EUROPEAN SOUTHERN OBSERVATORY

OPERATING MANUAL

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PISCO

PISCO

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Chapter 1

Introduction

PISCO is the ESO Polarimeter with Instrumental and Sky Compensation, a two channel, filter polarimeter using photon counting, offered on the ESO/MPI 2.2 m telescope.

The instrument is capable of high precision linear and circular polarimetry of objects down to $\approx 17^{th}$ magnitude.

This manual is intended to assist users of PISCO with their preparation of observations, observing and to give hints on data reduction. For observers with little or no polarimetry experience, appendix A gives some background on the techniques.

This manual is not intended for use as an in depth technical reference work. For detailed information of this kind a separate technical manual is available.

We strongly encourage users to make any comments and suggestions concerning this manual in order that we may refine future versions. Please do this by firstly writing on a copy of this manual which you will find in the control room of the telescope and secondly in your observing report to be completed at the end of your observing mission to La Silla.

Chapter 2

System description

2.1 Optical layout

PISCO is a two-channel polarimeter (see e.g. Serkowski, 1974 for polarimeter designs of this type). A schematic view of the instrument is shown in Figure 2.1. The light enters the instrument through the inclined diaphragm wheel DIAPW. Via the mirrored surface of this wheel, a TV camera views the observed field. Setting and guiding is done with the use of this camera. The compensating phase plate unit CPP corrects for the effects of the rotating half-wave plate RPP and automatically compensates for the sky polarization if a two-hole integration is used. The Foster prism FP separates the ordinary and the extraordinary beams. The selection of the wavelength range is done via the colour filter wheels XCFLTW and YCFLTW separately for the X and Y channel. If the same filters are chosen for both channels, the instrument operates in the two-channel mode. The density filters XDFLTW and YDFLTW are inserted if very bright stars are observed. The photons are detected by the multipliers XMP and YMP. A Z80 microprocessor performs the integration of the counts in 2×32 channels. The user controls all functions of the instrument via the HP 1000 computer and a CAMAC interface.

All lenses, prisms and cover glasses of the retarders are made of fused silica thus guaranteeing a high transparency between 3000 and 11000 Å. However, since the use of achromatic lenses is not possible in most parts of the polarimeter, the useful wavelength range remains restricted to the range from 3400 Å to 8500 Å. All optical surfaces are provided as far as possible with antireflection coatings. In contrast to the usual design it does not use a Wollaston prism but a modified Foster prism to separate the ordinary and the extraordinary beam. This design has the advantage of a large (45°) and wavelength independent beam separation.

The principal new feature of PISCO is the possibility to compensate directly for the sky polarization and partly also for the instrumental polarization. The sky compensation is achieved by using two apertures and two compensating phase plates with different orientation of the optical axes. The combined sky light is then in principle unpolarized (see Appendix A). The instrumental polarization of the phase plate can be compensated for by rotating the whole compensating phase plate unit by 180° during an integration. This can be done customarily.

The signal modulation is effected by a half-wave plate which rotates at 6 cycles sec^{-1}. Each turn of this half-wave plate is divided into 32 equidistant sectors corresponding to 32 counter channels. The sinusoidal modulation of the count rate describes the polarimetric signal which can be extracted using standard Fourier techniques.

2.2 Diaphragms, acquisition and guiding

PISCO has 8 sets of 2 diaphragms in an inclined, polished diaphragm wheel. The light reflected from the wheel is viewed by an intensified TV camera for acquisition and guiding.

Each aperture has a corresponding cross hair etched into the wheel. An object should be centered in a cross. When starting an integration the selected aperture will be rotated in place allowing the light to enter the instrument.

Any suitable star in the field can be used for guiding with the standard ESO auto guider. For bright objects, and when no other stars are in the field, guiding can be done on the aperture itself using the reflected starlight around the edge of the aperture.

The available apertures 1 to 8 are listed in mm and arcseconds in Table 2.1.

Table 2.1: PISCO diaphragms

aperture number	1	2	3	4	5	6	7	8
diameter [mm]	0.35	0.60	0.85	1.30	1.70	2.15	2.55	3.00
diameter ["]	4.00	6.90	9.70	15.0	19.4	24.8	29.4	34.6

The acquisition/guiding TV camera has two sets of lenses mounted in front of it, giving 2 fields of view for acquisition and guiding. The large field is about $4' \times 6'$ and the small field about $1'.5 \times 2'$ allowing very accurate centering of objects. These fields can be selected from the keyboard. Stars of $m_v \sim 18$ or brighter can be used for guiding. Figure 2.2 shows the acquisition (large) field of PISCO.

