E U R O P E A N   S O U T H E R N   O B S E R V A T O R Y

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral

Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

# La Silla Observatory

**TECHNICAL REPORT**

**on**

**The Polarimetric Mode of SOFI**

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# 1 Purpose

In this report we describe the use of the polarimetric mode of SOFI for scientific observations. In particular we discuss which calibrations are necessary, how to obtain them, how to carry out the observations, reduce and calibrate the data. The instrumental effects are discussed as well and quantified. For a more detailed description of the polarization mode of SOFI, such as technical aspects, we refer to the ``SOFI User's Manual''. An alternative version of this report, possibly more dettailed and with better figures, can be downloaded from: http://www.ls.eso.org/lasilla/Telescopes/NEWNTT/sofi/pol/report.ps

The results presented in this report have been obtained from the analysis of the data taken during the technical periods of May, June, July 2000, February 2001 and February 2002.

This document is mainly directed to the NTT staff performing the instrument calibrations and to the observers that need an advanced knowledge of the subject. The most important results of this work, mainly the information necessary to prepare a proposal and to perform basic reduction and calibration of polarimetric data of SOFI will be included in the next issue of the SOFI User Manual.

# 2 Observations

Polarimetric observations are performed in SOFI with the use of a Wollaston prism. The prism is introduced in the optical path and it splits the incoming light in 2 beams with perpendicular polarization. Since 2 images of the observed field are produced on the array it is necessary to limit the field of view of the instrument to avoid overlapping. This is achieved with a special mask (polarimetric mask) that can be inserted on the focal plane of the telescope. The polarimetric mask is mounted on the mask wheel of SOFI, it is made of three open areas about 40 x 300 arcsec in size and three corresponding dark areas (see Fig. 1 for illustration).At least three observations are required to cover the whole field of view of SOFI. The optics used by the polarimetric mode is the same as for the large field so that the pixel scale is unchanged respect to this mode.
Two observations must be performed at each pointing of the telescope with different orientation of the Wollaston prism, typically 0 and 45 degrees, these values are defined in the template and correspond to the Position Angle (PA) on the sky. Doing so measures at 0 and 90 degrees are actually obtained with the first observation (0) and measures at 45 and 135 degrees with the second one (45). The orientation of the Wollaston prism is changed rotating the whole instrument. Furthermore for each field and for each position angle several images must be acquired offsetting the telescope in order to provide a good sky determination. As in the normal imaging the jitter ON-ON (keeping the object always in the field) is used if the object is small enough. When the object is large compared with the size of one polarimetric mask strip the jitter OFF must be used and an independent sky must be acquired. The offset pattern better develops in the strip direction in the first case while it is free in the second case. In both cases the offsets must be explicitly indicated in the template, the auto-jitter mode is not available for the polarimetric mode.

# 3 Calibrations and Data Reduction

The reduction of polarimetric images basically follows the same recipes of standard image reduction. As in the case of any other (near-infrared) images, images taken with SOFI at the NTT in polarization mode have to be corrected for ``bad'' pixels, the sensitivity distribution of the pixels on the chip (flatfield) and the sky contribution. Additionally, one has to consider that:

