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Accurate Optical Polarimetry on the Nasmyth Platform

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ABSTRACT. The classical prescription for *accurate* optical and IR polarimetry is the following: a weakly polarizing telescope, a polarization modulator, imager/disperser optics, and a demodulating detector. This list needs to be modified when one is forced to use the Nasmyth focus, as often happens in large modern facilities. An extension of the basic paradigm is presented here and worked out in some detail.

1. SENSITIVE POLARIMETRY

1.1. Astronomical Requirements

At all accessible wavelengths, polarimetry in its various forms (e.g., imaging polarimetry, spectropolarimetry) is set to become a standard tool of astronomy. There are at least three technical reasons for this:

1. Increased spectral or angular resolution often leads to much higher degrees of polarization
2. Improved polarimetric instruments and techniques (§ 2) yield lower systematic errors
3. In the optical and near-infrared (hereafter lumped together as "optical"), the throughput of large telescopes and large efficient array detectors often lead to acceptable integration times, even at very high sensitivity.

Matching this technical development, one detects among observers an increasing feeling for the scientific reasons for polarimetric rather than, or additional to, photometric observations. Polarimetry is fundamental for determining:

1. Magnetic field configurations
2. Scattering configurations
3. Statistical parameters of source details far too small to be resolved directly (properties of aligned dust grains, stellar and exoplanet atmospheres, tangled magnetic fields, etc.).

In addition, polarimetry can often help where straightforward photometric methods fail, such as in detecting exoplanets ("glare reduction"; Schmid et al. 2005; for more detail see Tinbergen 2004) and detecting an active galaxy core hidden inside a dust torus ("looking round a corner"; for a simple illustration and references, see Fig. 3.10 of Tinbergen 1996). Finally, unbiased photometry of appreciably polarized objects or spectral features is enabled by the same instrumentation that provides the polarimetry; this is a point that is often overlooked.

The scientific project triggering the work reported here was an engineering prestudy for a polarimetric arm to a proposed adaptive-optics (AO) exoplanet finder (ESO second-generation VLT Nasmyth instrument, now known as SPHERE; the prestudy was called CHEOPS). An order-of-magnitude requirement for ground-based 10^{-8} relative photometry (AO-restored planetary image superposed on the stellar residual seeing disk) translates to perhaps 10^{-5} relative imaging polarimetry, which is ambitious but not necessarily impossible (Tinbergen 2004). Since most of the considerations raised in the polarimetric part of the CHEOPS study are applicable to future AO-equipped telescopes of the 30 to 60 m class with suitably more ambitious aims (e.g., searching for Earth-like exoplanets rather than Jupiters), I have reformulated the general aspects for a less specialized readership, such as astronomers and facility planners rather than instrumentation specialists. Introductory texts for nonspecialists I have listed at the end of § 1.2.

Scientific requirements set the levels of absolute *accuracy* or relative *sensitivity*[1] that have to be achieved for different applications. Source brightness, telescope size, detectors and required resolutions determine the *photon noise* one can achieve. It is up to the engineer to reduce *systematic errors* to match the photon noise level, and to provide *calibration facilities* to transform the sensitivity attained into certified accuracy. Some of the science will not require the full power of analysis, design, laboratory verification and operational calibration discussed here, but it is useful to be able to predict whether an instrument system *can* be designed for a given purpose. How to go about this, in spite of the handicap of the almost ubiquitous Nasmyth telescope (a blanket term used here for telescopes with a third mirror providing a 90° exit to the first real focus), is the main subject of this paper. Once an "ideal" procedure has been identified, one can determine with greater confidence what may be omitted or compromised under specific circumstances.

[1] This relative sensitivity is often referred to as "precision," a multipurpose term that should perhaps be avoided; I conform to the usage of Keller (2003).

1.2. A Polarized Frame of Mind

Neither astronomers nor optical engineers are used to thinking in terms of polarization. Polarimetric techniques are regarded as food for specialists, and this has impeded cross-fertilization of astrophysics, observing, and equipment design. There is no fundamental reason for this. One may note that:

1. The formalism of Stokes parameters and Mueller matrices is almost perfectly adapted to the usual circumstances of astronomy: polarization is partial and absolute phase is mostly irrelevant (however, see § A1);
2. If radiation transfer is formulated in Stokes-Mueller terms, polarimetrically valid astrophysical models may be constructed;
3. The Stokes-Mueller formalism also allows one to eliminate, or at least recognize, photometric errors due to polarization effects in both models and observations;
4. Polarimetric design and observing methods have developed to a point where "common-user" polarimetry is the rule rather than the exception; after reading the instrument manual, the observer is sufficiently specialist for most purposes;
5. Modern ray-tracing software in principle allows complete polarization treatment for tilted surfaces, off-axis rays, birefringent materials, and metallic or thin-film coatings, so that polarimetric equipment can now be simulated and optimized before construction.

In this paper I assume familiarity with the Stokes parameter 4-vector and the 4×4 Mueller matrix; the latter is explained very concisely in Keller (2003). An astronomical polarization primer with extensive bibliography is Tinbergen (1996), to be supplemented by Keller (2001) and Skumanich et al. (1997) for recent optical developments. For recent developments in the radio domain see Hamaker (2000, 2006) and other papers of that series.

1.3. The Instrumental System

The general polarimetric system discussed in this paper is illustrated in Figure 1. It includes both the existing prescription for accurate polarimetry as detailed in § 2 and the modifications that are necessary to obtain accurate polarimetry with Nasmyth telescopes. Implementations will depend very much on circumstances such as required science and a predefined telescope configuration, so a block schematic is the preferred vehicle. The information flow is represented by the vertical lines; the more important polarization cross talk effects are indicated. In the interests of simplicity, I have assumed that $(Q, U) \ll I$ and $V \ll (Q, U)$ (the usual astronomical situation), and I have chosen to show the nature but not the sign of cross talk (e.g., Nasmyth mirror and compensator are each other's opposite, but are represented similarly); for a complete description, the Mueller matrices of the optics should be used. Again for simplicity, I have omitted rotations of the coordinate system, except for the important one between sky and altitude-azimuth (alt-az) telescope. For any particular instrumental project, one may draw up a similar system overview; for the present discussion Figure 1 suffices.

