwave plate at 135 degrees

The angle offsets are twice as large as in linear polarimetry. Reduction to degree of circular polarization is identical to that for linear polarization.

For calibration purposes a very simple circular polarizer is available in the A&G main filter slide. If linear polarization of your source is strong, you must determine to what extent the telescope converts linear to circular. The way to do this is to set up ISIS for *circular* polarization, but observe a strongly *linearly* polarized star; obtain 2 complete observations, with a parallactic angle difference of 90 degrees (Fig. 5). External circular polarization is constant, but converted linear will be inverted in the two observations.

There is considerable confusion in the literature about the sign conventions for circular polarimetry. Handedness is defined with reference either to the instantaneous 3D e.m. field configuration, or to the sense of rotation of the electric vector projection as seen by either source or observer. For any of these cases, positive can be associated with left or right handedness. We do not recommend any one of the many versions; just be aware of the confusion and define *your* observations uniquely, both for yourself and in the paper you write.

5 Other polarimetry modes

5.1 Imaging polarimetry

During October 1991 a mode tried out briefly in February was commissioned (Charles Jenkins and Robert Laing, to whom we refer you for results and recommendations). In this mode, the grating is replaced by a flat mirror ('test flat'), so that a white image is recorded rather than a spectrum; the spectral range is restricted by a (post-slit) filter. The slit is opened to the full width of the calcite plate and a comb Dekker is used to create dark zones for the second image produced by the calcite plate. The polarimetric procedure is identical to that for spectropolarimetry; the only difference is that in this case *both* dimensions on the detector are spatial. The comb Dekker transmits only part of the image, so several complete observations are needed to fill the image plane.

The main purpose of this mode is to provide additional support to long-slit spectropolarimetry of extended objects; it is not necessarily an optimised polarization imager (the Durham polarimeter *is* in several aspects, and TAURUS may be when its time comes). For the time being, ISIS is the operationally most accessible imaging polarimeter; imaging and spectropolarimetry can be interleaved with any other ISIS observing programme. Do enquire for up-to-date status.

5.2 Modulation mode

In ISIS/FOS spectropolarimetry, the usual method of observing will be the "staring" mode, described in Section 3. As mentioned above, it can be looked on as a very slow modulation method, but we wish to distinguish it from another option, which makes use of telescope movement to implement a method with somewhat faster modulation (0.05 Hz, as opposed to 0.005 or thereabouts). Such a method could be used when the analyser has only one beam (Polaroid), which may be unavoidable in some applications (e.g. when a spectrum along the full length of the slit is required at one go, rather than with the comb-type Dekker); it will be referred to as the "modulation" mode.

Ideally, the frequency of modulation should be of order 10 Hz. The polarization module is mechanically capable of this, but no rapid-readout detectors are available. An alternative is to use separate pixels for the 2 states of the modulator by moving the telescope to another position to expose another part of the CCD without reading it out. Flat-field information is then required to relate one part of the CCD to the other. The rate of modulation will be determined by delays in moving the telescope, Dekker and waveplate between their 2 positions; at present, a rate of 0.1 Hz is likely to be the maximum attainable.

Is it worth it, and if so, under what conditions and for what projects? If not, we shall have to wait for the rapid-readout CCDs to be implemented, or the advent of other types of detectors.

Whenever the calcite slab can be used, atmospheric noise (due to scintillation, seeing or extinction variations) can be eliminated fairly effectively, and the calcite plate eliminates light loss. However, when using the calcite slab, long-slit objects have to be split into sections, to accommodate the other beam. The calcite slab may also not be fully compatible with the cross-dispersion option planned for the future (and very desirable for polarization work: at lowest dispersion, the whole wavelength range can be covered in one exposure with 2 CCDs, ideal for 10-Angstrom resolution spectropolarimetry). Similarly, FOS multi-slit or aperture-plate spectropolarimetry will have to use a Polaroid analyser (mounted in the multi-slit unit). In all those cases, a Polaroid analyser will have to be used, necessitating modulation to reduce atmospheric noise.