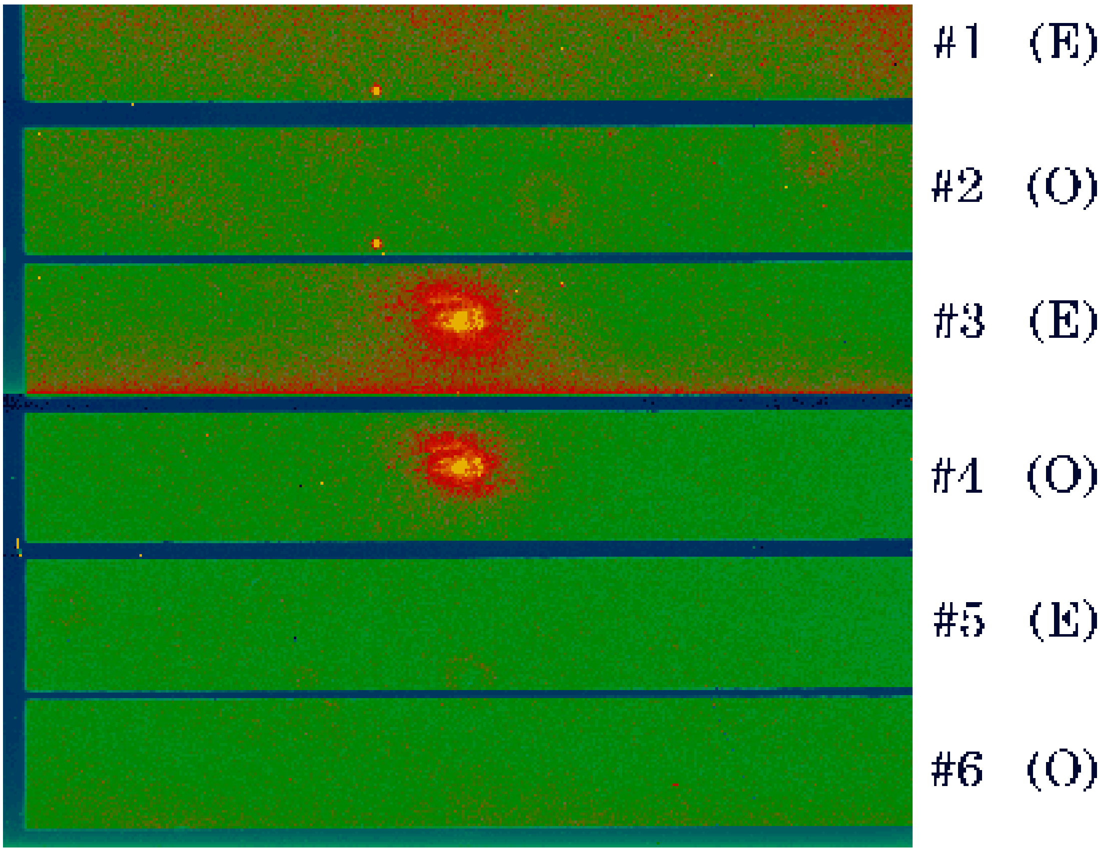


Fig. 1 Frame resulting from a single exposure with SOFI using the Wollaston prism and (therefore) the polarimetric mask in the optical path. The two beams are denoted as ordinary ray (``O'', component of the incoming light parallel to the axis of the analyser) and extra-ordinary ray (``E'', component of the incoming light perpendicular to the analyser axis)

1) The flatfield image may be intrinsically polarized,

2) The instrument and the telescope may influence the polarization state of the incoming light (instrumental polarization - IP). The IP may arise from:

a) a deviation of the transmission of the Wollaston prism for the two beams (whose plane of polarization differs by 90 degree),

b) the reflection on the primary and secondary mirror of the telescope,

c) the reflection on the tertiary mirror of the telescope

The main contribution to the instrumental polarization is expected to arise from a) and c). The contribution by a) and b) are expected to be constant (for a given wavelenght/filter), while the contribution due to the reflection on the mirror M3 is expected to depend on the angle between M3 and the detector that is defined by the altitude of the telescope and position angle. Furthermore each contribution is wavelength-dependent.

In this section we will point out only those steps of the reduction that are peculiar to polarimetry. We will then assume that the reader is already familiar with bad pixel correction, flatfielding, combination of dithered images and so on.

### 3.1 Flat-Fields

A flatfield reduction is strongly recommended in order to take into account the sensitivity distribution of the chip. If the flatfield correction is not applied, the photometric error may result in about 2% (Ks band). The flatfield exposure should be performed using the same filters as the subsequent object exposures and with the Wollaston prism in the optical path. This is important since the flatfield without Wollaston prism may differ substantially from that taken with the Wollaston prism, mainly due to a slightly different illumination of the chip. Since the whole instrument rotates to provide a certain orientation of the Wollaston prism, separate exposures at different orientations are not required for the flatfields.
The flatfield may either be deduced from dome exposures (``dome flatfields''), where a series of exposures with and without a lamp illuminating the inner dome is taken, or from a sky map.

1) Dome Flatfield (recommended) are obtained from the difference of frames taken with the lamp ON and OFF.

Exposure 1 (e1): lamp - off

Exposure 2 (e2): lamp - on (typically 4000 ADU)

Exposure 3 (e3): lamp - on

Exposure 4 (e4): lamp - off

$$FF = \frac{e2 + e3}{2} - \frac{e1 + e4}{2}$$

Fig. 2 shows the fields #3 and #4 in case of an exposure with the lamp switched off. The background structure, being typical for SOFI exposures in the polarimetric mode, is due to the infrared background radiation (direct and scattered light) whereby the relative brightness profile is due to the Wollaston and the polarimetric mask in the optical path, i.e., it appears only in the polarimetric.
The resulting flatfield image is polarized, i.e., the median value of the upper field is different from the median value of the lower field. However, this problem can be overcome by an independent normalization of the flatfield in each field.

2) The flatfield may also be deduced from the background sky of many images, if the object islocated at different positions on the chip during the measurements. However, it is not recommended because "ghost" of the object on consecutive images may result in a wrong flatfield especially at the position(s) of the object.

To perform the flatfield reduction, we recommend the following procedure (in the following is assumed that the object does not exceed the size of a single field 0.5′ x 0.7′):

1) Create a flatfield for each of the two fields on the detector. Let $f_u$ ($f_l$) be the upper (lower) flatfield.

2) Select the upper/lower field from the flatfield f (take care not to get in the range blended by the mask; see Fig 3): $f_{u,0}$, $f_{l,0.}$ Measurements in the Ks band show that the change of the flatfield

polarization within $f_{u,0}$, $f_{l,0}$ is not zero but less than 0.05% and therefore negligible compared to the other sources of error. Therefore, the assumption that no pixel-to-pixel polarization in $f_{u,0}$, $f_{l,0}$ exists is valid.