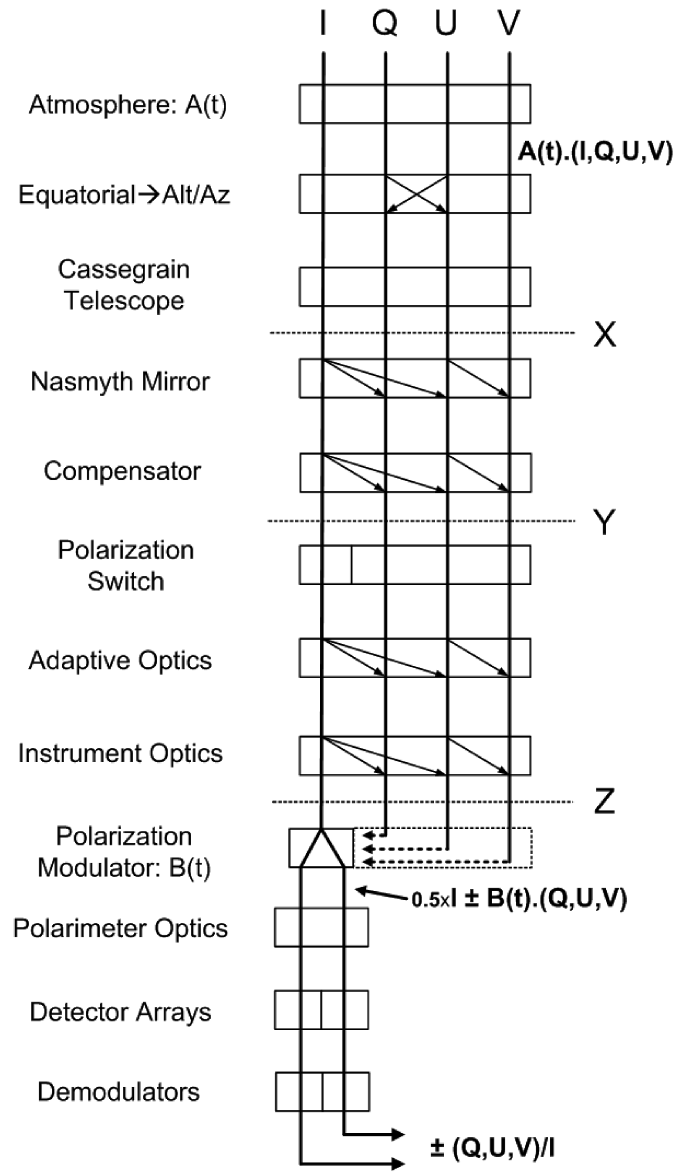

FIG. 1.—System as discussed in this paper, using a cascade of techniques to obtain the final performance. See § 1.3 and 2 for more detail.

The classical paradigm is represented by the section upstream of X, followed immediately by the section downstream of Z. When one is forced to use a Nasmyth system, insert the section between X and Y: the compensator eliminates the effect of the Nasmyth mirror approximately, and the Nasmyth focus is a good point to insert efficient polarization optics. Instrument optics (including adaptive optics) upstream of the full-Stokes polarimeter (which starts at Z) produce substantial cross talk; in such a case, a polarization switch may be used to invert Q, U, or V periodically, thus coding the sky + telescope polarization; polarization effects due to the adaptive and instrument optics are constant and can therefore be recognized for what they are. The modulation by the atmosphere $A(t)$ affects I, Q, U, and V equally to a high approximation; the normalized Stokes parameters $(Q, U,\ \text{or}\ V)/I$ are not affected. The polarimeter modulation $B(t)$ should be much faster than $A(t)$, while the polarization switch may be much slower than $A(t)$. After the modulator, the polarization (Q, U, or V, or some combination, depending on the polarimeter's optical setting) has been recoded as the modulated part of the intensity I; polarization-modifying optics can no longer spoil the measurement of the *normalized* Stokes parameters. The polarization information is in push-pull for the two channels, while any residual atmospheric or other gain-noise is common-mode and may be eliminated by combining the two channels. If the polarization transfer (Mueller matrix) between X and Z can be calibrated, very small (switched) sky + telescope polarizations may be measured reliably. For very small linear "sky" polarization, the rotation of the telescope with respect to the sky may be used as an additional polarization switch (very slow, except near the zenith), potentially eliminating all instrumental effects.

Some of the properties, subsystems, and components of the above generalized system will be discussed in more detail in later sections.

1.4. Trail-blazer: Solar Polarimetry

In the optical region, the technical state of the art is represented by solar physics, where differential (i.e., line vs. continuum) spectropolarimetry of order 10^{-5} in degree of polarization is achieved (with subarcsecond seeing, speckle processing or adaptive optics, and at spectral resolutions of 10^5 and better, and what is more, with telescopes that are hardly "polarization-friendly"). As far as available photons are concerned, large telescopes and long integrations allow one to apply such sensitive polarimetry to the brighter stars, their planets, and circumstellar disks, particularly when a wide spectral bandwidth is acceptable. Very much fainter objects can still yield a polarimetric sensitivity of about 10^{-3}, which is often adequate for the science in hand.

The daunting task confronting us is to transfer the solar know-how to nighttime-astronomical mainstays such as broadband (polarimetric) imaging and efficient spectro(polari)metry. Much of the most advanced solar work uses differential line versus continuum spectropolarimetry, which is similar to but not quite the same as, for instance, broadband polarimetric imaging of a point source against its background. To get an idea of the problems and orders of magnitude involved, read § 8 (Conclusions) of Skumanich et al. (1997), who report *systematic* error levels of order 3×10^{-4}. Even allowing for the fact that the Vacuum Tower Telescope discussed by Skumanich et al.(1997) is, in terms of polarization, a difficult telescope, it should be clear that further reduction of the error level by a factor of the order of 30 will not be easy and that cutting corners in design, simulation, manufacture, or testing of equipment will be out of the question.

In striving for the best performance of a state-of-the-art nighttime polarimetric system (as opposed to solar systems, or to classical nighttime systems using photomultipliers and Cassegrain telescopes), at least the following aspects require detailed consideration:

1. An AO sensor will work best with one input beam, while the best polarization modulators have two output beams;
2. Most nighttime work is broadband in at least some parts of the instrument;
3. The combined action of instrumental polarization and detector nonlinearity is to produce nonnegligible polarization artefacts;
4. Light scattering within complex instruments or by segmented telescope mirrors will to some extent be both polarizing and polarization-dependent.

In such a complex and demanding situation, it is likely that we shall succeed best using a cascade of techniques that individually are not exploited to their limits; this leaves some room for unpleasant surprises or later upgrading in the light of experience. Such techniques should include a low-polarization telescope, a good full-Stokes polarimeter, low instrumental polarization and detector nonlinearity, calibration of nonideal behavior, differential measurement schemes, polarization switching and full-Stokes image processing software (cf. LOFAR [Hamaker 2006], mutatis mutandis). Some of these techniques may be developed during commissioning or even later, but others will require attention from the start. Important aspects in the latter category are telescope configuration, the need for daytime calibration in order to conserve telescope nighttime, injection points for calibration light, and reserved space near the telescope focal plane for specifically polarimetric components (which are generally small, and therefore must reside near a focus).

In spite of the differences between solar and nighttime applications, it is worth reading Keller (2003) (§ 6 in particular) to experience modern thinking in the solar community; there is no need to reinvent the wheel when it is going in the right direction anyway.

2. OPTICAL POLARIMETERS

For several decades, the received wisdom in designing sensitive and accurate optical polarimeters has included the following:

1. An on-axis Cassegrain or Gregorian telescope, because it is rotationally symmetric and therefore does not appreciably corrupt the polarization of the incident radiation;
2. A so-called polarization modulator. This consists of a polarization switch (which alters the state of polarization periodically), followed by a linear polarizer (which converts the

modulated, i.e., the polarized, component into an intensity-modulated signal of constant polarization);

3. A demodulating detector system, which has separate outputs for the AC (originally polarized) and DC (originally unpolarized) parts of the signal. The basic observable is AC/DC; depending on the optical settings, this corresponds to Q/I, U/I, V/I, or some combination. Such detector systems have mostly been based on photomultipliers or (avalanche) photodiodes; the only array system working really well so far is ZIMPOL (Schmid et al. 2005), but other possibilities are fast low-noise frame-transfer CCDs, or complementary metal-oxide semiconductor (CMOS) detectors with two charge-storage condensors per pixel (Keller 2003).

Because the state of polarization of the signal after it leaves the modulator is irrelevant (the original polarization information has been recoded as intensity modulation), one may insert *any* nonvarying optical system between components 2 and 3. The above scheme is therefore applicable to both imagers and spectrometers, and in fact to almost any optical configuration, including notorious polarization spoilers such as inclined mirrors, prisms, diffraction gratings, beam splitters, or tilted interference filters.[2] The exact form of the equipment depends to some extent on the application, but the basic scheme is almost ubiquitous. The observables are the normalized Stokes parameters (e.g., Q/I), in "degree of polarization" scale; if the modulation is fast enough, atmospheric effects such as scintillation and variable extinction are eliminated, as is variable photometric sensitivity of the equipment; see Tinbergen (1996) for a more complete discussion. For the state of the art for this kind of instrument, see Hough et al. (2006).

