SYSTEM REQUIREMENTS FOR POLARIZATION CAPABILITY

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The purpose of this paper is to point out that

1) proper treatment of polarization by a telescope is not only important for polarimetry, but also for other observations requiring high signal-to-noise ratio, and
2) this does put a constraint on telescope design, which, however, is not unduly restrictive.

Polarimetry is the observational technique which can detect anisotropies in point sources, their environment, or the medium between them and us. Modern optical polarimetry can be linear or circular, and is making progress towards spectropolarimetry and imaging polarimetry using panoramic detectors (e.g. McLean, 1984). Given sufficient photons, the precision obtained is as high as 1 part in 50 000 (see Odell, 1981 for a project requiring this precision), but more often a precision between 1 part in 1 000 to 10 000 is sufficient. (Spectro)polarimetry has been applied to planets, the Sun and other stars, stellar systems and galaxy nuclei; for a few modern investigations, see Baur, 1981; Jones et al, 1981; Schmidt and Miller, 1980. Experience in radio-astronomy has shown that when facilities for polarimetry are offered, many applications emerge from the astronomical community, yielding data that cannot be obtained by other techniques. It is essential that at least some of the large optical telescopes are capable of observing polarization cleanly. It is even more essential that the largest telescope of a generation has this capability, since, for the required precision, one must collect on average 100 times as many photons as for (spectro)photometry with similar resolution.

All oblique reflections influence the state of polarization; unpolarized sources will appear to be polarized due to the difference in reflection coefficients for the two linear polarizations, while polarized sources will have their polarization converted out of all recognition by the phase difference and by the difference in reflection coefficients (Clarke and Grainger, 1971; Borra, 1976). Gratings and dichroic mirrors as used in modern efficient instruments, are even worse: their action is often strongly wavelength-dependent (Bausch and Lomb, 1970, fig. 21; Breckinridge, 1971; Velt and Tinbergen, 1981). This means that also spectrophotometry of partially polarized sources can have errors that are not suspected and vary according to the polarization of the object (unknown; not

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enough photons). These errors can amount to several percent, from one wavelength to another nearby (the maximum error is the product of source polarization and partial polarizer efficiency); this should be compared with the precision of a few tenths of a percent which is claimed for the best existing relative photometry and is being used to good astronomical purpose (examples: Hβ photometry; eclipsing binary light curves e.g. Andersen et al., 1983; pulsations in stars like the δ Sct and β CMa variables).

Since, in a statistical sense,

a) a larger telescope is required for fainter and more distant objects, and

b) fainter and more distant objects are more polarized,

the largest telescope of a generation is the one that is most likely to encounter these problems. This is aggravated by the wish to provide the most efficient instrumentation possible for the largest telescope, instrumentation that will inevitably contain polarization-sensitive components.

Another consideration for the very largest telescopes is that one of their main functions is to detect faint sources against sky background ("measuring sky brightness with the greatest possible precision" — Oke, this Colloquium). Apart from sufficient photons, this requires sufficiently low noise of all kinds. The sky is generally polarized and its polarization varies with time, position and wavelength. For the darkest skies, we do not know much about the polarization and virtually nothing about the "polarization noise" (e.g. the contribution by faint unresolved sources may well be noticeably polarized, its polarization angle varying spatially over all possible values, quite randomly). If the observing system is a partial polarizer, the measurement of sky brightness (I Stokes parameter) could become dominated by "noise" in the polarization (Q, U and V Stokes parameters). To measure to a precision of 10 percent a source which is 1 percent of sky brightness requires 0.1 percent total precision. If the telescope is a 10 percent polarizer (e.g. a Nasmyth mirror), it only requires 3 degrees of angle variation (temporally, spatially, or with wavelength; that depends on the type of measurement) of a 10 percent polarized sky background to provide this 0.1 percent "noise". On further investigation the problem may turn out not to be serious, but a safer investment is to build a clean telescope, that does not respond noticeably to Q, U or V when one is expecting to observe I.

The last category of polarization-sensitive observation I wish to mention is image reconstruction of partially polarized sources. If one wishes to obtain the polarization distributions, the same arguments apply as for polarimetry: the telescope must faithfully reproduce the incident Stokes parameters and one reconstructs for each Stokes parameter separately.