To avoid spurious system gain variations (causing apparent polarization) by wandering of the stellar image (spectrum) over the surface of the non-uniform detector, it will be necessary to pay special attention to slit use: the centering in the 2 states of the modulator should be the same as far as possible. On point sources the method will probably require either a very narrow, short slit (say 0.5 arcsec for 1 arcsec seeing) or a very wide one resembling a photometer aperture (say 5 arcsec for 0.5 to 1 arcsec seeing). Use of the autoguider is highly desirable in all cases.

We have tried to implement an automatic routine based on an ICL procedure with observer control of some of the parameters. These parameters are: the total number of partial exposures, the 2 waveplate positions, the Dekkers in the 2 states, the "throw" of the telescope position, and the length of the partial exposures, separately for the 2 CCDs. While this way of observing is essential only when using the Polaroid analyser, the routine can be used with the calcite plate, for instance when it is important that both Stokes parameters be observed as far as possible at the same time. With the polaroid analyser, one switches between 2 halfwave plate positions 45 degrees apart and deduces one Stokes parameter from this; the other Stokes parameter needs another frame. With the calcite plate, the halfwave positions may be taken 22.5 degrees apart and a second observation (with positions differing by 45 degrees from the first) is needed to correct for the gain ratios (see the section on the staring mode); the Stokes parameters are then effectively observed at the same time.

Experiments quickly showed that modulation by this method will only work well for point sources if conditions are photometric and essentially photometric practice is adopted: the focal-plane aperture should admit very nearly all of the stellar light. It seems therefore that it will be limited to the cases above and that for compensation of atmospheric noise we shall rely mostly on the calcite slab analyser.

5.3 An alternative way of correcting for sky

A totally different approach to sky correction from that described in Section 3.3 is to compensate it optically by allowing the e-beam from a sky aperture to coincide with the o-beam from the star and vice versa (Fig. 10). The sky contribution in both stellar spectra now contains both polarizations and the ratio obtained is the square of $(\mathrm{I} + \mathrm{Q} + 2 \cdot \mathrm{I}_{\mathrm{sky}})/(\mathrm{I} - \mathrm{Q} + 2 \cdot \mathrm{I}_{\mathrm{sky}})$. Ignoring the sky spectra and just reducing the stellar spectrum as before, we obtain the uncontaminated stellar polarization, but with a scale factor of $\mathrm{I}/(\mathrm{I} + 2 \cdot \mathrm{I}_{\mathrm{sky}})$. Often such a scale error is preferable to an additive (vector) polarization error,but it can be ruinous at the wavelengths of sky emission lines. Since these probably are unpolarized, they only cause a scale error in 'normal' operation, whilst the 'compensation' method doubles their strength. If experiments with such automatic sky compensation are undertaken, the spacing of the Dekker apertures should be equal to the beam separation caused by the calcite plate. This is quoted by the manufacturer as: 2.57, 2.20 and 2.14 mm at 300, 633 and 1000 nm respectively. Experiments will be necessary to find the best Dekkers for this method.

Figure 10: Optical elimination of sky polarization.

GOOD LUCK !

APPENDICES

The appendices are intended for fluid but (we hope) up-to-date information on the polarization unit and its performance. Please communicate to us any results or considerations which you feel ought to be recorded here and tell us when the information has ceased to be useful.

A Calibration polarizers

The calibration polarizers are mounted in one of the A&G main filter slides. This severely limits their use in combination with pre-slit filters; however, post-slit filters (if and when available) are preferable anyway, as they do not contribute to instrumental polarization. The present calibrators are: 2 UV polaroids, a calcite slab and a (plastic, scratched, fixed by sticky tape) circular polarizer. The polaroids can be preset to any orientation you wish, but once the filter slide has been inserted into the A&G, they are fixed. The most useful orientation is that corresponding to the 2 beams of the calcite slab (see the discussion on flat fields); this is the default adjustment and instructions for retrieving this orientation are available on site.

In the long run, it would be better to calibrate at astronomical levels of polarization (of order 5 %). A suitable component would be a pair of oppositely tilted silica plates, as in the Multi-Purpose Fotometer MPF. Space for this is available (and has been claimed) upstream of the A&G. Equally desirable would be a proper achromatic circular polarizer. Future implementation of such components will depend a good deal on pressure from the community.