3. MODERN LARGE TELESCOPES

Modern large telescopes (including those that are very, extremely and overwhelmingly so) impose special requirements on the associated observing instrumentation. This is particularly true for instruments with polarimetric capability.

3.1. Instrument Evolution

Three developments in optical observing systems make things difficult for the traditional polarimetric scheme:

1. Modern telescopes carry large and complex observing equipment, and equipment changes are avoided where possible. This can mean that the Cassegrain focus is reserved for an infrared instrument. Alternatively, the equipment may be so large that the Nasmyth platform is the only realistic location for it. The "Nasmyth flat" (or "M3") at an angle of incidence of 45° then becomes an integral part of the telescope;

2. For many applications, some form of adaptive optics (AO) is part of the system. The deformable and tip/tilt correctors are reflective and are mostly used off-axis;

3. Most detectors are now array devices, so that effective baffling becomes more difficult and the scattering properties of the optical system become important, perhaps even critical.

These aspects introduce new polarization (polarizer action) and convert incident polarization to some other form (retardance, or "wave plate" action). M3 is the main culprit, because it is too large to be preceded by a polarization modulator and because its inclination is much more than that of most AO mirrors.

The result is that, by the time the light reaches the modulator, the incident polarization has been modified and linear polarization on the order of 5% has been added. For some types of observation, this may be overcome by suitable if time-consuming calibration, but for others (such as observing an exoplanet 10^8 times fainter than its parent star, which amounts to doing 10^{-5} polarimetry inside the speckled residual seeing disk), the limits on detector nonlinearity (see Keller 2001) become excessive, and a more foolproof method needs to be devised.

3.2. The Nasmyth Flat M3

The Mueller matrix for an inclined mirror takes the form (e.g., Capitani et al. 1989; Collett 1993[3])

$$\begin{pmatrix} \overline{R_a} & p & 0 & 0 \\ p & \bar{R}_a & 0 & 0 \\ 0 & 0 & \overline{R}_g \cos\Delta & \overline{R}_g \sin\Delta \\ 0 & 0 & -\overline{R}_g \sin\Delta & \overline{R}_g \cos\Delta \end{pmatrix}, \qquad (1)$$

where $\overline{R}_a$ is the arithmetic mean of the reflectivities $R_\parallel$, $R_\perp$ for linearly polarized light (electric vector within the plane of incidence and at right angles to it, respectively); $\overline{R}_g$ is their geometric mean; $p = 0.5(R_\parallel - R_\perp)$; $\Delta = \delta_\parallel - \delta_\perp$ is the difference in phase jump at the reflection. $\overline{R}_a$, $\overline{R}_g$, p, and Δ are functions of the complex refractive index of the mirror material and therefore are functions of wavelength. For bare bulk aluminum at 45°, p has a maximum of 0.047 at 800 nm and Δ varies from more than 40° in the blue/violet to 5° at 1 μm. Gold has smaller p-values, but Δ is larger. A rule of thumb for metals in the infrared is that p is generally less than in the visual, but Δ tends to be larger. In real life, thin-film properties (refractive index, surface oxidation and contamination, multilayer design) will differ from the bulk properties (see, for instance. Capitani et al. 1989; Koschinsky & Kneer 1996). In view of this complexity, all we can safely predict is that polarization conversions ($\overline{R}_g \sin\Delta$) from linear to circular and vice versa are substantial, similarly for conversions (p) between linearly polarized and unpolarized. For a common-

[2] One does have to bear in mind that crossed (partial) polarizers reduce the photon flux striking the detector, which can occasionally lead to excessive noise (in other respects, the normalized Stokes parameters are not affected).

[3] Collett (1993, p. 493) appears to have the wrong sign for the 44 element; see Tinbergen (1996, p. 16) for a caveat on sign conventions in polarimetry.

user facility, regular in situ calibration of the polarization behavior of such mirrors is essential for accurate (as opposed to sensitive) polarimetry with a Nasmyth telescope; the detailed tolerances of such calibration are installation- and science-dependent.

The telescope rotates with respect to the Nasmyth platform for different zenith angles θ, and we should take this into account by premultiplying the matrix for M3 by the rotation matrix

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & \sin 2\theta & 0 \\ 0 & -\sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{2}$$

thus converting from the telescope coordinate frame to that of the platform. The effect is that the Nasmyth telescope matrix will contain even fewer zero elements and observed polarizations will be a function of zenith angle as well as wavelength (Giro et al. 2003). For all but the simplest observing programs, adequate calibration is a daunting task (discussed in § A2.5).

4. FUNDAMENTAL SOLUTIONS

Most of our problems would be solved if we could place the polarization modulator upstream of M3. Unfortunately, the maximum size of polarization optics is on the order of 10 cm, and generally we must install them at or near a focus. A Gregorian telescope is a possibility, but the prime focus has a very fast beam. This would degrade the performance of the polarization optics, so that an intermediate, slower focus is preferable; such a feature was included in the proposed solar telescope LEST (for an accessible illustration, see Fig. 5.1 of Tinbergen 1996) and has returned in options for GREGOR (Hofmann & Rendtel 2003). The sophisticated optical system proposed for the OWL 100 m telescope offered good possibilities. However, we need a scheme for the Nasmyth and other folded beams of existing Cassegrain telescopes of the 8–10 m class and for the proposed extremely large telescopes.

One possibility would be the Cassegrain equivalent of LEST/GREGOR, but this may require a mirror in the space normally occupied by the Cassegrain instrument. Another possibility would be a telescope modified along the lines of Figure 2. Such solutions have the serious drawback that one either loses half the light in the polarizer or one is stuck with two beams for the rest of the optical path. The latter can lead to double images in the AO sensor, twice the optical field, and half the signal at the detector and AO sensor. Although this may quite conceivably be acceptable in some applications, it will not always be so. So some other solution is needed for general use, even if concessions have to made in polarimetric elegance and precision. I was forced to confront this problem when I became involved in SPHERE/CHEOPS (see § 1.1).

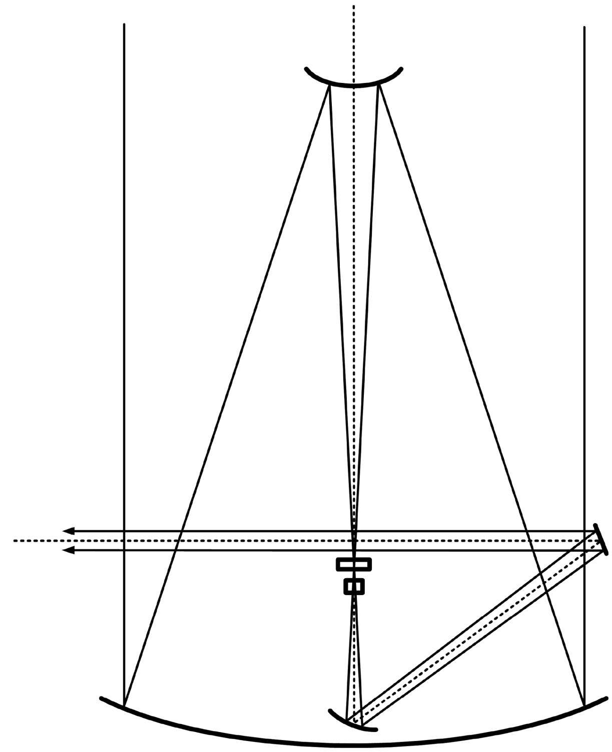

FIG. 2.—Cassegrain-like telescope, as modified for sensitive polarimetry without having to remove the Cassegrain instrument. The units near the relocated Cassegrain focus are the polarization switch (upstream) and the polarizer (downstream). For clarity, the focus is shown much further from the primary mirror than would, in fact, be the case. See Tinbergen (2003) for other layout examples.