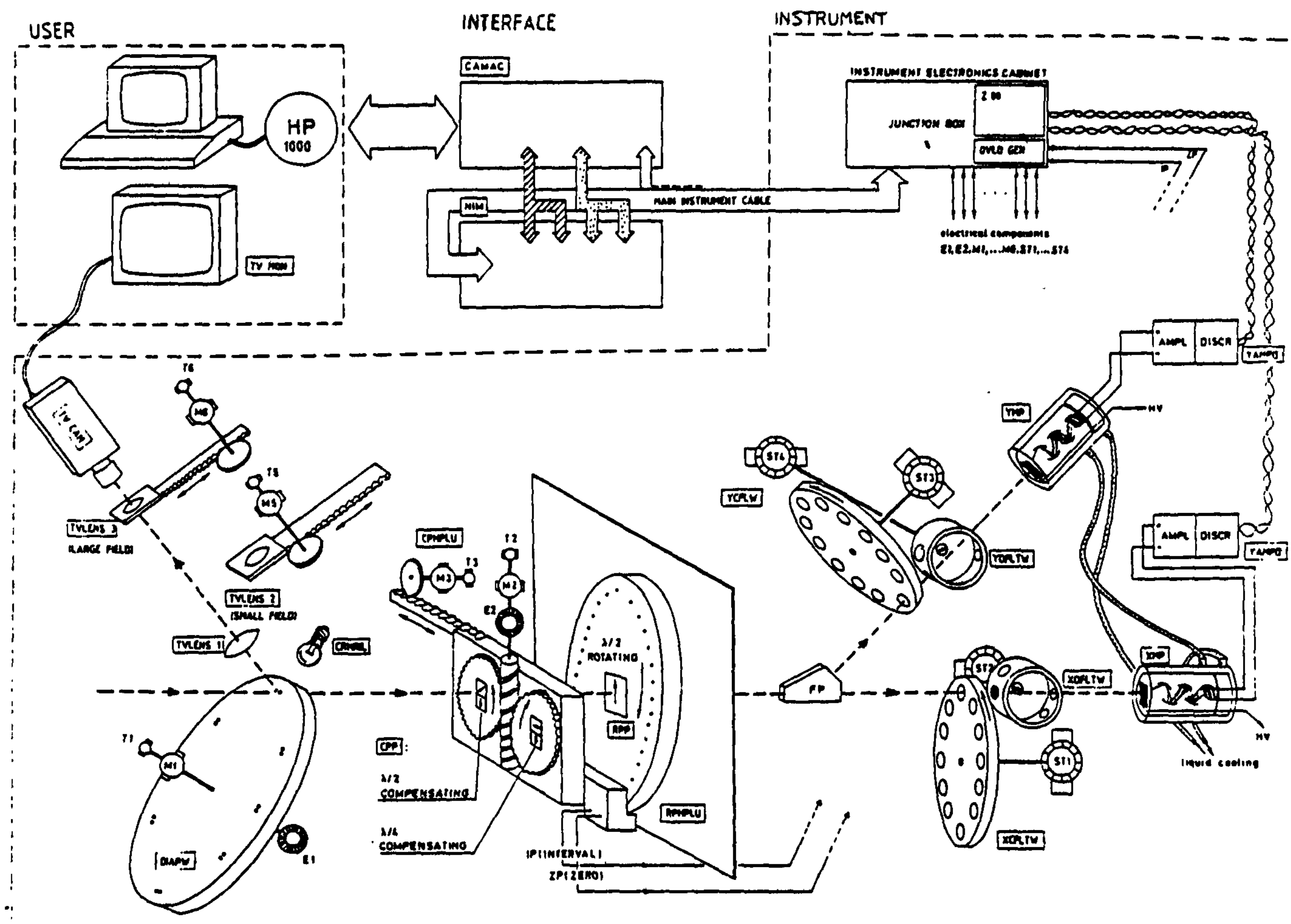

Figure 2.1: Schematic drawing showing the most important parts of the instrument.

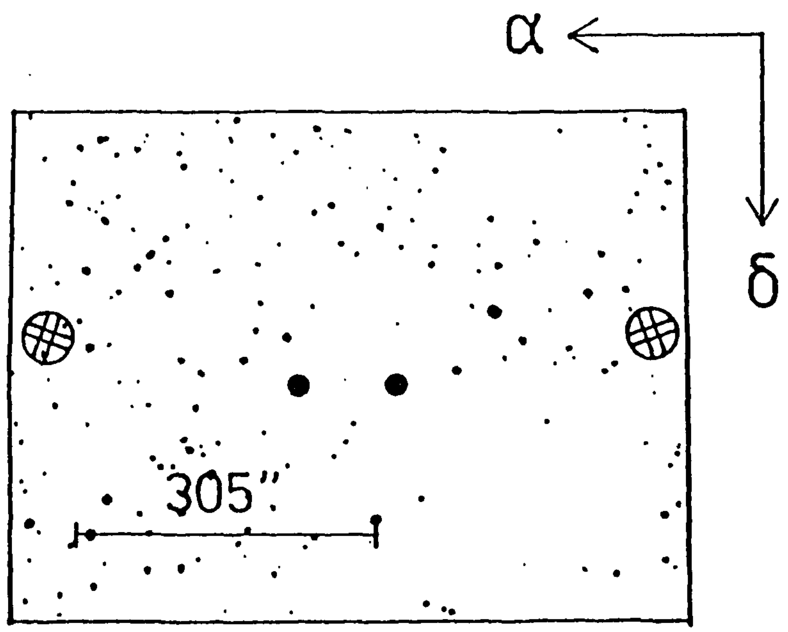

Figure 2.2: The field of view of the polarimeter (large field)

2.3 Phase plates and polarizer

After passing through the diaphragm, the light encounters the compensating phase plates which invert the appropriate Stokes parameters to eliminate the sky polarization (see Appendix A). After a field lens the light passes through the rotating halfwave plate which is the modulator of the signal.