B Dekkers

For ISIS, individual Dekker masks are mounted in a frame (Fig. 11) which in turn is inserted by hand into the motorised slide. For polarimetric observations, specialised Dekkers are required. A simple mask to your own special design can usually be made up on site (give advance notice of weeks, preferably months). Enquire with your support astronomer what the current situation on polarization Dekkers is. To be able to see a source on the Dekker, the Dekker must be polished and/or aluminised, which cannot be done on site. Dekkers run up on site will appear dark on the acquisition TV and you will have to slide the Dekker masks out when acquiring your object.

We hope to provide soon the following Dekkers for general use:

- point source + 2 sky apertures.
- long-slit: combs of duty fraction 1 : 3.5 (4 exposures) and 1 : 2.5 (3 exposures). Scattered light may be a problem with 1 : 2.5.

Note that one position in the frame is usually left empty for finding faint objects on TV. It takes far less time to move to the last Dekker position than to move the entire Dekker slide out of the beam; however, to see the entire field, the latter course may be necessary.

C More on scattered light

Early polarimetric tests showed the presence of a considerable scattered component with some structure. We have conducted experiments to identify the source of the scattered light, with a view to eliminating it. We identified several distinct modes of scattering, each of which can be quantified to a large extent from our data. They include:

- a very symmetrical halo round each point source on the chip, which does not show any preference for dispersion or spatial direction and could be due to out-of-focus reflections on optical surfaces or scattering by dust on optics; it is of a reassuringly low (but not necessarily negligible) level. About 50 pixels from the centre, the intensity has dropped to less than 0.15 %. Since this corresponds

Figure 11: Dekker frame with Dekkers used during commissioning. Actual suite of Dekkers will be different from this. See text.

to 17 arcsec in the spatial direction (with the o and e spectra separated by about 10 arcsec) and we are aiming at polarimetry of 0.1 % or better, it is clear that this component can influence our polarimetry. Since astronomical spectra do not normally consist of just isolated emission lines, the scattered light is usually much more; at any one point in one of the spectra it is an integral over a certain length of *both* polarized spectra. Light scattered within a spectrum just affects the spectral purity, but light scattered from the other spectrum causes errors of polarimetry. When more than one of the Dekker apertures is filled, as in lamp or blue sky exposures, the effect is more complicated still. Such scattered light can be extremely troublesome in a blue spectrum, since CCDs are much more sensitive in the red and even small amounts of scattered red light can yield appreciable signal. A possible cure will be to use red-cutoff post-slit filters (nature has not provided suitable glasses, but thin-film technology can help). Whatever remains after such filtering will have to be modeled from known point-spread functions and observed spectra, and removed from the data. We shall conduct experiments towards such modeling and hope to advise in future on what auxiliary data to collect when utmost accuracy is required; please keep us informed of any successful modeling on your part.

- local scattering in the dispersion direction only; it is difficult to see how this could be due to anything else than imperfections of the grating (e.g. long-period irregularities in groove spacing). It is of no particular significance except for a minor effect on spectral resolution; it does not affect polarimetry.

- scattering in the spatial direction only, with 'the slit' being visible where it is ostensibly blocked by the Dekker; these slit images show slight flaring or defocusing at the ends of the slit. The considered opinion of RGO detector staff is that this is probably a CCD effect due to the inherent gross overexposure of the test frames and that it should be of no significance in normal use.

- a highly structured ghost image generated when there is a lot of light just outside the spectral range that is being recorded. It is not clear whether the light is scattered on camera components or on the immediate environment of the chip, within the cryostat. The ghost is well focused and shows a dark rectangular feature and an ostensible 'spider'. RGO optical staff are investigating and hope to eliminate it once the cause has been found; a first guess from its complex structure is that both a pupil-plane and an image-plane ghost are involved. Under most astronomical conditions, much of its structure will be smoothed by spectral integration. To attempt to detect it in your application, the best possibility is to set the wavelength of one of the available blue-cutoff filters roughly on the (red) edge of the CCD and take a long exposure of your object with the filter in position; such a wavelength setting may not be ideal for your programme, but at least you can estimate one of the potentially harmful scattered-light components.

- a narrow long-range dispersed component, slightly skew; it shows up also in a single-slot-Dekker exposure, making it look like a calcite-slab polarization spectrum; in polarimetry this would be a particularly vicious kind of error if it turns out to be of significant strength (it would seem that usually it is not).