5. COMPENSATING M3

Potentially the best way out of the problems posed by the Nasmyth flat M3 is to compensate for its effects by a further mirror M4, identical to M3 in all respects except size, and crossed with it (i.e., planes of incidence mutually at 90°). This not only eliminates the polarizer action, it also compensates the retarder effects, as multiplication of the appropriate Mueller matrices will verify. Just downstream of M4, the polarization will be as it was before the beam struck M3; we may put the modulator close to the first real focus after M4, encoding the restored polarization as intensity modulation.

With M3 inside the telescope and M4 on the Nasmyth platform, possibly within an instrument, M3 and M4 will not remain identical forever. The mirror surfaces will oxidize and aerosols will accumulate on them, altering their polarization properties. However, the effects of the combination can be reduced considerably compared to M3 by itself, making calibration a less daunting prospect (reduction by a factor of 10, to the level of the AO mirrors, is sufficient). Changes will be slow compared to the length of an observing run.

The modulator problem still requires a solution: either we lose 50% of the light, or we are stuck with two beams.[4] Moreover, after M4 the beam is at right angles to the Nasmyth platform optical axis, and it rotates with telescope elevation. We cannot use mirrors to bring the beam back on axis, as these will reintroduce the polarization effects we have just eliminated.

What we can do, however, is to use prisms rather than mirrors. Total internal reflection produces retardance (§ A2.2), but does not polarize. It is possible, by selecting glass of the correct refractive index and/or choosing the angle of incidence suitably, to use retarders of approximately half-wave retardance to bring the beam back on-axis without introducing harmful polarization effects (Fig. 3). Such an assembly could perhaps be constructed as a very thick field lens, with curved entrance and exit surfaces, and with other glass components for achromatization. Alternatively, the beam could be collimated first, though this introduces further optics and thus unwanted polarization. Yet another option might be to construct the prisms after the fashion of a Fresnel lens, but only if the light scattered by such a component can be eliminated by baffles elsewhere. In short, this type of solution seems fraught with difficulties.

As an alternative to the crossed-mirror setup, the instrument geometry may be kept simple (Fig. 4). This will be an approximate compensation and could involve considerable light loss around 800 nm (four aluminum mirrors). Whether these configurations can be as successful in broadband work as for solar applications is a matter for detailed analysis.

A much more practical, but approximate, solution was originally proposed by Adam (1971) and reinvented by Martinez Pillet & Sanchez Almeida (1991). A half-wave retarder "reflects" the plane of polarization with respect to its own fast axis direction, so we can use a driven half-wave retarder to cross the polarization produced by M3 with that due to (fixed, nonrotating) M4, for all elevations (Fig. 9). It turns out (Mueller matrices) that both the polarizations *and* the retardances by M3 and M4 cancel out. If the retarder is a half-wave *plate*, the beam is not deflected. The exit beam is now stationary, though at right angles to the Nasmyth platform optical axis (which may or may not be convenient). It so happens that a particularly achromatic half-wave plate can be constructed for the optical region (§ A2.1), so that this really is a feasible solution of fairly general applicability,[5] although we are still stuck with the modulator conundrum (50% or two beams). For an elevation of 45°, at the worst wavelength of 800 nm and including realistic manufacturing errors in the superachromatic half-wave, a (paraxial) Mueller matrix for such an application is (F. Joos & H. M. Schmid 2007, private communication):

$$0.901\begin{pmatrix} 1 & 0.005 & 0.000 & -0.003 \\ -0.005 & -0.998 & 0.009 & -0.066 \\ 0.001 & 0.012 & 0.999 & -0.050 \\ 0.004 & 0.066 & -0.050 & -0.997 \end{pmatrix}. \quad (3)$$

The instrumentally induced polarizations (first column) are now reduced by about a factor of 10 (cf. eq. [1]), roughly to the level expected anyway for an AO system or a real-life converging beam. The largest conversions are from circular to linear polarization and vice versa, but they are manageable. The polarimetric efficiencies (diagonal elements) are nearly perfect, the transmission is as expected for two aluminum mirrors at 800 nm. All elements will be slow functions of wavelength and will also depend on elevation, but the amplitudes of the variations will be much less than without compensation by M4. Calibration (§ 8) should not be a real problem, for all but the most exacting applications. Sanchez Almeida et al. (1995) describe a laboratory test on a Pancharatnam achromatic half-wave retarder; attention to design and manufacturing of a superachromatic half-wave (§ A2.1 and A2.4) and more tests should further improve the technique.

6. NASMYTH SUBSYSTEMS

We are now in a position to specify what building blocks a complete Nasmyth system for sensitive and/or accurate polarimetry might contain (Fig. 1).

The rearmost subsystem is the polarimeter proper. Because the preceding optics produce polarization conversions, this should in general be a "full-Stokes" polarimeter, i.e., one capable of measuring all three normalized Stokes parameters Q/I, U/I, and V/I, either simultaneously or, more normally, consecutively. This polarimeter most probably will contain a modulator to eliminate the effects of atmospheric variability (§ 2); all the subsystems that modify the polarization vector (such as spectrometers, image rotators, and beam splitters) should be included within the polarimeter. By suitable insertable components, this polarimeter may be calibrated and we may assume that, at its input (Z in Fig. 1), we can truly characterize the polarization of any beam presented.

In practice, it may not be possible to locate every polarization-sensitive subsystem within the polarimeter (atmospheric dispersion compensator, AO system including beam splitters and pre-optics, beam splitters for multiple science instruments; "instrument optics" in Fig. 1 covers all of these). We shall then need to calibrate the impact of such extra optics on the polarization vector of our science object: a transformation with 16 elements, each of which is a (mostly) smooth function of wavelength and elevation.

[4] An interesting development by Keller et al. (2003) is to split the modulator into a front-end polarization switch (which does label the incident polarized radiation, to distinguish it from the much larger unpolarized component and from constant instrumental polarization further down the optical train, but does not split the beam) and a back-end polarization beam splitter (which translates the polarization encoding into something the detectors can see).

[5] For high-resolution spectropolarimetry, the fringes produced in these components (Aitken & Hough 2001; Clarke 2004a, 2004b, 2004c, 2005) pose serious problems, but future component development may well solve this.

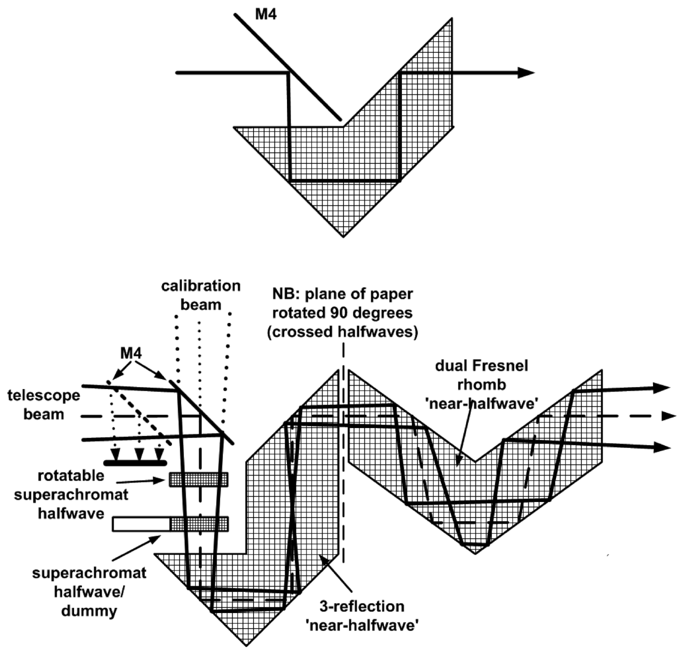

FIG. 3.—Hypothetical M4 assemblies to bring the beam back in line; the entire assembly rotates with the telescope in elevation. *Top*: single near-half-wave, which modifies the polarization, but in a known way; *bottom*: two crossed but not-quite-identical near-half-waves, leaving the original polarization approximately intact. Small prisms, i.e., close to focus, are a necessity, to limit birefringence and chromatic effects.