Next is the polarizer which here is a modified Foster prism (Foster, 1938) splitting the light into two orthogonally polarized beams which emerge at 45° to each other. Cemented on the output faces of the Foster prism are depolarizers. These prevent unwanted polarization effects in the subsequent optics.

We now have two unpolarized beams which are modulated sinusoidally in intensity depending on the amount of linear polarization of the incoming beam. The two channels are indicated by X and Y.

2.4 Filters

The X and Y beams pass through one of the apertures in the colour filter wheels and density filter wheels. The colour filter wheels can hold up to 11 different filters while the density filter wheel has 3 positions: open, density ND2 and closed (shutter).

PISCO has two identical sets of UBVRI filters permanently mounted in positions 1 to 5, positions 0 and 6 are closed and position 7 is open, for white light observations. Positions 8 to 11 can be used for any filter 25.4 mm in diameter and up to 10 mm thick. This is the same for both wheels.

The transmission curves for the UBVRI filters are included in the ESO filter inventory under numbers 558 to 567. The U filter has a red leak but CuSO4 filters will be installed in the near future.

2.5 Photomultipliers

After passing through the filter wheels, the X and Y beams enter Fabry lenses which form a pupil image on the photocathodes of two Hamamatsu R 943–02 photomultipliers. These are GaAs types with properties similar to the Quantacon or RCA 31034A–02 tubes.

The tubes are cooled by refrigerated glycol to give a darkcurrent of $\sim$ 20 cts s^{-1} at 1950 V. The cooler is mounted on the telescope next to the instrument and should be set to $-40°$. The display should normally indicate $\sim -30°$.

2.6 Polaroids

A polaroid polarizer in a metal holder is available for measurement of wave plate fast axis angles and calibration. The unit can be inserted in the light path before the aperture wheel by removing the diaphragm illuminating lamp unit. This operation is not remotely controlled but must be done manually at the instrument.

2.7 Modes

PISCO can be used in several different modes: linear and circular polarization with either single or double apertures (for sky polarization compensation), and with or without a rotation of the compensating wave plates half way the integration to correct for some of the instrumental effects (mainly the wave plate self polarization).

Below the available modes are briefly described and suggestions given regarding the appropriate circumstances in which to use a particular mode.

1. **Linear polarization measurement.**
    (a) One aperture: telescope movement for sky.
    (b) Two apertures: one star + sky, the other sky. Telescope movement for sky intensity measurement.

Modes 1a and 1b can be used without (NO) or with (ER) a rotation of the compensating wave plates by 180° halfway each integration to compensate for the polarization of the wave plate.

A total of 4 linear modes are therefore available.

2. **Circular polarization measurement.**

   One hole, movement of telescope for sky intensity and polarization measurement.

   Mode 2 can be used without (NO) or with (ER) the 180° rotation of the compensating wave plates. Using ER mode does not eliminate the self polarization of the wave plate but allows the linear polarization of the source to be determined albeit with reduced efficiency when compared with straight linear polarization measurement (modes 1a and 1b).

   A total of 2 circular modes are therefore available.

3. **Filter selection.**

   (a) Different filters in the X,Y channels.
   (b) The same filters in the X,Y channels.

   These selections can be used with all modes (1a, 1b and 2).

A total of 12 observing modes are therefore available and here some recommendations are made for the optimal use of these modes under different circumstances.

i) **Moonlit sky-linear:** use mode 1b with ER

ii) **Dark sky-linear:** use mode 1a or 1b both with ER.

iii) **Dark sky circular polarization:** circular polarization should *only* be measured with *dark* sky since the sky compensation (two apertures) mode does not help and only increases the sky intensity by a factor 2.

Use of ER is recommended since the linear component of polarization in the V Stokes parameter is eliminated and a measure of the sources' linear polarization is also obtained.

Unless two different wavelengths *must* be measured simultaneously it is *always* recommended to measure with the *same* filters in the X,Y channels. The effects of any differential influences are fully compensated by doing this. Scintillation and the uncertainty in the calibration values (see section 2.8) are the main contributions which will be eliminated.

2.8 Calibrations

2.8.1 Rotating wave plate time intervals

The rotating wave plate contains 32 small magnets passing a Hall sensor. The pulses from the sensor define the time intervals over which measurements are made. Since these intervals are not perfectly equal, these values have to be calibrated. There are several softkeys for this purpose which can be accessed as follows. Press [CALIBRATION]. You are now in the calibration menu. [Measure calibration] will measure 7 sets of values and store the average in an IHAP file. ***These files should be used to divide into all raw data.*** Calibration values should be measured regularly during the night.