3) Normalize each flatfield by its median value

4) Divide the upper/lower field of the (object) image by the corresponding flatfield

This way, the flatfield correction can be done without introducing an artificial polarization due to a possible intrinsic polarization of the flatfield. This procedure is based on the assumption that if the flatfield is polarized, the polarization (degree and orientation) is constant over the whole field of 0.5′ x 0.7′ (= area of the upper [lower] field), i.e., the pixel-to-pixel polarization is negligible as stated above.

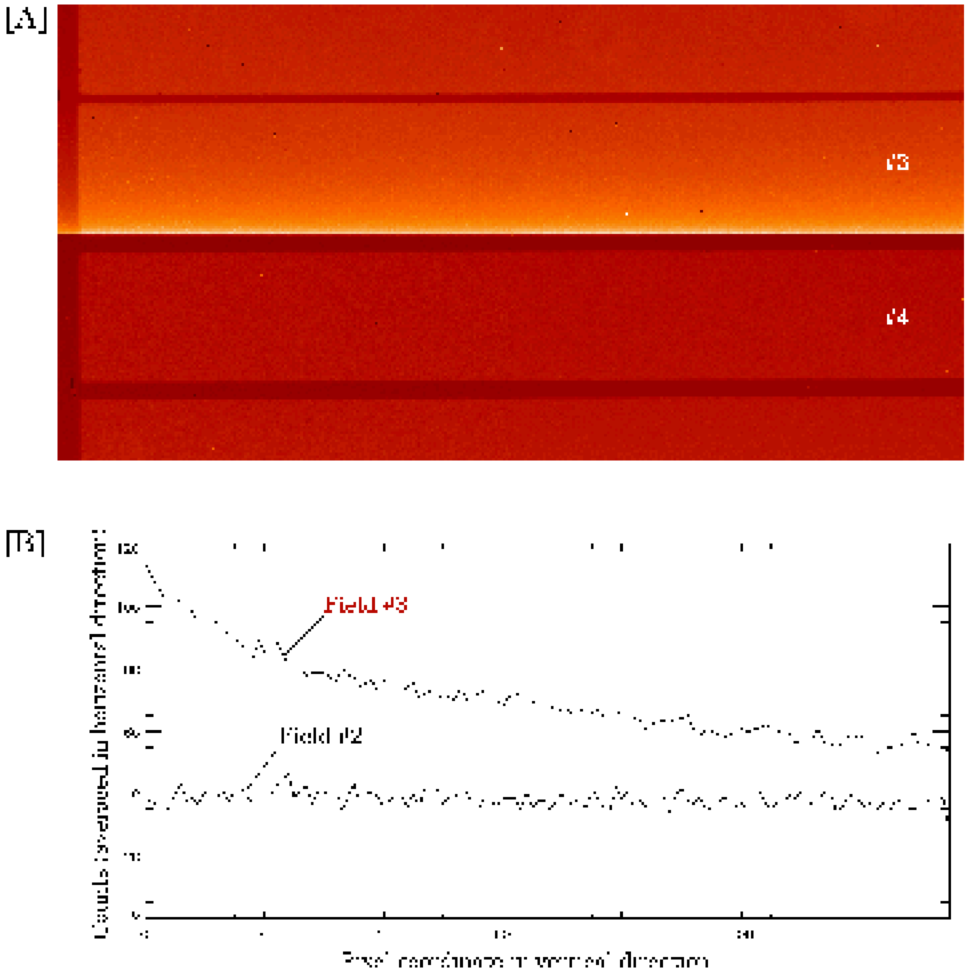


Fig. 2 Fields [A] #3 and #4 of a dome exposure with the lamp switched off. [B] Vertical intensity profile in the upper (#3) and in the lower field (#4), averaged in horizontal direction.

### 3.2 Correction for the wrong transmission ratio of the Wollaston prism

Artificial polarization is introduced by a deviation of the transmission ratio of the Wollaston prism. Ideally the Wollaston prism should split an unpolarized beam in 2 beams of equal intensity, however we have notice that this is not the case and there is a difference in the transmission of the 2 beams. Due to the intrinsic polarization of the flats this effect is not corrected by the normal flatfielding and must be explicitly taken into account. The following three alternatives for the correction of the wrong transmission ratio are proposed:

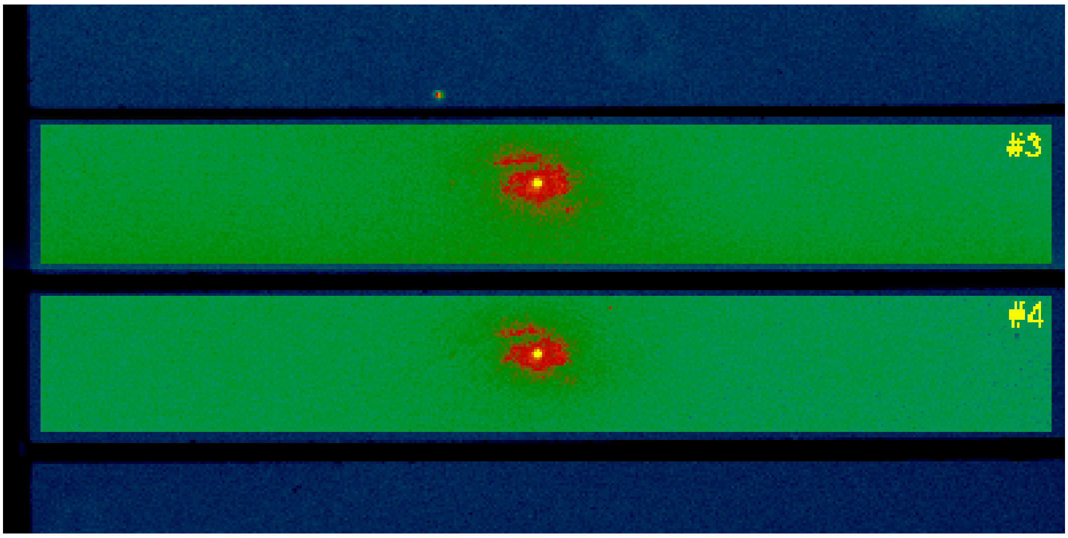


Fig. 3 Areas considered in the flatfield for the data reduction.These areas have the pixel coordinates [35:1010,516:651] (upper field) and [35:1010,354:484] (lower field).

1) Multiplying each strip of the field by a suitable factor. Such a factor has been measured in different occasions and the values obtained are listed in the next table as ratio between the upper and lower strip (see Section 6 for details):

| Date | J | H | Ks |
|---|---|---|---|
| July 00 | 0.94 | 0.94 | 0.96 |
| Feb. 01 | 0.952 +/- 0.007 | - | 0.971 +/- 0.007 |

Tab. 1 Differential transmission factors of the Wollaston prism

2) Since the sky is also affected by this effect, a good measure for the intensity ratio of both beams can be derived from the median of the lower/upper image. This method may not be applied if the polarized object covers a large fraction of the lower/upper image (because then the median value may be influenced by the possibly polarized object). This method works properly only if the background radiation of the sky is unpolarized and the images are not affected by scattered moonlight.

3) Fitting a cos(2θ) function to the intensity of the object on the image as a function of the orientation (θ) of the wollaston prism (see Ageorges 2000).

### 3.3 Correction for the Instrumental polarization

The remaining IP is expected to be mainly caused by the reflection on the tertiary mirror M3. It should therefore depend on the altitude angle of the telescope. However, the remaining IP was found to be <0.3% (Ks band) and <0.4% (J band) in our investigation. Since the (statistical) error of the results from which these limits have been derived is in the same order of magnitude, a possible contribution by the mirror M3 could not be extracted.

### 3.4 Sky Subtraction

Since the intensity of the background radiation (also after passing the Wollaston prism) is an **additive** component to the intensity of the object, the subtraction of the sky will also result in the removal of the contribution of the sky polarization to the net polarization of the object. Therefore, the sky has to be estimated and subtracted independently for both the upper and the lower field.
If the observations have been carried out offsetting the telescope the sky subtraction is performed by simple subtraction of one image from the other, or median combining all the images to obtain a sky frame to subtract from the other ones. In any case the usual techniques of image processing apply to polarimetric data.
Additionally one may verify and, if necessary, correct the removal of the local sky background by fitting a bi-dimensional polynome to the background measured in areas free of cosmic rays and faint objects. Polynomials of the first degree have been found to produce the best results.

## 4 Analysis

After the images have been processed as described in the previous sections the main polarimetric parameters can be measured.

### 4.1 Stokes Parameters

The Stokes parameters are given by the following relations:

$$I = I(0) + I(90) = I(45) + I(135)$$

$$Q = I(0) - I(90)$$

$$U = I(45) - I(135)$$

Here I(0), I(90), etc., are the intensities of the object at the corresponding polarization direction (0, 90, etc.). Hereby, the orientation (angle) of the lower field's polarization is that of the Wollaston prism. The polarization direction of the upper field differs by 90 degree from this (see Fig. 4). The normalized Stokes parameter are q = Q / I and u = U / I.

### 4.2 Orientation and degree of the Linear Polarization

The degree of the linear polarization is given by:

$$P = \sqrt{q^2 + u^2}$$

The orientation of the polarization by:

$$\gamma = 0.5\,\mathrm{atan}\frac{u}{q}$$

Alternatively, the polarization degree and orientation can be derived from the polarization curve (intensity of the object as a function of the polarization direction of the Wollaston prism). In both cases, an oversampling by measuring the intensity (difference) for more than two orientations of

the Wollaston prism increases the accuracy of the polarization measurement.
If the polarization measurement is based on the determination of the Stokes parameters q an u measurements for a pair (two) orientations of the prism differing by 45 degree are required.
If x is the (arbitrary) initial orientation of the Wollaston prism, the polarization can be derived from:

$$q' = \frac{I(x) - I(x+90)}{I(x) + I(x+90)} \quad \text{and} \quad u' = \frac{I(x+45) - I(x+135)}{I(x+45) + I(x+135)}$$

being

$$P = \sqrt{q'^2 + u'^2} \quad \text{and} \quad \gamma = 0.5\,\mathrm{atan}\frac{u'}{q'} + x$$