Finally, there is the Nasmyth telescope itself. As we have seen, it needs to be calibrated as a function of both wavelength and elevation; fortunately, both of these relations will also be smooth functions. If our telescope is alt-az mounted, we can use the fact that it rotates with respect to the sky. If we observe a source at two moments such that the parallactic angles differ by 90°, then the linear Stokes parameters Q/I and U/I will have reversed in sign. For linear polarization this constitutes a "polarization switch" (see below); it is very slow and a little awkward to operate (since both the sky background and the telescope properties will change while switching), but it can help to eliminate spurious polarizations from the measurements. The "switched" component in this experiment (as measured just downstream of M4) is the true sky polarization; the constant part is the contribution from the Nasmyth telescope, which may thus be calibrated. The two observations should be scheduled at the same elevation of the source. The method works best near the zenith, since the parallactic angle changes fastest there.

Between M4 and platform optics is the point of transition between elevation-dependent and more or less constant polarization-converting subsystems. It would be useful to be able to distinguish in some way or other between the two kinds. One way to do this would be to insert at this point a polarization switch, i.e., a subsystem that on demand can reverse the signs of Q/I, U/I, and V/I (in fact, a polarization modulator without its final polarizer, therefore avoiding the "50% or two beams" dilemma).[6] Such a switch may be constructed out of two more of the superachromatic half-wave plates (Fis. 6 and 9, § A2.1 and A2.3). Operating at a frequency (say 0.1 Hz) very different from those of the AO system and the polarimeter's own modulator, this switch would ensure that we can identify sky polarization as modified by the telescope as the switched component, relaxing the requirements of the calibration of the platform optics (we do still need the conversions, but the tolerances can be relaxed; the injected polarizations are now of academic interest). Since the above transition point is near the Nasmyth focus (Fig. 9), the switch optics do not have to be unreasonably large.

A point of some interest is to what extent such a switch will help in eliminating the effects of scattered light. The answer will be different for light scattered at segmented telescope mirrors, for light scattered from optics after the switch, and for light scattered within the switch itself. Questions as well as answers will depend very much on detailed implementation.

7. SYSTEM PERFORMANCE

Our ultimate aim is to express the action of the entire system, from a source at infinity to the detector output image, in some compact way suitable for image deconvolution. Such a point-spread function (PSF) should include polarization. The Mueller matrix is the key to this: we can replace the single scalar PSF of photometry by a Mueller matrix of 16 scalar PSFs. The input signal from an area of sky is a set of Stokes 4-vector plane waves and the output is a pattern on each of the I, Q, U, and V virtual detectors of the full-Stokes polarimeter. This set of 4 patterns is a convolution of the input sky Stokes vector, premultiplied by the Mueller matrix PSF. In this convolution, a Mueller matrix row specifies how each of the Stokes parameters of the input set of plane waves contributes to a point on one of the virtual detectors of the polarimeter. Sanchez Almeida & Martinez Pillet (1992) display the top 2 rows of such an array PSF for a Cassegrain-like telescope, although they had to use non-Mueller methods to obtain their results (cf. § A1, paradigm 3). A deconvolution procedure will have to employ matrix methods. Problems will no doubt arise, but (mutatis mutandis) one may draw on a wealth of experience in radiopolarimetry; recent papers on this (and on something more ambitious still: polarization self-calibration) are Hamaker (2006), which contains references to earlier work, and Hamaker (2000).

One might wonder whether a "Mueller-PSF" specification will not require full polarized treatment of diffraction. I think not, fortunately; my reasoning is as follows:

• Diffraction at the primary mirror may be described as a scalar process, without including polarization effects. Most of the

[6] Similar dual modulation at two distinct points within the optical train has been used in solar physics, for a somewhat different purpose viz. reducing cross talk noise due to the combination of image motion with Stokes-parameter spatial gradients in the observed object (Lites 1987; Elmore et al. 2003, 2006); it is conceivable that dual modulation may usefully be applied to yet other situations.

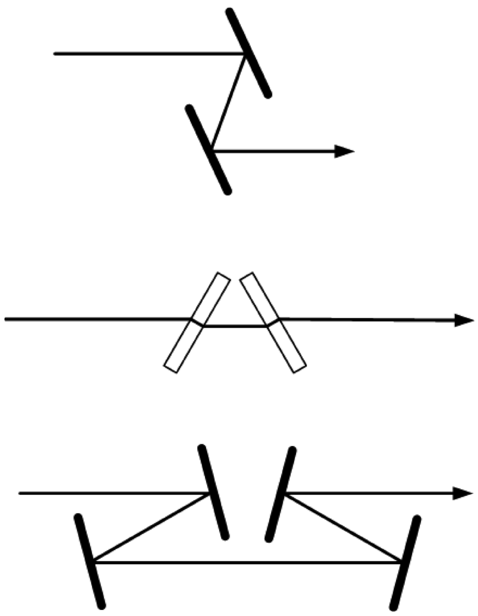

FIG. 4.—Alternative M3-compensators; the tilted plates may be very thin indeed. In all these cases, compensation of M3 is only approximate. Note that the compensator has to rotate with telescope elevation, resulting in changing exit beam translation for the top solution. All three options have been used successfully at the McMath-Pierce solar telescope (C. U. Keller 2007, private communication).

light strikes the primary mirror so far from the rim that, in a manner of speaking, it has no way of knowing where the rim is. We know that spectrograph slits only cause measurable polarization when they are narrower than several tens of wavelengths (Keller 2001). Taking half that as the rim width, for a 10 m mirror less than 0.001% of the mirror area can cause polarization effects, at something like 10%; this is negligible and is reduced further still by symmetry. This argument will also apply to the spider of the secondary mirror, if it has a slightly oversized mask to guard against scattered light from the sides of the spider structure *and* the mask is fitted to the spider itself rather than at a much smaller reimaged pupil.

• If we sufficiently oversize[7] the optics that follow the primary mirror, then the polarization of the diffracted light is determined by oblique reflections and departures from symmetry of these. Such effects may be computed by polarization-capable ray-tracing software (§ A2.4).

Such a combination of scalar diffraction with polarizing reflections was in fact what Sanchez Almeida & Martinez Pillet (1992) used, without explicitly saying so. Their model, using methods equivalent to Jones calculus, predicts polarization sidelobes when an optical telescope is diffraction-limited and we must expect AO-restored polarimetry to encounter them, too.

8. CALIBRATION

The purpose of polarimetric calibration is to determine how the combination of Q/I, U/I, and V/I, as measured by the back-end polarimeter, corresponds to Q/I, U/I, and V/I of the plane wave entering the top of the atmosphere. For a "classical" installation (as defined in § 1.3, the conventional approach is to point the telescope at a star previously found to be "unpolarized" and to do observations with calibration polarizers of various kinds in the beam; an observation without any polarizer serves as the zero point. Using a celestial source has the advantage that the beam geometry is identical to that of the science observations, and therefore the calibration is automatically valid for these. However, given the extensive calibration that is probably necessary for high-accuracy use of a Nasmyth system (in the worst case, all 16 Mueller-PSF elements, which vary with both wavelength and elevation), this might well take too much valuable observing time. More suited to the circumstances of a large Nasmyth system is to inject laboratory-generated light of several known polarizations, use the full-Stokes polarimeter to measure the exit polarizations and obtain the elements of the Mueller matrix for the optical system, as a function of wavelength and elevation. Such calibration should be done during the daytime; this means so much for the observing efficiency of the system that proper calibration-light facilities as outlined below must be seriously considered. Once installed, the daytime monitoring would be highly automated and would yield a valuable database on the aging of polarization-sensitive subsystems. To produce the beam for these calibrations, both spectral conditioning and beam conditioning are required. I suggest these be done in separate units, connected by a (multi)fiber; one spectral source could feed several beam-forming units, for different points of entry into the system. An alternative location for the *spectral* conditioning is within the (back-end) polarimeter, after the final polarizer.