[Load meas'd values] loads the most recently measured values into a table which is then used to calibrate all the on-line results. [Load permanent values] loads the originally recorded values. [Test calibration] compares the permanent values with the current set of values and gives a warning when differences of more than 0.05% are detected. [Display calibr. values] and [show calibr. values] show the calibration values in graphical and written form respectively. Press [PREVIOUS MENU] to quit the calibration menu.

2.8.2 Angles, self polarization, and efficiency

When measuring linear polarization the following calibration measurements have to be taken:

a) One or more unpolarized standard stars to determine the instrumental self polarization. This has to be done for each filter used and every run since the value can depend on the cleanliness and aluminization of the telescope mirrors.

b) One or more polarized standard stars to determine the instrumental angle in the equatorial frame.

c) One or more arbitrary (preferably bright) stars with the polaroid inserted in the beam to determine the instrumental efficiency. For PISCO the values should be between 95% and 97% depending on the filter used.

For circular polarimetry calibration a) is necessary for the same reason, b) can be omitted, and c) has to be done to find the instrumental angle Φ (see section 3.7).

Lists of reliable polarized and unpolarized standard stars are available in the control room of the 2.2 m telescope.

2.9 Data format

All files produced by PISCO are written to disk and tape in the following format:

IHAP files with 8 scanlines with 32 data points each. The contents are the accumulated raw counts in each of the 2×32 channels.

Scanlines 1 and 2 contain values for integrations in the direct mode, scanlines 3 and 4 values from the rotated mode of the compensating phase plates.

Scanlines 5, 6 and 7 are used to keep the results of the on-line data reduction. Table 2.1 shows the contents of scanlines 5, 6 and 7.

Scanlines 1,3,5 contain results for the X channel; 2,4 and 6 results from the Y channel, while line 7 contains X and Y channel combined results. Line 8 is unused at present.

The calibration measurements are stored in files with the same format. Seven sets of calibration data are stored in the first 7 scanlines; the normalized mean of these data is kept in the 8th scanline.

The instrument status and the relevant parameters of the observation are stored in the `WICOM` of the file and can be inspected with the IHAP command `WICOM,#n`. The IHAP header in addition contains as 'User Integer' the integration times in both channels and as 'User Float' the degree of polarization which was determined by the on-line reduction. Use the IHAP command `DLIS,#n,LO` to see these values. Note that the actual integration time is shorter than *end time* - *start time* since some time is lost for communication between the microprocessor and the HP computer.

Table 2.2: Content of scanlines 5, 6 and 7 in the data files

x-pos.	content	x-pos.	content
01	Int. counts/sec	17	int.time rotated
02	error of 1	18	not used
03	$P_{x}(,V)$	19	not used
04	error of 3	20	not used
05	$P_{y}(,L)$	21	dark counts/sec
06	error of 5	22	density filter
07	Q(,V)	23	Int. sky counts/sec
08	error of 7	24	error of 23
09	U(,L)	25	Q(,V) for sky
10	error of 9	26	error of 25
11	degree of pol. (%)	27	U(,L) of sky
12	error of 11	28	error of 27
13	angle of pol. (^{o})	29	
14	error of 13	30	
15	int. time total	31	
16	int. time direct	32	

In parentheses, the contents are given for circular measurements. For linear measurements the Stokes parameters Q, U are given, for circular the circular Stokes parameter, V, and the linear component, L are given. The definitions of P_x and P_y are given in sections 3.6 and 3.7.

Chapter 3

Observing

3.1 Starting up and closing down

Check the following before starting your observations.

In the dome:

1. Temperature setting (−40°) and display (∼ −30°) of the cooler mounted on the telescope.
2. Setting of the high voltage (1950 V) on the HV unit in the NIMBIN.
3. No polaroid in the instrument for normal use.

In the control room:

1. Program is running. If not start by typing `PISCO` with carriage return ("CR") at the `USERNAME?` prompt. The program will now start up. Note that the TCS program must be running before PISCO is started up.
2. Press the softkey [initial seq. #] and fill in the form. As with other instruments all softkey commands are followed by "ENTER" not "CR".
3. Run a few dark integrations (`DK`) to check the dark currents. They should be ∼ 20 to 30 cts s^{-1}.
4. Do some calibration measures.
5. `PURGE` and `PACK` the IHAP database if necessary.

End of night:

At the end of the night there is nothing to do except the normal telescope closing down procedure. This is normally done by the night assistant. If necessary (e.g. work during the day by technical staff) the high voltage of the PMs can be turned down to 500 V. This must be turned back to 1950 V *several hours* before observation start.

3.2 Instrument control and data acquisition

The whole instrument is remotely controlled from the control room via the HP terminal. Commands can be sent to the instrument via form-filling, softkey menus or typed commands, in a manner similar to other ESO instruments. The accumulated counts in the 2×32 channels are updated and displayed every 30 seconds on the graphics screen. In addition, an on-line data reduction is performed, displayed on the screen, and printed out so that the observer can immediately check the quality of the data obtained. Since the accuracy of the calibration values can determine the accuracy of the observations, the calibration values should be measured many times during the night, at least when observing with different filters in X and Y. Only the loaded values (once per night), however, are used for the on-line reduction. To obtain the results of the on-line reduction, type SC at the instrument console.