- when a dichroic is used to split the light for simultaneous use of the red and blue arms of ISIS, light reflected from the back of the dichroic will be displaced along the slit and will corrupt polarization data. It may be possible to cure this by an anti-reflection coating on the back surface of the dichroic, but for the time being we advise against using dichroics. Pressure from the community might help.

Since CCDs are preferentially red-sensitive, one is more likely to run into scattered-light problems when observing in the blue, particularly if the source is strong in the red. The evidence indicates that light just longward of where the recorded spectrum stops is the worst culprit. At present this is all the guidance we can give, but the question is being actively pursued. For quantitative estimates and detailed structure of the scattered light, we obtained (in February 1991) over 400 CCD frames under various conditions of illumination and spectrograph settings. This database is slowly being analysed and is available to users via the LPO archive at RGO; it includes an ASCII observing log.

D How to measure CCD properties in situ

In this section, we proceed on the assumption that, by the time CCDs are installed into scientific instruments, they will have been subjected to a good grilling in the lab and have had their controlling voltages and timings adjusted optimally. It is now up to us to characterise them in actual use, optimise the way we expose them and finally to provide feedback to the lab for new control aims and specifications. We shall discuss ways of testing them by lamps or stars. Please report back (TINBERGEN@HRDKSW5) any improvements you may invent.

Shutter stability CCDs are not shuttered electronically in astronomical applications. A physical shutter controls the exposure. Since this is a key point in some of the tests and in some observations, a shutter test should be part of any pre-run tryout of the system. The shutters were not designed with millisecond stability in mind. They are mechanical, have been known to stick, they are controlled pneumatically, therefore are sensitive to gas supply pressure, finally are operated via 4MS and Ethernet, with possibilities of delays.

To test shutter stability, configure ISIS so that you obtain a well exposed (but not saturated) CCD frame with the tungsten lamp in about 10 seconds. Let the tungsten lamp (Quartz-halogen type) stabilise for at least half an hour. Then take a number of say 1 second and 10 second exposures and determine the rms spread of intensities in one or more pixel groups (using the DMS). Our tests indicate that the rms spread should be well below 0.1 % at 10 seconds, which is a minor miracle.

Pixel sensitivity stability Having obtained flat fields on daytime or Moonlit sky, one transfers these to observations made many hours later. It is not possible to use lamps for flat fields, but one may use them to monitor pixel sensitivity *ratios*. Do a normal polarimetric observation for Q or U, and determine the G ratio from it (subsection 3.2). If these ratios stay constant, all is well; if not, the variations tell you the extent of your trouble, but not which of the 2 pixels involved in the ratio is causing it.

Linearity Having ascertained shutter reliability, you are ready to test linearity. Set up as described above, except that full scale output should take a 100-second exposure.

Expose for various lengths of time and divide output by nominal exposure time. For exposures of more than 10 seconds, departures from the overall mean (that are significant given the rms spread) should be attributable to the CCD; below 10 seconds, the shutter mechanism could cause non-linearities or field dependence.

A purely polarimetric way to determine non-linearities, not depending on shutter stability but very time consuming, would be the following: allow the tungsten lamp to stabilise, insert the calibration polarizer and take pairs of CCD frames with halfwave plate at angles X and X+45 degrees. Use some 10 to 20 different values of X in a total range of some 120 degrees. Do the normal staring-mode reduction, then fit the Stokes parameter values for different X by a sinusoid in 2X. Deviations from a pure sinusoid will be due to non-linearities in the high or low intensity parts of the data. Repeat the test with peak intensity halved; if the effect is reduced, it must arise at the high intensities.

Finally, remember that most of polarimetry is *relative* photometry of nearly equal intensities. As long as non-linearities are similar in corresponding pixels, they are not very important, since it is the intensity *ratio* that counts.

E ICL and system control

The control system for the polarization optics is integrated in the general ISIS system. The following list specifies the commands that are available (1991) to control the polarization optics from the ICL level. This list will change; consult site staff when you arrive and insist on being given an up-to-date list.