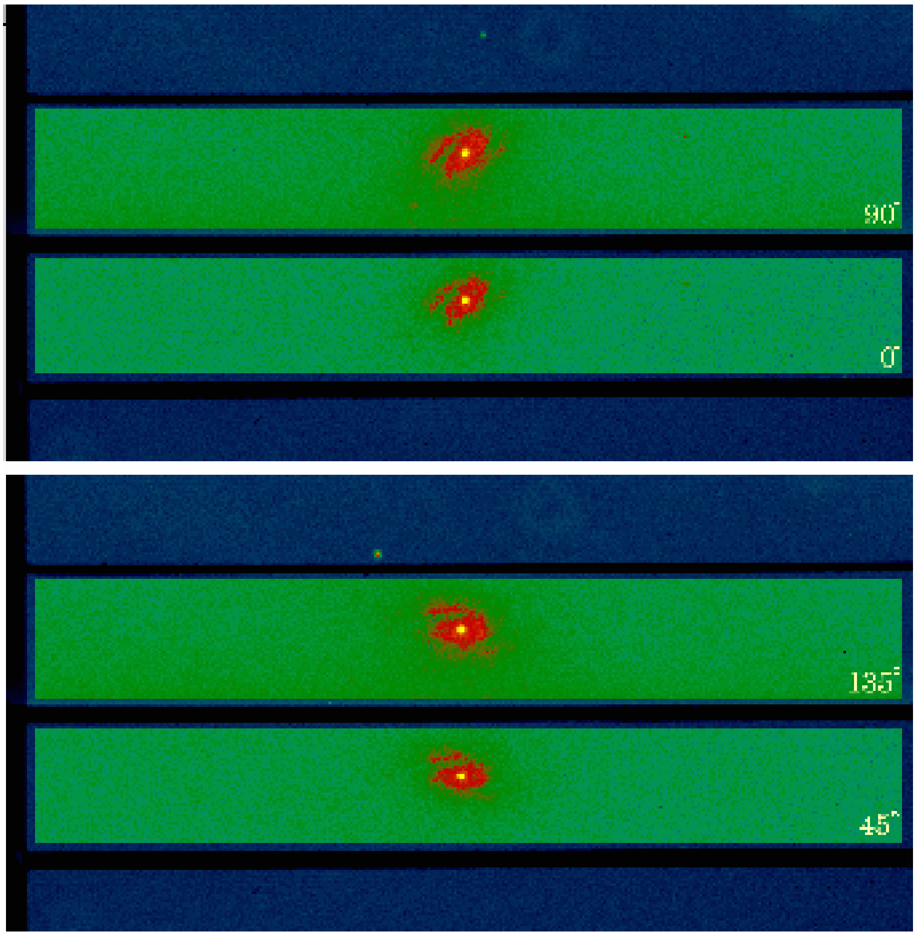


Fig. 4 Orientation of the Wollaston prism and resulting preferential direction of the electric field vector of the light projected on the two inner fields of the chip (#3 and #4)

## 4.3 Errors Estimation

Following the work by Wardle & Kronberg (1974), the standard deviation of the degree and the orientation of the linear polarization σ(P) and σ(γ) can be derived as follows:

$$\sigma(P) = \frac{\sqrt{(\sigma(q)q)^2 + (\sigma(u)u)^2}}{P}$$

$$\sigma(\gamma) \cong 29\frac{\sigma(P)}{P} \quad \text{if} \quad P \gg \sigma(P)$$
$$\sigma(\gamma) \cong 52 \qquad \text{if} \quad P \cong 0$$

If the polarization degree is derived from several individual measurements and $\bar{P}$ is the arithmetic mean of these polarization degrees, correct polarization is derived from

$$P = \sqrt{\bar{P}^2 - \sigma^2(P)}$$

This correction (which is necessary since the polarization degree is a positive definite value) has **not** to be applied if the polarization degree was derived from the (arithmetic) mean of the Stokes parameters.

## 5 Take many exposures

Using the definition of the polarization degree based on the Stokes parameters I, Q, and U for a single polarization measurement, i.e., two exposures of the object with the Wollaston prism at two orientations differing by 45, it is a reasonable assumption that the absolute errors of the Stokes parameters are given by

$$\Delta Q \approx \Delta U \approx \Delta I \approx 2\Delta I'$$

where $\Delta I'$ is the absolute error of a single photometric measurement. Then, the absolute error of the polarization degree can approximately written as:

$$\Delta P \approx [2\ldots2(1+\sqrt{2})] \times \frac{\Delta I'}{I}$$

where the amount of the coefficient depends on the polarization degree and the amount of the ratio Q/U=q/u. Thus, the absolute error of the polarization measurement is directly related to the relative photometric error! The orientation of the linear polarization $\gamma$ is even more sensitive to the accuracy of the photometric measurement and the degree of the polarization:

$$\sigma_\gamma = \frac{\sqrt{(q\sigma_q)^2 + (u\sigma_u)^2}}{P^2}$$

which is valid for $P \gg \sigma_P$ ($\sigma_\gamma$, $\sigma_q$ and $\sigma_u$ are the standard deviations of the orientation of polarization and the reduced Stokes parameters q and u). Since the net polarization of many astrophysical objects does not exceed a few percent, the required accuracy can be achieved often only on the basis of a large number of (dithered) exposures.