The earliest point of entry is through $M3_{cal}$ (Fig. 9), which is a copy of M3 mounted on the Nasmyth platform, upstream of the half-wave retarder that matches M3 to M4. If $M3_{cal}$ can rotate around the Nasmyth axis, we have approximately a miniature copy of the telescope, through which we can inject calibration light and investigate how the $M3_{cal}$–half-wave–M4 system behaves. This is not quite the same as testing the telescope itself, but it will come close and may well be sufficient in many cases. If necessary, the slight differences may be investigated by mounting, alongside the tube of the main telescope, an auxiliary refractor feeding $M3_{cal}$. This refractor need not be larger than about 30 cm for acceptable integration times on the brightest polarization standards; the signal from the main telescope may need to be attenuated, by some sort of ND filter *within the polarimeter*. To be quite sure that the refractor does

[7]The only objection to oversizing I can see is that occasionally an undersized cold pupil stop is required; presumably this can be avoided for the optical and near-infrared.

not itself introduce significant polarization effects, it may be rotated around its optical axis. These observations to compare the main telescope with the auxiliary refractor and $M3_{cal}$ are the only observations of standard stars that would be needed, and they can be limited to the bandwidths and elevations of the scientific program being carried out. The telescope time involved is now acceptable.

9. CONCLUSIONS

AO-assisted high-accuracy polarimetry can be implemented at the Nasmyth focus. Compared to Cassegrain focus one does pay in greater complexity, extensive (though daytime) calibration, and 10%–15% loss of light (M3, M4, polarization switch), but all of these are acceptable, given the opportunities for sophisticated instrumentation offered by the Nasmyth platforms of large telescopes.

The CHEOPS planet-finder study for ESO's VLT was a stimulating experience for someone reared on photomultipliers and analytical design methods. I thank C. U. Keller, J. P. Hamaker, H. M. Schmid, F. Snik, D. Clarke, L. Venema, and an anonymous reviewer for extensive and thoughtful comments on earlier versions of this paper.

APPENDIX

BACKGROUND

In this appendix to the tutorial paper, I have collected a few relevant background topics. The appendix is intended for the interested nonspecialist (astronomer or engineer) in the modern consortium environment. I have indicated areas in which technical development may well be possible.

A1. Polarimetric Paradigms

Although Kuhn's concept of paradigms (Kuhn 1962) is heavy ammunition for the essentially simple technique of astronomical polarimetry, a description in those terms may be useful. In optical polarimetry we may distinguish three paradigms, listed below. Although run of the mill astronomy has hardly progressed beyond paradigm 1, polarimetry itself is poised to make the transition from paradigm 2 to 3, while currently most optical polarimetry (including the present paper) operates within paradigm 2.

1. PHOTOMETRY *is about intensities and* POLARIMETRY *is concerned with patterns (such as lines, circles, ellipses); never the twain shall meet*. In this world view, photometry and polarimetry are quite separate techniques, with separate ways of thinking, terminology and methods of measurement. At best, the influence of one on the other is considered an error of measurement; far more often, such errors are not even recognized.

The general photometric instrument is represented by the left-hand side of Figure 5. Intensity I, squared amplitude averaged over some ensemble of states, is the relevant quantity; phase is random (within the ensemble of states considered). An input intensity is processed by N stages of zero-point shift and gain to yield the output intensity at the detector. Polarization of the input signal may in fact modify the gains and zero points, but there is no natural way to include polarization within the photometric protocol.

Polarimetry is performed in various ways, all employing an optical component to modify (only) the state of polarization and noting the consequent change of detector signal. The results are reported as degree and kind of polarization, polarization angle and ellipticity. These concepts are a far cry from those of photometry; note that "intensity" does not even figure in this characterization of polarimetry.

2. POLARIMETRY *is a generalization of* PHOTOMETRY *(Fig. 5)*. The four Stokes parameters I, Q, U, and V characterize the signal sufficiently for both photometry and polarimetry (Stokes 1852; see also Tinbergen 1996, § 2.2).

Photometry is now the measurement of I, unaffected by the polarization of the signal, while polarimetry is measurement of Q/I, U/I, and V/I, unaffected by variations of the gains and zero points of the intensity measurement. Photometry and polarimetry are carried out by the same instrument, using different measurement and observing protocols, and often under very different sky or weather conditions.

In the Stokes parameter formulation phases are still unimportant, except as implicit in the polarization.[8] Seeing-limited optical astronomy has used this formulation extensively. The Stokes "4-vector" (I, Q, U, and V), very rarely but more correctly denoted by "column matrix," replaces the I of photometry, zero points are also 4-vectors and the equivalent of a gain is a 4×4 matrix known as the Mueller matrix. Figure 1 illustrates how one appraises a system in such terms. Skumanich et al. (1997) is an excellent example of a fully fledged application of the Mueller calculus.

3. Recently, astronomy has spawned instruments for which *the Stokes-Mueller formalism is no longer adequate, since phases of independent signals do matter*. Examples are interferometers and the concatenation of atmosphere, telescope, and adaptive optics. To represent these, phases must somehow be

[8] If you do not feel comfortable with polarization concepts under such circumstances, try Tinbergen (1996) chapter 2 for a step-by-step nonmathematical presentation.

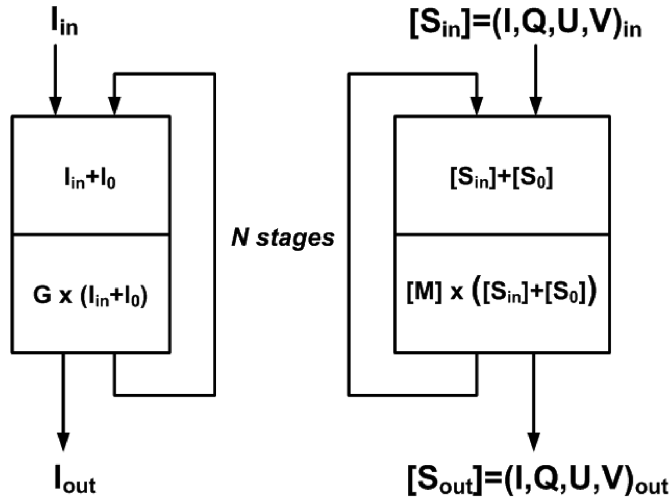

FIG. 5.—Optical systems for photometry (*left*) and polarimetry (*right*). In the photometric case the quantity being processed and the N zero-point errors are scalars I, for polarimetry they are Stokes 4-vectors $[S]$. The scalar gains G of photometry translate into 4×4 Mueller matrices $[M]$ for polarimetry. The generic system illustrated here has N stages of optical processing; detector nonlinearity is not represented in this purely optical schematic.

included in the formulation, since separated (and separately handled) parts of the input signal are recombined coherently further down the optical train.

The formalism available for such applications is known as the Jones calculus. The Jones vector has two orthogonal electromagnetic field components in the usual complex notation, the ratio of amplitudes and difference in phases of these defining the polarization. Zero points are Jones vectors, and gains are 2×2 Jones matrices with complex elements.