ICL command	action
HW_POLAR MOVE IN	move halfwave plate in beam
QW_POLAR MOVE IN	move quarterwave plate in beam
HW_POLAR MOVE OUT	move halfwave plate out of beam
QW_POLAR MOVE OUT	move quarterwave plate out of beam
HW_POLAR ANGLE n	set halfwave plate position angle to n/10 degrees
QW_POLAR ANGLE n	set quarterwave plate position angle to n/10 degrees
HW_POLAR ROTATE n	set halfwave plate rotating at n/10 Hz.
QW_POLAR ROTATE n	set quarterwave plate rotating at n/10 Hz.
HW_POLAR STOP ROTATE	stop rotation of halfwave plate
QW_POLAR STOP ROTATE	stop rotation of quarterwave plate
HW_POLAR INIT	initialize halfwave plate
QW_POLAR INIT	initialize quarterwave plate
CALC	move calcite analyser in beam
POL	move polaroid analyser in beam
FCP CLEAR	move calcite/polaroid slide to clear position

F FOS

Much of what can be done with ISIS should be possible with FOS, with the same advantages of the waveplates that work for ISIS. Refocusing FOS for the calcite slab analyser may be involved in some applications; this can be done, but is not trivial. The Polaroid analyser can probably be used without refocusing, but requires "telescope chopping". It should be possible to mount an analyser (Polaroid or thin calcite slab) in the multi-slit unit for survey work. All of this needs development before it can be used.

Our report on the February 1991 commissioning run contains the following statement (which we still believe to be true): "FOS has been proved to give good polarization spectra without refocusing (mode without FOS lens, first order only). This means that, as with ISIS, polarimetry can be done with FOS in the course of a normal spectroscopic run. Interest within the community should be sounded for partaking in a commissioning run on this option, particularly for multi-slit applications, for which the useful field is about 35 x 8 mm (150 x 36 arcsec)". Any offers? Email to: TINBERGEN@HRDKSW5.

G Telescope and slit polarization

All telescopes produce some linear polarization. This is usually measured by observing nearby stars known to be unpolarized. For the WHT such observations indicate an instrumental polarization of less than 0.1 %, which is excellent; Fig. 12 shows such an observation. After re-aluminization of the telescope mirrors, the telescope polarization may have changed.

Metallic slits can produce polarization. Because the halfwave plate precedes the slit, slit polarization will be cancelled as long as the stellar image is recentred for each exposure. The low value of instrumental polarization indicates that effective slit polarization cannot be very strong. A way to search for it would be to open the slit wide, under good conditions, and observe a zero-polarization star. Move the star from centre to slit edge when rotating the halfwave through 45 degrees; this introduces any slit polarization that may be present *while you are inverting the object polarization.* Compare this with a normal observation of the object. For normal use, one should be almost totally immune from slit polarization when operating ISIS like a photometer, with a 5-arcsec slit and Dekker in 1-arcsec seeing (accepting some uncertainty of the wavelength scale).

An out-of-focus image can lead to polarization effects if one samples it asymmetrically with the spectrograph slit. To some extent, one samples a certain part of the primary mirror and will see the polarization due to oblique incidence on that part of the mirror. With accurate focusing, all parts of the primary contribute equally and the average is zero.

Figure 12: Tests on 'unpolarized' star during commissioning (courtesy Dave Axon, Jim Hough). Lower panel is with calibration Polaroid in the beam; drop-off of degree of polarization at low pixel numbers is due to Polaroid failure.

H Polarization standard stars

This section should be read with Section 3.6 on calibration. Standard stars exist for many purposes and it is essential to select those that *your* programme requires; lack of calibration is fatal, but too much is wasteful. There is very little that can really serve as standard in the practice of spectropolarimetry; be wary of narrow-band polarization effects when reducing standard star measurements. Basically, for spectropolarimetry we shall have to create our own set of standard stars; if you are interested in starting a cooperative long-range programme, contact TINBERGEN@HRDKSW5.