3.3 Measurements

Set the object to be observed at one of the crosshairs which correspond to an aperture each. No object should be visible on the other cross hair if sky compensation mode is to be used. If a suitable guide star is visible somewhere in the field the normal ESO autoguider system can be used. Experience has shown that the field of view and the sensitivity of the instrument allow autoguiding in almost all cases. For bright stars the autoguider can be used on the aperture itself using reflected light from the object under observation.

For objects fainter than V $\sim$ 9 mag the density filter does not have to be used (F). For brighter objects a B has to be entered, otherwise OVERLOAD will occur and the shutter will be closed.

3.4 Integration times

The correct integration times with the instrument depend on a variety of factors. In order to estimate these times we give in the following table 3.1 typical count rates which have been calculated from the results of tests. The limit of photon shot-noise can hardly be reached in reality. Note that the brightness of the moon-lit sky, especially if it is variable, sets a faintness limit on the stars which can be observed. As a general rule, the *sky* *brightness* × *sky polarization* should be sufficiently small compared to *object brightness* × *object polarization.* It is recommended to use the sky compensation mode always in moonlight and for observations of linear polarization. A smaller diaphragm may be used to reduce the sky background. For brighter stars, the accuracy of one-channel observations is probably limited by the accuracy of the calibration values, which are variable at the level of 0.1%. In two-channel mode, the calibration values cancel to first order in the computation of the polarization and much higher accuracies can be obtained.

In Table 3.1 are given the count-rate (in counts/sec) which can be expected for a star which has magnitude 10.0 in all filters, if the counts of the X and the Y channel are added (two-channel mode). These numbers have been computed from observations of standard stars. The corresponding limiting magnitude for a given integration time and a desired photon noise error ϵ for the normalized Stokes parameters can then be calculated from the formula $\epsilon(Q/I) = \epsilon(U/I) = \sqrt{2N}$, where Q/I and U/I are the normalized Stokes parameters and N is the total number of photons counted (cf. Serkowski 1974). The limiting magnitude for an integration time of 10 min and a photon noise error of 0.1% is given in the table. It should be noted that the *actual* limiting magnitudes are somewhat brighter since photon shot noise is not the only source of errors. Nevertheless, the numbers can serve as a guide for planning observations.

Table 3.1: Sensitivity of PISCO in UBVRI filters

filter	U	B	V	R	I
counts/sec(10th mag.star)	$1.2\ 10^4$	$8.0\ 10^4$	$1.4\ 10^5$	$1.3\ 10^5$	$6.5\ 10^4$
limiting magnitude	11.4	13.5	14.1	14.0	13.2

3.5 Linear polarization

The multichannel analyse for the X and Y channel accumulate the following values:

$$\text{Channel X: } J_{xi} = +\sigma \times (P_x \cos(4\Phi_i) + P_y \sin(4\Phi_i))$$

$$\text{Channel Y: } J_{yi} = -\sigma \times (P_x \cos(4\Phi_i) + P_y \sin(4\Phi_i))$$

where i=1,...,32 is the counter address and $\Phi_i = i \times 11.25° + \Phi_2$ where Φ_2 is the wavelength dependent instantaneous angle of the rotating retarder.

σ describes seeing effects, the transmission through the atmosphere, and also the scatter in the calibration values. If the same colour filters are used for the X and Y channels, the two-channel method can be applied and the polarization can be derived from the following values:

$$J_i = J_{xi} + J_{yi}$$

where $J_{xi,yi}$ are now the count rates after subtraction of dark current and sky and normalization. This formula is also valid for high polarization. Due to the two-channel procedure, σ is cancelled in first order. In one-channel mode, J_i is replaced by

$$J_i = \sigma_{x(y)} \times J_{xi(yi)},$$

where $\sigma_{x(y)}$ tends to unity with increasing integration time due to the smoothing effect of the multichannel analyzer.

The Stokes parameters Q and U can be derived from J_i by Fourier analysis. Since the signal average consist of discrete channels, the final values have to be multiplied by a factor which takes the depolarization of the discretization process into account. For PISCO this factor is $\pi \cdot \sin \pi/8$.

The mean error of the quantities Q and U can be derived from the following formula:

$$\epsilon = \sqrt{\frac{\sum_{i=1}^{32} \frac{J_i^2 - 16Q^2 - 16U^2}{3}}{16 \times 30}}$$

The combined power in the 5th and higher harmonics of the Fourier transform give the error in the degrees of polarization, p, which is equivalent to the power in the 4th harmonic.

3.6 Determination of linear polarization

The following points have to be considered:

- The compensating phase plates eliminate the strong wavelength dependence of the fast axis angle Φ_2 of the rotating retarder. It should thus be sufficient to determine Φ_2 for one wavelength only by measuring at least two polarized standard stars.
- The compensator allows to eliminate the sky background polarization by observing with two holes. However, this increases the sky background by a factor two. In practice a factor of about 10 to 15 improvement in S/N ratio can be obtained on moonlit nights.
- The instrumental polarization of the compensator can be eliminated by measuring also in the rotated position of the compensator (ER mode).
- The instrumental polarization which depends not only on the effective wavelength but also on the momentary shape of the telescope mirrors has to be measured by observations of unpolarized standard stars.