The polarization pattern of spatially resolved objects on the other hand, such as the circumstellar shells around young stellar objects and galaxies, show (locally) high polarization degrees. Thus, these measurements are much less effected and easier to perform. Furthermore, the SNR can be drastically increased, in particular by a factor of n, if areas of n x npixels are combined. The main difficulty in case of extended objects is to find a correct superposition (a) of dithered images obtained with the Wollaston prism at the same position and (b) of the co-added exposures obtained at the different orientation of the Wollaston prism.

# 6 The Star HD 64299

This polarization standard star was chosen to develop the data reduction procedure presented in this work (including the investigation of the instrumental polarization). Furthermore, additional observations of unpolarized polarization standard stars have been used to verify the reduction procedure and to enforce the conclusion made about the IP and the transmittance of the Wollaston prism. The main parameters of the considered polarization standard stars and their observations are compiled in Tab. 2.

| Name | RA (2000) | DEC (2000) | V | ref. |
|---|---|---|---|---|
| | PJ(%) | PK(%) | $\gamma$_J | $\gamma$_K |
| HD 64299 | 07 52 25.5 | -23 17 45.9 | 10.15 | Turnshek |
| | | | | |
| HD 11021 | 01 47 40.5 | -29 43 23.4 | 8.83 | |
| | | | | |
| HD 195455 | 20 32 14.7 | -24 04 03.7 | 9.20 | |
| | | | | |
| HD 222126 | 23 38 04.5 | -23 51 46.9 | 9.76 | |
| | | | | |
| HD 150913 | 16 37 16.4 | -23 47 56 | | Whittet |
| | 3.27 +/- 0.06 | 1.68 +/- 0.02 | 57 +/- 1 | 60 +/- 1 |
| HD94851 | 10 56 44.17 | -20 39 51.6 | 9.10 | Turnshek |
| | | | | |
| HD98161 | 11 17 11.84 | -38 00 52.0 | 6.27 | Turnshek |
| | | | | |

Tab. 2 Stars observed for the measure of the Instrumental Polarization

Assuming that the polarization of HD64299 is mainly determined by interstellar polarization, the expected J/Ks band polarization is $P(J) \cong 0.05\%$ / $P(Ks) \cong 0.03\%$ (see, e.g., Nagata 1990). Since these values are smaller than the polarization accuracy achievable with SOFI, the polarization of this star is negligible in the following discussions.
The object was mapped in the Ks and the J band at orientations of the Wollaston prism of 0, , 22.5, 45, and 67 degree and at the following altitude angles of the telescope: 24, 26, 32, 41, 54, 64, 68, 72, and 83. In each case, three exposures have been taken with a constant offset in right ascension between consecutive exposures (offset: 40’’). No correlation between the measured polarization degrees and the altitude of the telescope and the orientation of the Wollaston prism was found. The

derived polarization degree (entirely produced by the instrument) and orientation are[1]:

| | |
|---|---|
| P(Ks)=2.05+/-0.43% | $\gamma$=115 +/- 6 |
| P(J)=3.11 +/- 0.62% | $\gamma$=116 +/- 6 |

Here, the (relative) intensities of the object have been estimated by two different methods.
1) Fitting a Gaussian profile to each object image and Integrating the intensity within an aperture with a radius R=n($\sigma$) x $\sigma$, where

$$\sigma = \frac{1}{\sqrt{2\ln 2}}\frac{\sigma'}{2}$$

Here $\sigma'$is the FWHM of the Gaussian profile and in agreement with the investigation of Lamy & Hutsemekers (1996) concerning polarimetric measurements with EFOSC2 at the ESO 3.6-m telescope, n($\sigma$)$\cong$ 2.5 was found to define an optimum area of integration. The integration was performed on sub-pixel scale. In this context it was found that for a sufficient integration each pixel has to be divided into a field of > 10 x 10 sub-pixels.
2) Integrating inside an aperture with a fixed radius (corresponding to the seeing dominated size of the object, radii of 5, 6, and 10 Pixels have been chosen).

Before each integration it was verified that the median intensity of the "local" sky around the object was zero (the radius of the local sky around the object was chosen 4...8 times larger than the integration area of the object). The results of both routines (and the different integration areas applied in the second method) are equal within the error intervals. Under the assumption that the measured polarization is mainly determined by the different efficiency of the Wollaston prism for the two polarization directions, following correction factors for the ratio of the intensities measured in the lower/upper field have been derived. The error intervals include the values being derived for the different orientations of the Wollaston prism (see also Fig.~3 in Ageorges~2000; consider that the correction factor provided there is based on the inverse intensity ratio compared to the values discussed here). The lower-to-upper intensity ratios of the single exposures of HD64299 and further unpolarized polarization standard stars (see Tab. 2), taken at an orientation of 0 and 45, are shown in Fig. 6.
The small, statistically distributed variations of the correction factors, derived for exposures obtained for different altitudes of the telescope and different orientations of the Wollaston prism, confirm the assumption given above, i.e., the IP is determined by the wrong transmission ratio of the Wollaston prism. If -- in contrast to this -- the measured polarization was due to reflections on the mirrors of the telescope, the intensity ratio between the object in the upper and the lower field would depend on the orientation of the Wollaston prism. Furthermore, it was expected to depend on the altitude of the telescope if the mirror M3 was a significant source of IP. Here, the opposite behavior was found: The modification of the polarization of the light due to reflection occurring {\sl before} the light passes the Wollaston prism is negligible compared to the effect of the different efficiencies of the Wollaston prism for the two polarization directions. The derived polarization of the unpolarized polarization standard star HD64299 after the correction of the different transmission efficiencies of the Wollaston prism are[1]:

1. The estimation of the polarization error intervals is based on the work of Wardle & Kronberg (1974)

| |
|---|
| P(J)=0.36 +/- 0.21% |
| P(Ks)=0.31 +/- 0.25% |

Due to the large σ(P)/P ratio, it is not possible to derive the remaining IP. Thus, the polarizations given above are upper limits for the (remaining) IP.

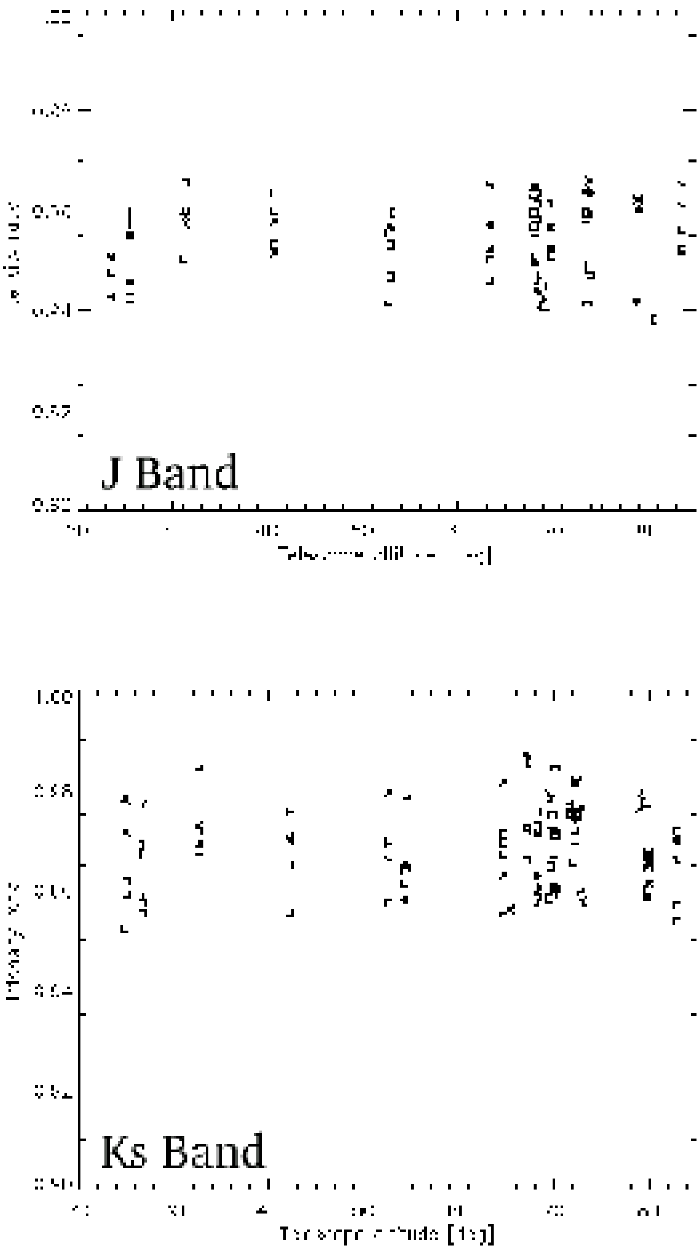


Fig. 6 Upper-to-lower intensity ratio in the J and Ks band of the considered unpolarized polarization standard stars derived from single exposures. The asterisks symbolize the intensity ratios obtained at an orientation 0 of the Wollaston prism, while the open squares represent the ratios obtained at orientation 45.

# 7 Elias 14 (r Oph) and Circinus

To test the method described so far we have observed the polarized star Elias 14 whose parameters are listed in Table 3.

| Name | RA (1950) | DEC (1950) | P_J (%) | P_Ks (%) | γ_J (deg) | γ_Ks (deg) |
|---|---|---|---|---|---|---|
| Elias 14 | 16 23 01.7 | -24 16 50 | 4.95 +/- 0.02 | 1.95 +/- 0.03 | 3 +/- 1 | 2 +/- 1 |

Tab. 3 Polarized star observed as a test

The star was observed in the Ks and J bands at orientations of 0 and 45 degree and altitude ALT = 19, 28, 42, and 52 degree. In each case four exposures have been taken with a constant offset (25") in right ascension between consecutive exposures. Since the object was very bright, the exposures have been taken with the telescope strongly defocussed. The values derived for the polarization are:

| | |
|---|---|
| P(J) = 5.06 +/- 0.43 % | γ = 8 +/– 7 |
| P(Ks) = 2.01 +/- 0.48 % | γ = 6+/- 4 |

The polarization pattern of spatially resolved objects on the other hand, such as the circumstellar shells around young stellar objects and galaxies, show (locally) high polarization degrees. Thus, these measurements are much less effected and easier to perform. Furthermore, the SNR can be drastically increased, in particular by a factor of n, if areas of n x n pixels are combined. The main difficulty in case of extended objects is to find a correct superposition (a) of dithered images obtained with the Wollaston prism at the same position and (b) of the co-added exposures obtained at the different orientation of the Wollaston prism. In Fig. 7 the polarization pattern of the Circinus galaxy obtained with SOFI is shown as an example.