Useful references, which between them cover wavelength dependence, zero-point, degree and angle, are listed below. Figs 13 to 19 have been copied from some of these papers for ease of use at the telescope, but we advise you to scan through the original papers. A very recent paper, covering a wide range in wavelength, is:

> **Whittet D C B, Martin P G, Hough J H, Rouse M F, Bailey J A and Axon D J, 1992,** Astrophysical Journal **386**, 562
> 'Systematic variations in the wavelength dependence of interstellar linear polarization'
> *U to K on 105 stars; use with Bailey and Hough 1982, Hsu and Breger 1982*

Bailey and Hough, 1982, Pub Astr Soc Pacific **94**, 618	*U to K on 11 stars*
Tinbergen, 1979, Astron & Astrophys Suppl **35**, 325	*zero-point*
Hsu and Breger, 1982, Astrophysical Journal **262**, 732	*degree, angle; U to I*
Dolan and Tapia, 1986, Pub Astr Soc Pacific **98**, 792	*time variations*
Bastien et al., 1988, Astronomical Journal **95**, 900	*time variations*
Turnshek et al., 1990, Astronomical Journal **99**, 1243	*rough and ready single reference*

Some years ago one of us constructed a bibliography of all polarimetry thorough enough to serve as standards. Though no longer up-to-date, it will serve as a guide for a literature search and is reproduced here, with later additions, as Fig 20.

Finally we quote two recent workers in the subject, whose opinion on standards we value and to whom we specifically put the question of spectropolarimetric standards in connection with this manual. Note their caution.

From: bastien@PHYSCN.UMontreal.CA (Bastien Pierre)
To: TINBERGEN@HRDKSW5.BITNET
Subject: poln stds

Dear Jaap, believing in what I published, my suggestion would be to use as best candidates the ones which have the lowest ratio of sigma1 to sigma2, as defined in the 1988 AJ paper you referred to earlier. Fig. 1 in my Vatican paper on poln standards – reproduced here as part of Fig 16 – *presents them according to the value of this ratio. I would stay away as much as possible from the ones with the largest values of this ratio. So this covers the variability concerns for the standards.*

For their suitability as spectro*polarimetric standards, I think that the work has not been done properly yet on this subject. I think that an observing campaign is needed. What do you think?*

Best regards, *Pierre*

\- -

Jaap,

I have not done spectropolarimetry and do not feel qualified to give anyone advice on spectropolarimetric standards. As far as broad-band polarimetry is concerned, the Buenos Aires meeting of Commission 25 heard abundant evidence that standard stars are not good enough to do conversion of internal to external co-ordinate systems with an accuracy of 1 degree or better. Their percentage polarization is likewise variable (by as much as a few tenths of a percent night to night). The likelihood of finding bright, highly polarized stars with no variability is small, because these stars appear to have a component of intrinsic polarization. I recommend the fairly straightforward calibration method at the telescope outlined by Tapia and myself in PASP, vol 98, 1986 (on p793) for any precision work.

Regards, *Joe Dolan.*

Conclusion. To sum up the present situation: for high-accuracy spectropolarimetry, it is probably best to use stars for zeropoint, twin-tilted-plate for degree of polarization, and suspended polaroid or Dolan & Tapia's method (or possibly asteroid or zenith blue sky) for angle. Standard stars are probably satisfactory for less demanding programmes.

Figure 13: Extract from Tinbergen 1979: zero-polarization stars.

Figure 14: Extract from Hsu and Breger 1982: standard stars for degree and angle of polarization, in 5 broad bands. Use with Bailey and Hough 1982, Whittet et al 1992.

Figure 15: Extract from Dolan and Tapia 1986: polarization variations in 'standard stars'.

Figure 16: Extract from Bastien et al. 1988: polarization variations in 'standard stars'.

Figure 17: Extract from Turnshek et al. 1990: HST polarization standards.

Figure 18: Extract from Turnshek et al. 1990: HST high-polarization extended objects.

Figure 19: Extract from Bailey and Hough 1982: standard stars for degree and angle of polarization, in 9 broad bands (U to K). Use with Whittet et al 1992, Hsu and Breger 1982.

Figure 20: Bibliography of polarization standards up to 1985.

I References

Specific references for standard stars are listed in Appendix H. The listing here is intended as background reading for those expecting to use polarimetry more than just incidentally.