3.7 Determination of circular polarization

The quarter-wave plate simply converts the circular polarization into a linear one (and partly vice-versa). Therefore, circular polarization can be measured in exactly the same way as linear polarization by means of the rotating phase plate. The disadvantage of using the quarter-wave plate in front of the rotating retarder is that the second coefficient of the self-polarization (described by the quantity β in Metz (1986)) cannot be eliminated only by a rotation of the compensator by 180°. In addition, the resulting orientations of the optical axes of the rotating half-wave and fixed quarter-wave plate depend on the effective wavelength. The following formula can be used for the reduction.

$$(P_x, P_y) = ((P_x^d - P_x^r)/2,\ (P_y^d - P_y^r)/2),$$

where $(P_x^{d(r)}, P_y^{d(r)})$ are the normalized Stokes parameters determined by Fourier analysing the data from the signal averages obtained with the quarter-wave plate in the direct (^{d}) and in the rotated position (^{r}). If the measurement is carried out only in the direct position, we have

$$(P_x, P_y) = (P_x^d, P_y^d).$$

Defining $\Phi = (4 \times \Phi_2 - 2 \times \Phi_4)$, where Φ_2 and Φ_4 are respectively the zero positions of the fast axes of the rotating half-wave and compensating quarter-wave retarders (which depend on the effective wavelength in a similar but not identical way), one gets for the circular Stokes parameter P_V:

$$P_V = -\sin(2\Phi) \times P_x + \cos(2\Phi) \times P_y - \beta,$$

where it can be seen that β cannot be eliminated by measuring in the rotated retarder position. However, by this additional observation it is possible to derive also (with reduced accuracy) a measure of the degree of the linear polarization:

$$P_l = \sqrt{((P_x^d + P_x^r)/2)^2 + ((P_y^d + P_y^r)/2)^2}$$

Please note that P_x and P_y here are instrumental quantities which should not be confused with the Stokes parameters P_x and P_y of the object. If P, θ are the degree and angle of linear polarization, we have:

$$P_l = |P \times \cos 2(\theta - \Phi_4)|$$

It follows immediately that the degree of linear polarization can be determined only if the angle θ is known. Consequently, before starting observations of circular polarization, the observer should consider the following points:

- The measurements should be done with one hole, since otherwise the sky intensity is doubled without eliminating the linear polarization of the sky background.
- The rotation of the compensator does not help to eliminate the self polarization coefficient β. It is useful, however, since the contribution P_l of the linear polarization to P_V in P_x and P_y is eliminated completely. It also allows to get a rough estimate for the degree of linear polarization. The coefficient β has to be determined from unpolarized standard star measurements.
- Since the quarter-wave plate transforms circular to linear polarization (and partly vice-versa), the precise knowledge of the angle Φ is necessary. Special polaroid sheets are available for this purpose. (See section 2.6).

3.8 Data reduction

The reduction of PISCO data requires in principle more or less only a Fourier transform of the data. Thus the data reduction is straightforward. It can be done e.g. with the IHAP or MIDAS systems of ESO at Garching or La Silla. An IHAP batch is available for reduction of linear polarization data. First all data have to be divided by the calibration values. Sky has to be subtracted from the object+sky data and a Fourier transform of the resulting data will then give p, the power in the 4th harmonic, θ, the phase and the error on p in the power of the 5th and higher harmonics. The modulation of the intensity with and without sky compensation is illustrated by Stahl et al. (1986). The user can, of course, use his/her own data reduction procedure, since the data can be easily transported to other computing facilities. *The results of the on-line reduction should be regarded as quick-look results only. Every observer is responsible for the final reduction of his/her data.*

3.9 Trouble shooting

PISCO rarely hangs up. If this should happen, go to the system terminal and get the attention of the FMGR (`RU,FMGR`). Then type: `TR,OFPISC` and leave the FMGR again (`EX`). Then at the instrument console type `TR,*HPISC` or log off and log in again with PISCO.

Under special circumstances it may sometimes happen that you cannot leave a softkey menu but the program does not hang up. In this case it may suffice to type `MM` to come back to the MAIN MENU and continue.

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Appendix A

Polarimetry

Since polarization measurements are a rather specialized form of astronomical observation, a short introduction to the technique is given below.

The first thing that has to be realized is that, unlike with other measurements, the *intensity* of the light is not the measured quantity. Typically, the difference between 2 intensities is measured. Any light beam can be described by four parameters forming a vector, the "Stokes vector" after Stokes (1852). The usual designation is I,Q,U,V, where I = intensity; Q,U = linearly polarized intensity; V = circularly polarized intensity. That the "Stokes parameters" are intensities means that (always assuming *incoherent* beams of light) the vectors can be added, etc. and that any optical element or medium in principle can be represented by a 4×4 matrix. Premultiplying the input vector by all the appropriate matrices then produces the right vector. This way of calculating the effects of optics on light is called the Mueller calculus after Mueller (1948).