Although it is not clear yet exactly what shape this paradigm will take, it seems likely to me that in optical astronomy it will be sufficient to analyze selected parts of the optical train in Jones calculus, then convert to the Stokes-Mueller formalism under conditions of random common-mode phase and analyze the complete system in Stokes-Mueller terms (indeed, Sanchez Almeida & Martinez Pillet [1992] proceed somewhat like this). However, for radio interferometers, especially at the low frequencies for which LOFAR is being built, Jones calculus may be employed extensively, converting to Stokes only after the correlators and for the final sky maps (Hamaker 2006 and earlier papers in that series).

A2. Design Evolution

Since technical polarimetry is not in every optical designer's toolkit, I discuss briefly some of the relevant developments in astronomical polarization design. All of these are crying out for further development, which is the reason for this appendix. For more detail and other components, start with Tinbergen (1996) and its references, and Keller (2001), then use electronic search for the most recent developments.

A2.1. Superachromatic Wave Plates

Wave plates are flat-plate retarders, components which retard (phase shift) one polarization form with regard to its opposite. Generally these two orthogonal polarization forms are linear.

Simple crystal wave plates are chromatic, they are exactly quarter-wave or half-wave at only one wavelength. There are two ways to achromatize them; for details see Tinbergen (1973) and Goodrich (1991):

1. Use two crystal materials of different spectral dispersion of the birefringence, and combine a positive and a negative wave plate to yield the exact retardance at two wavelengths, like an achromatic doublet lens. The wave plate will be approximately correct over the working wavelength range. Three-material combinations have not yet appeared, but might be possible with recently synthesized crystals.
2. Use three slices of the same material, but combine them according to a prescription worked out by Pancharatnam (1955). For the half-wave retarder, the three slices are identical. A slight disadvantage of the Pancharatnam prescription is that the orientation of the retarder axes has become a (slow and slight) function of wavelength.

One may combine these two constructions by regarding the two-material retarder as made up from a virtual material of peculiarly favorable spectral dispersion of the birefringence and thus arrive at an even more achromatic component: the "superachromatic" wave plate, usually constructed from quartz and magnesium fluoride (three slices of each; Fig. 6; feasible wavelength ranges, e.g., 310–1000 nm, 600–2000 nm). Manufacture is not easy and these components are expensive; they also generate (faint, but polarized) spectral fringes by multiple internal reflections (Clarke 2004a, 2004b, 2004c), which at present disqualifies them for high-resolution spectropolarimetry. There is room for considerable improvement in the choice of materials, in the use of antireflective coatings, in control of manufacturing tolerances, and in assembly (§ 10.1.2 of Tinbergen 2004) ; their performance in uncollimated and/or oblique beams also needs to be elucidated by polarized ray-tracing (§ A2.4).

A2.2. Internal Reflection Retarders

There is another class of linear retarders that has its uses in optical astronomy: those based on total internal reflection. No polarization is generated, but the two eigenmode polarizations suffer different phase shifts. Since for a certain angle of incidence the retardance is only a function of the refractive index, it is a fairly slow function of wavelength. In contrast to the superachromatic retarders, the axis directions of the retarder do not vary with wavelength.

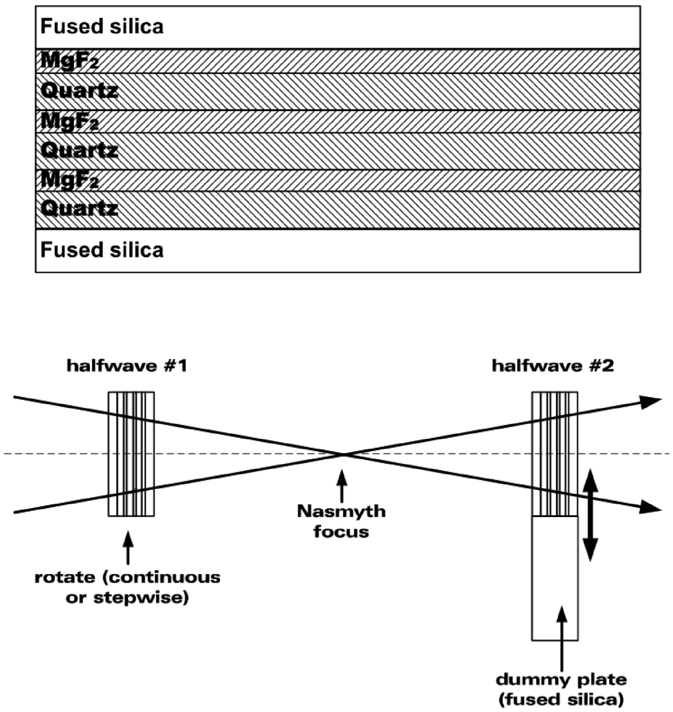

FIG. 6.—Construction of a superachromatic half-wave retarder (*top*) and its use in a polarization switch (a.k.a. time-averaging depolarizer, § A2.3), generally near a focal image because of the small size of polarization optics. Design details are found in Tinbergen (1973).

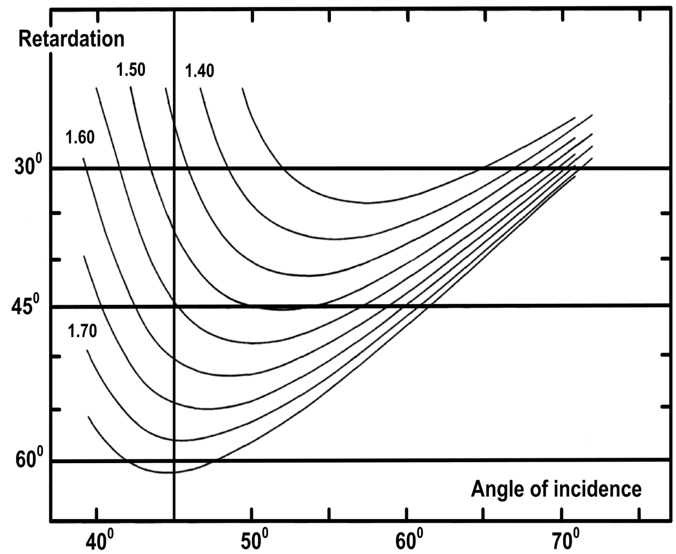

FIG. 7.—Total internal reflection: retardance as a function of angle of incidence for various refractive indices. The term "retardance" is used in polarization literature for the numerical value of the property "retardation"; retardation is the phase difference between two opposite polarizations, as induced by a "retarder."

Figure 7 displays just about all there is to be known about this phenomenon. Note the following:

1. For a refractive index of 1.51 (crown glass), the maximum retardance is about 45° and is a very slow function of angle of incidence. Two such reflections make up a quarter-wave retarder (Fresnel rhomb). A similar condition holds for a retardance of 60° (one third of a half-wave) and refractive index of 1.73 (dense flint).

2. Even where retardance is a fast function of angle of incidence, an even number of reflections may be configured to be self-compensating for retardance as a function of angle of incidence.

3. The fractional change of retardance with refractive index is least at high angles of incidence.

4. At an angle of incidence of 45° (right-angled prism), there are several ways to make up a half-wave retarder; one of them uses fused silica (refractive index 1.47).

5. The chromatic optical path through these components is usually considerable, but for some applications one could conceive using the prism analog of a Fresnel lens.

6. Suitable coatings on the reflection face can improve the achromatism still further (King 1966).

Examples of internal-reflection retarders are shown in Figure 8. Altogether, there is probably room for considerable creativity in applying high-quality retarders of this general kind to broadband optical systems.

A2.3. Depolarizers

So-called "depolarizers" are actually polarization averagers and therefore are sometimes referred to as pseudodepolarizers. Since Q, U, and V can be positive or negative, the average can tend to zero. Randomized wave plates will convert well-defined polarization forms into randomized ones and under the right conditions can serve as depolarizers.