However, one may not have, or not wish to collect, the photons required for this and be interested in (and instrumented for) the I distribution only.

If the telescope is in fact a polarization modifier, the system will respond to Q, U or V (differently in each case) when it is supposed to be responding to I only; the reconstructed I image will then contain artifacts due to the source polarization. Since in image reconstruction one often obtains spatial detail partly in exchange for S/N ratio, these artifacts could become considerable.

Fortunately, for all the problems I have raised, there is a single general solution. A rotationally symmetric telescope, such as a Cassegrain, is "clean" in the polarization sense: the effects average out over the total reflecting surface, apart from a certain depolarization and some minor zeropoints and conversion factors which are of importance only for precision polarimetry and can then be calibrated. The observing instrument will contain polarization-sensitive components, certainly in the case of the large and expensive VLTs. To eliminate the unpredictable effects of these components one needs a polarization modulator. This is a component which ideally leaves the intensity I unchanged, but modifies Q, U or V in a time-dependent way (generally switching between orthogonal polarization states). Such a device makes the time-average of the output polarization zero (the sum of two orthogonal polarizations), which effectively decouples the instrumental system from the source polarization, thus solving the (spectro)photometry problem. Addition of a polarizer (= analyser) solves the polarimetry problem, by converting the vulnerable polarization information into intensity modulation, which is safe from degradation in any practical system.

Polarization modulators exist in many forms (e.g. Baur, 1981, fig. 11; Kemp, 1969; Miller et al., 1980; Piirola, 1973; Serkowski 1974; Tinbergen 1974); some are very fast (50 KHz), others very achromatic (0.3 to 1 micron) or very transparent (fused silica), but they have one property in common: they are small when considered as part of a telescope. The present limit is about 10 cm and with development one may hope for 20 cm, but probably not much more. This puts a constraint on the design of large telescopes and this constraint is the main reason for the present paper: hopefully it is not too late to constrain some of the VLT designs in order to gain the advantages of a "clean" system.

The best way to use the polarization modulator is to bring the beam to a focus (which need not have image quality worth speaking of) before the first oblique reflection of any kind. The modulator (and any other equipment which usually competes for focal-plane space with defining apertures, but does not require superb imaging) should be placed near this auxiliary focus. The most recent design of the Large European Solar Telescope (LEST, poster paper at this Colloquium) is in fact an example of this, for precisely the reasons I have given. As another example, MMT versions of the NNTT (e.g. Meinel and Meinel, 1982, fig. 1) could also be adapted, replacing the beam transfer flats by a reimaging system. Further thought will lead to acceptable solutions in many cases. For a 15-metre primary and an f/5 secondary beam (the fastest I consider likely for a polarization modulator), the 20-cm linear size, if used in the focal plane, leads to a field of 9 arc-minutes; clearly, the modulator must be removable, but as an option for high-signal-to-noise observations its field would be quite satisfactory.

I strongly urge that scientific and technical teams associated with the various VLT projects consider the above facts of life. It is my personal belief that, having largely exhausted the possibilities of quantum efficiency, parallel detection and telescope aperture for going to ever fainter objects, we may in coming decades be forced to make increasing use of observations of higher precision. VLTs, built to last for decades, should be designed with that in mind.

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DISCUSSION

J. Beckers: When doing interferometry one has to be careful to maintain the original state of polarisation of the light coming into the different apertures of the interferometer or to at least modify it the same way. If that is not done the fringe visibility is decreased. This is a concern with the MMT. It also requires polarisation control.

J. Tinbergen: This is a second-order subtlety which I had not realised. It is also one of those (rare?) cases where a depolariser does not cure the problem completely. This reinforces my main point, viz. that we do not think often enough of how polarization-induced errors can enter into other kinds of measurements.

R.G. Bingham to J. Beckers (on paper by Tinbergen): One characteristic of the two-mirror telescope which I described this morning is that the polarisation of the two interfering beams matches, because the oblique mirrors in one beam are rotated 180 degrees from those in the other beam.