In a polarization measurement the usual quantity of interest is the percentage polarization p and the angle of vibration, θ, and not just the intensity of the light.

The products: star intensity $\times$ polarization and sky intensity $\times$ polarization are the important quantities.

A.1 The Stokes parameters

In 1852 G.G. Stokes presented a set of four numbers which described completely a beam of light (Stokes, 1852). Other four-number sets would serve this purpose but the "Stokes parameters" as they are called have properties that make them especially suitable. They are simply derived from the classical equations describing electromagnetic waves, and most importantly, they are additive. This latter property means that to obtain the Stokes parameters of a beam of light which is the superposition of several (incoherent) beams, one simply has to add the Stokes vectors of the individual beams. Conversely, any single beam can be thought of as being the sum of several beams; the concept of considering partially polarized light as being made up from an unpolarized and a fully polarized component is particularly useful.

The Stokes parameters can be defined in terms of a plane electromagnetic wave travelling along the positive z–axis, viz.

$$\begin{aligned} E_x &= a_x \cos(\omega t - \mathbf{k}\cdot\mathbf{r} + \delta_x) \\ E_y &= a_y \cos(\omega t - \mathbf{k}\cdot\mathbf{r} + \delta_y) \\ E_z &= 0 \end{aligned} \qquad (A1)$$

where

$$\begin{aligned} \omega &= \text{frequency} \\ \text{t} &= \text{time} \\ a_x, a_y &= \text{amplitudes} \\ \mathbf{k} &= \text{wave vector} \\ \mathbf{r} &= \text{radius vector} \\ \delta_x, \delta_y &= \text{arbitrary phases} \end{aligned}$$

From equations (A1) we obtain:

$$(E_x/a_x)^2 + (E_y/a_y)^2 - 2E_xE_y\cos\delta/(a_xa_y) = \sin^2\delta \qquad (A2)$$

where $\delta = \delta_y - \delta_x$

(A2) is the equation of an ellipse with semi-major axis a and semi-minor axis b tilted with respect to the positive axis by an angle ψ, where a, b and ψ are defined by

$$\begin{aligned} \tan 2\psi &= \tan 2\alpha \cos\delta \\ \tan x &= \pm \text{b/a} \\ a^2 + b^2 &= a_x^2 + a_y^2 \\ \sin 2x &= \sin 2\alpha \sin\delta \\ \tan\alpha &= a_y/a_x \end{aligned} \qquad (A3)$$

This implies that, generally, light will be elliptically polarized. Two special cases of interest are linear and circular polarization. These occur under the following conditions:

$$\begin{aligned} &\text{linear} \quad \delta = m\pi \\ &\text{circular} \quad a_x = a_y \text{ and } \delta = \pm\pi/2 + 2m\pi \end{aligned} \qquad (A4)$$

where m is a positive integer and the "handedness" of circular polarization is defined in a variety of ways (see Clarke, 1974) giving confusion in the literature. Here we will use the positive sign for righthanded and the negative sign for the lefthanded polarization.

The Stokes parameters are defined by

$$\begin{aligned} \mathrm{I} &= a_x^2 + a_y^2 \\ \mathrm{Q} &= a_x^2 - a_y^2 = I\cos 2x \cos 2\psi \\ \mathrm{U} &= 2a_x a_y \cos\delta = I\cos 2x \sin 2\psi \\ \mathrm{V} &= 2a_x a_y \sin\delta = I\sin 2x \end{aligned} \tag{A5}$$

The set of four numbers I,Q,U and V is often used, but in the literature other symbols are also in use such as:

A,B,C,D,	Stokes, 1852
I,M,C,S.	Jones, 1941

The normalized stokes parameters are defined as:

$$\begin{aligned} \mathrm{q} &= \mathrm{Q/I} \\ \mathrm{u} &= \mathrm{U/I} \\ \mathrm{v} &= \mathrm{V/I.} \end{aligned} \tag{A6}$$

For a physically more meaningful vector one can be obtained by transforming from q, u space to p, θ space, as follows:

$$\begin{aligned} p &= \sqrt{(q^2 + u^2)} \\ \theta &= 0.5\tan^{-1}(u/q) \end{aligned}$$

The statistical properties of p and θ are not straightforward and are described by Serkowski (1958, 1962). For a discussion of the statistics of normalized Stokes parameters see Clarke et al. (1983) and the in-depth review by Clarke and Stewart (1986).

Under the assumption that q and u are normally distributed about their mean values, determined values of p are biased relative to p_o, the true polarization according to the value of ϵ, the observed uncertainty on an individual normalized Stokes parameter. For simplicity it is assumed that $\varepsilon_q = \varepsilon_u = \varepsilon$.