I.1 Books

Van de Hulst 'Light Scattering by Small Particles', Wiley, also Dover 1981
Contains a clear and concise introduction to Stokes parameters.
Gehrels (ed) 'Planets, Stars and Nebulae, studied with photopolarimetry', Univ.of Arizona 1974
Still the best applications overview; no spectral or imaging polarimetry worth speaking of, though.
Serkowski 'Polarization Techniques', chapter 8 of 'Methods of Experimental Physics', vol 12 'Astrophysics' (**Carleton** ed.), Academic Press 1974
The classic on astronomical polarimetry
Shurcliff 'Polarized Light, production and Use', Harvard/Oxford 1962
The classic on instruments, components and polarization calculus.
Simmons and Guttmann 'States, Waves and Photons: a modern introduction to light', Addison-Wesley 1970
Quantum-mechanical formalism for polarization.
Clarke and Grainger 'Polarized Light and Optical Measurement', Pergamon 1971
Very useful companion to Shurcliff.
Azzam and Bashara 'Ellipsometry and Polarized Light', North-Holland 1977 (paperback 1987)
Polarization calculus.
Kliger, Lewis and Randall 'Polarized Light in Optics and Spectroscopy', Academic Press 1990
Excellent modern treatment of polarization calculus; best single buy.

I.2 Journal articles

The list below is necessarily very incomplete and reflects personal prejudices. Never mind, its purpose is purely educational.

Lyot, 1948, Comptes Rendus Acad. Sciences Paris **226**, 137
First modulator (narrowband, solar)
Dollfus, 1963, Comptes Rendus Acad. Sciences Paris **256**, 1920
Development of above (still solar)
Tinbergen, 1973, Astron. & Astrophys. **23**, 25
Broadband development of above (stellar)
Behr, 1956, Veröff. Univ. Sternwarte Göttingen no 114
Two-channel DC polarimeter
Treanor, 1968, MNRAS **138**, 325
Rotating halfwave, photographic
Scarrott et al., 1983, MNRAS **204**, 1163 and **Scarrott, 1991,** Vistas in Astronomy **34**, 163
The Durham imaging polarimeter for faint objects, in regular use around the world; originally electronographic, now CCD
Gehrels and Teska, 1960, PASP **72**, 115
Contains the suspended-polaroid trick for angle calibration
Kemp, 1969, Jour Opt Soc Am **59**, 950
Photo-elastic modulator
Angel and Landstreet, 1970, Ap.J. **160**, L147
Electro-optic crystal modulator

Piirola, 1973, Astron. & Astrophys. **27**, 383
Calcite plate analyser, chopper modulator
McLean, 1984, SPIE **445** (Instrumentation in Astronomy V), 547
CCD and IPCS systems
Metz, 1984, Astron. & Astrophys. **136**, 175
Sky compensation
Hayden Smith and Smith, 1991, Experimental Astronomy **1**, 329
Acousto-optic tunable filter polarimetry

\- -

Clarke and Stewart, 1986, Vistas in Astronomy **29**, 27
Statistical methods for polarimetry
Hiltner and Schild, 1965, Sky and Telescope, September issue
Rotatable telescope
Borra, 1976, PASP **88**, 548
Problems at Coudé focus
Tinbergen, 1988, ESO Conference on VLTs and their Instrumentation, 1267
Measurement errors caused by polarization effects

\- -

Smith et al., 1988, MNRAS **233**, 305
Crab pulsar synchronised polarimetry

\- -

Tinbergen 'Polarimetry at the WHT', Gemini no 32, p.6, 1991
Tinbergen 'Array detectors in astronomical polarimetry', draft of part of joint paper (with Ian McLean) for IAU Buenos Aires Commission 25, 1991. *Available from TINBERGEN@HRDKSW5*

J Contacts

The following persons might be able to help you whenever you need the latest information on the ISIS polarimetry system:

Jaap Tinbergen	`TINBERGEN@HRDKSW5`	Kapteyn Observatory, Roden, NL
René Rutten	`A41ORGMR@HASARA11`	University of Amsterdam, NL
Charles Jenkins	`CAVAD::CRJ`	RGO Cambridge, UK
Marc Balcells	`BALCELLS@RUG.NL`	La Palma; local polarimetry expert
	`CAVAD::LPVA::BALCELLS`	
	`PSI%02145222020109::BALCELLS`	