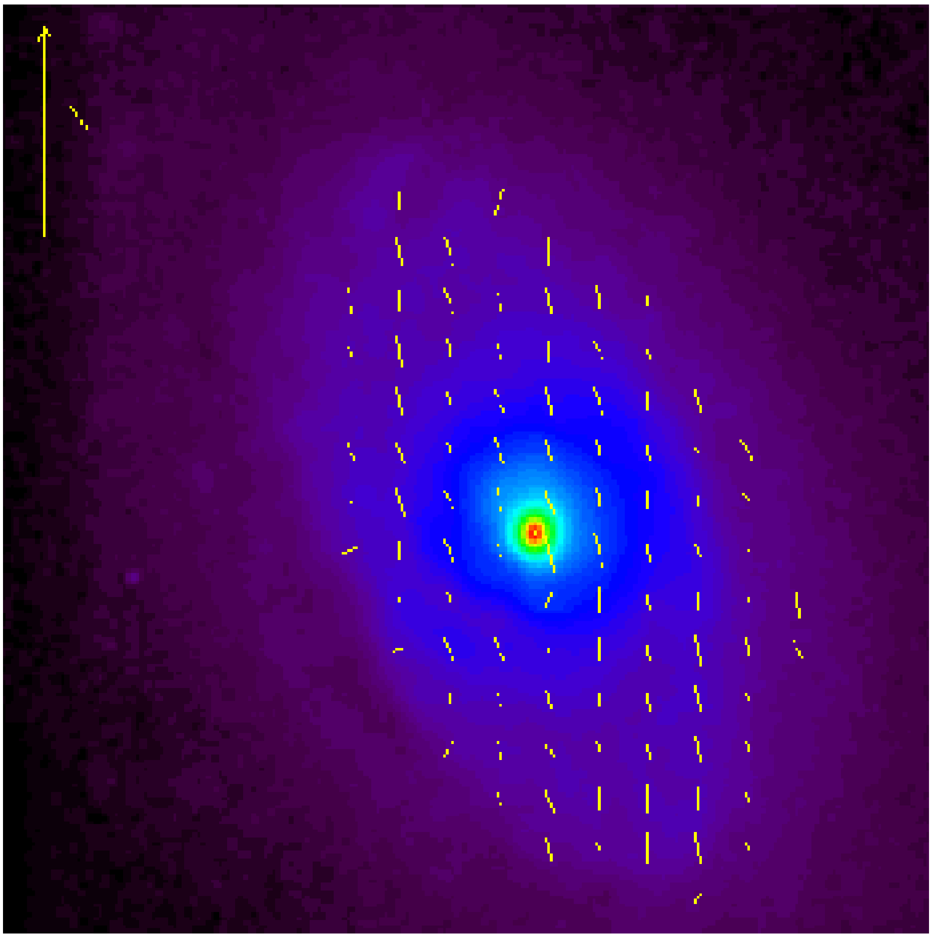

Fig. 7 Polarization pattern of the Circinus galaxy obtained with SOFI/NTT on May 5, 2000. 12 exposures and 2 orientations of the Wollaston prism have been used (Filter: NB-CO). Only polarization vectors with P > 5 σ(P) are shown.

## 8 References

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http://www.ls.eso.org/lasilla/Telescopes/NEWNTT/sofi/manual/SOFImanual.html,
Technical Report, ESO, 1997-1999

Wardle J.F.C., Kronberg P.P., ``The linear polarization of quasi-stellar radio sources at 3.71 and 11.1 centimeters'', ApJ 194, 249, 1974

Whittet D.C.B., Martin P.G., Hough J.H., Rouse M.F., Bailey J.A., Axon D.J. ``Systematic variations in the wavelength dependence of interstellar linear polarization'' ApJ 386, 562, 1992

## 9 Appendix. Catalogue of Polarized/Unpolarized Stars

a- Unpolarized Polarization Standard Stars see:
http://www.jach.hawaii.edu/JACpublic/UKIRT/instruments/irpol/irpol_stds.html#Unpolarized

b- "Serkowski" Polarization Standard Stars see:
http://www.jach.hawaii.edu/JACpublic/UKIRT/instruments/irpol/irpol_stds.html#Serkowski

c- Polarized Stars from Whittet et al. (1992) see:
http://www.jach.hawaii.edu/JACpublic/UKIRT/instruments/irpol/irpol_stds.html#Whittet

d- Polarized and Unpolarized Polarization Standard Stars: Turnshek D.A., et al., AJ 99, 1243, 1990

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