The relationships between p and p_o and between the uncertainty ε_p on p_o and ε_θ on θ are as follows:

$$p^2 = \left\{ \begin{array}{ll} p_o^2 + \pi\varepsilon^2/2 & p_o \approx o \\ p_o^2 + \varepsilon^2 & p_o \gg \varepsilon \end{array} \right\}$$

$$\varepsilon_p = \left\{ \begin{array}{ll} \varepsilon(2 - \pi/2)^{0.5} & p_o \approx o \\ \varepsilon & p_o \gg \varepsilon \end{array} \right\}$$

$$\varepsilon_\theta = \left\{ \begin{array}{ll} \pi/\sqrt{12} = 51^\circ.96 & p_o \approx o \\ \varepsilon/2p = 28^\circ.65\varepsilon/p & p_o \gg \varepsilon \end{array} \right\}.$$

which are the asymptotic cases of the general distributions of p and ε, given by

$$f(p) = p/\varepsilon^2 \exp[-(p^2 + p_o^2)/2\varepsilon^2] J_o(ipp_o/\varepsilon^2)$$

$$g(\theta) = \pi^{-0.5}[\pi^{-0.5} - \eta_o \exp(\eta_o^2)(1 - erf(\eta_o))] \exp(-p_o^2/2\varepsilon^2) \text{ where,}$$

$J_o(ix)$ is the zero order Bessel function of the imaginary argument and $\eta_o = p_o/\sqrt{2}\varepsilon \cos 2(\theta - \theta_o)$.

The approximate expressions above will, in most cases and where the signal to noise ratio is not too low (see Clarke and Stewart, 1986), give accurate results.

A.2 Mueller calculus and PISCO

Mueller (1948) developed the calculus for handling the effect of any optical device on a beam of light of arbitrary polarization. This calculus makes use of 4×4 matrices to represent optical elements such as polarizers and retarders. The matrices operate on the Stokes vector representing the incoming light beam to determine the outgoing beam. Each elements' matrix is premultiplied by the matrix of the device through which the light passes next, thus forming a new 4×4 matrix representing the combined effect of the two elements. For a simple exposition on the use of Mueller matrices see for instance Walker (1954), Shurcliff (1962), or Clarke and Grainger (1971).

Applying the Mueller calculus to PISCO, we can write the effect of the half-wave plate and polarizer on an incoming beam with Stokes vector (I,Q,U,V) as,

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}' = [P] \times [-R] \times [\pi] \times [R] \cdot \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \qquad (A7)$$

where,

[P] is the polarizer matrix
[R] and [-R] are the rotation matrices
[π] is the retarder. Primes denote the emerging beam.

The rotation matrices transform the optical elements to the appropriate reference frame. Substituting the transformed matrices for the polarizer and the retarder into equation (A7) we obtain

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}' = \begin{bmatrix} 1 & \frac{1}{2}C_2(\psi) & S_2(\psi) & 0 \\ \frac{1}{2}C_2(\psi) & C_2^2(\psi) & C_2\,S_2(\psi) & 0 \\ S_2(\psi) & C_2\,S_2(\psi) & S_2^2(\psi) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_2^2 - S_2^2(\phi) & 2C_2\,S_2(\phi) & 0 \\ 0 & 2C_2\,S_2(\phi) & S_2^2 - C_2^2(\phi) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

where:

$$S_2(\psi) = \sin 2\psi; \quad S_2(\phi) = \sin 2\phi$$
$$C_2(\psi) = \cos 2\psi; \quad C_2(\phi) = \cos 2\phi \qquad \text{(A8)}$$

and

ϕ is the angle of the fast axis of the half-wave plate;
ψ is the angle of the polarizer, both with respect to an arbitrary reference frame.

Corresponding to the two orthogonal beams emerging from the Foster prism, we set $\psi = 0$ or $\psi = \pi/2$ in equation (A8). After some reduction we obtain an intensity modulation given by

$$I'\,(\phi) = \tfrac{1}{2}(I \pm Q\cos 4\,\phi \pm U\sin 4\,\phi), \qquad \text{(A9)}$$

where the plus sign corresponds to $\psi = 0$.

Note that these equations only apply for *perfect* optical elements.

By integrating equation (A9) using the appropriate limits, the intensity I and the two Stokes parameters Q and U can be obtained. This integration is performed electronically in PISCO by the opening and closing of the scalers at appropriate times in the cycle of the rotating half-wave plate.

Every rotation of the $\lambda/2$ plate is split into 32 bins which are displayed by the on-line reduction software. For polarized sources, a clear modulation at four times the rotation rate can be seen in the data. The power in the 4th harmonic is equivalent to the polarization degree, and the phase is equivalent to the angle of polarization.

Appendix B

Typed commands

Some of the soft-key functions can also be used by giving a direct, typed command. In some cases this saves time.

By typing ?? or HELP a list of the available typed commands is obtained.

The following commands are available:

Typed deviation	Command	Notes
MM	main menu	use only when PISCO hangs up.
L1	lamp on	acquisition field illumination
LO	lamp off	" "
L+	lamp brighter	" "
L--	lamp darker	" "
LF	large field	acquisition field of view
SF	small field	" "
DA RE	data restore	graphic output modifiers
BO RE	box restore	" "
GD ON	graph display on	" "
GF OFF	graph display off	" "
AD ON	alpha display on	" "
AD OFF	alpha display off	" "