The original Lyot depolarizer consists of 2 very thick multiwave chromatic retarders and converts incident polarization into a rapidly alternating function of wavelength. It works well for a wide bandwidth and a fast beam, but should not be used for narrowband signals such as we might wish to use in our calibration system.

A pupil-averaging depolarizer may be constructed from a rough-cut birefringent crystal, immersed in oil or cement of about the same refractive index (Peters 1964). It is located at a pupil of the optical system. Unpolarized light sees just a "slab of glass," while polarized light sees a multiwave retardance varying randomly over the pupil. The sum of all the contributions, at an image point, will have very small polarization, it will be "depolarized." As long as we limit ourselves to (close to) an image plane, we shall not notice that there is strong random polarization elsewhere in the system. The random polarizations will be functions of wavelength, but their average will always be small. This kind of depolarizer works for every wavelength

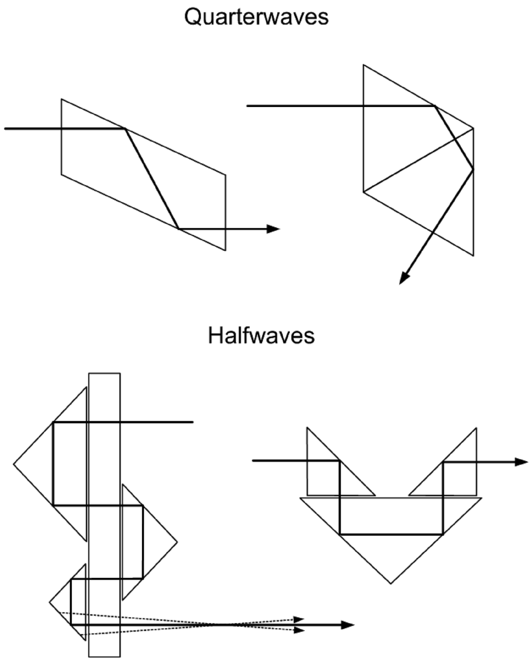

FIG. 8.—Total-internal-reflection retarders. The refractive index required is 1.51 (borosilicate crown; *top left*), 1.65 (extra-dense flint; *top right*), 1.47 (fused silica; *bottom left*) and 1.55 (extra-light flint; *bottom right*). Coatings on the reflective faces can modify the characteristics. Other designs and references can be found in Tinbergen (1996) and Tinbergen (1973).

within the passband and could be used for a first reduction of the polarization of a calibration source, before feeding the light into an optical fiber (fibers can be polarization-sensitive; it is best not to feed them too polarized a signal).

Apart from averaging over wavelength or ray direction, one may average polarization over time and thus obtain depolarization of the time-averaged signal. The necessary condition is that one never exceeds the linear range of the detector system. The most suitable component for time-averaging depolarization is the superachromatic half-wave plate (Fig. 6): if it is permanently in the beam and rotated, it will rotate the plane of exit polarization which will thus average to zero for an integral number of (quarter-)revolutions. If such a half-wave is alternately in and out of the beam, the circular polarization will be reversed periodically and average to zero. Such a depolarizer is optically identical to the polarization switch of § 6: if one measures the alternating polarization, the *switch* function is selected; if one uses the average polarization, one selects its *depolarizer* function. In fact, any polarization modulator without its exit polarizer can thus serve as a depolarizer.

A2.4. Polarized Ray Tracing

Until fairly recently, polarization analysis only treated the central ray, along the component's optical axis. The effect of oblique rays within a noncollimated beam was only estimated and one guessed at the minimum f-ratio that a particular polarization component could handle. Together with experimental verification, this worked well enough for beams of $f/10$ and slower, the typical Cassegrain telescope values. If we want to use faster beams or predict performance with greater accuracy than has been possible until now, we need to include polarization effects within our ray-tracing activities. If we wish to optimize polarization performance while designing real-life instrument systems, we certainly need a way of constructing a realistic representation of polarization including oblique rays.

Modern ray-tracing programs do allow this. For astronomy, one would like to replace the scalar flux (intensity) by the Stokes vector and derive the Mueller matrix of the system for any ray one cared to specify. Software such as ZEMAX allows the user to specify the input signal as 100% linearly polarized and obtain the polarization of the output signal. Using this for two polarizations at right angles, one can obtain the Jones matrix which includes phase effects but only applies to 100% polarization. However, every component or system that has a Jones matrix also has a Mueller matrix (though the reverse does not hold). The relation between the two, due to van de Hulst (1957), is derived in more detail by Azzam & Bashara (1987) as equation (2.243). This approach has been used for the Advanced Technology Solar Telescope (C. U. Keller 2007, private communication) and for the Advanced Electro-Optical Telescope (Harrington et al. 2006).

A2.5. Calibration

In § 8, I justified calibration of the complete Mueller matrix of the total optical train. Here I outline a brute-force approach, which may be regarded as a fallback option if more elegant solutions cannot be devised.

Three sets of signal properties are important in calibrating the polarimetric system:

1. The optical beam should be as much as possible geometrically identical to that from the telescope; this in practice means that the pupil and image planes must be in the correct positions and that the pupil has the correct shape. The condition is necessary because polarization properties of optical components depend on tilt and orientation of the rays.
2. Spectral content of the beam should be under the experimenter's control (filters or a simple monochromator; use of too wide a bandwidth would result in an effective wavelength that depends on color temperature of the source, as is notoriously the case in UBV photometry).
3. There should be at least four choices of polarization: (approximately, not necessarily exactly) unpolarized, linear (Q and U), and circular. The level of polarization generated should be similar to a real-life astronomical situation (this is important in order to avoid potential nonlinearity errors in the AC/DC quotient of the detector signal). The combination of a rotating

polarizer and (at a different rate) a rotating retarder may be a very effective way to obtain the entire Mueller matrix in a single experiment (Skumanich et al. 1997; Snik 2006).

I suggest that a suitable configuration for calibrating our hypothetical Nasmyth system will be a light source, followed by a monochromator and depolarizer (pupil-averaging, § A2.3), followed by feed optics for an optical fiber bundle. This fiber bundle may be split to feed the several points of entry (§ 8), at each of which an integrating sphere or diffuser feeds the beam-forming optics. Each beam-forming unit should include the polarization compensators and insertable *depolarizer* of steps 2 and 3 of the calibration procedure below. The final components in the beam will be the insertable calibration polarizers.

Outlawing the use of precious nighttime for the main body of calibration work and substituting daytime calibration using a laboratory source means that a light-tight instrument is required.[9] Controlling the polarization of the injected beam is not easy, because all laboratory sources are polarized to some uncertain but considerable extent. It is possible that techniques such as described in Snik (2006) can cope with this; if not, the following ab initio procedure could help:

1. Using any laboratory source with stable polarization, reduce the polarization by passing the light through stable adjustable polarization compensators and a pupil-averaging depolarizer. Reduce the polarization still further, at will, by inserting yet another depolarizer, preferably a rotating or in/out (super) achromatic wave plate (§ A2.1).
2. With this last depolarizer inserted, use the polarimeter to do a measurement.
3. Take the depolarizer out, and adjust the compensators until the polarimeter output is the same as in the previous step; the injected beam is now less polarized than before (one does not have to know exactly how much less).
4. Iterate the previous two steps until there is no further change; finally insert the depolarizer again. To a tolerance depending on the system measurement accuracy, one should now have an unpolarized beam with which to define the system Stokes vector–zero point
5. Into this unpolarized beam, insert calibration polarizers to define Q/I, U/I, and V/I.

There are in fact three suitable points of entry for such calibration signals:

1. The most obvious one is the input to the polarimeter (which includes whatever spectrometer or imager one has chosen to incorporate);

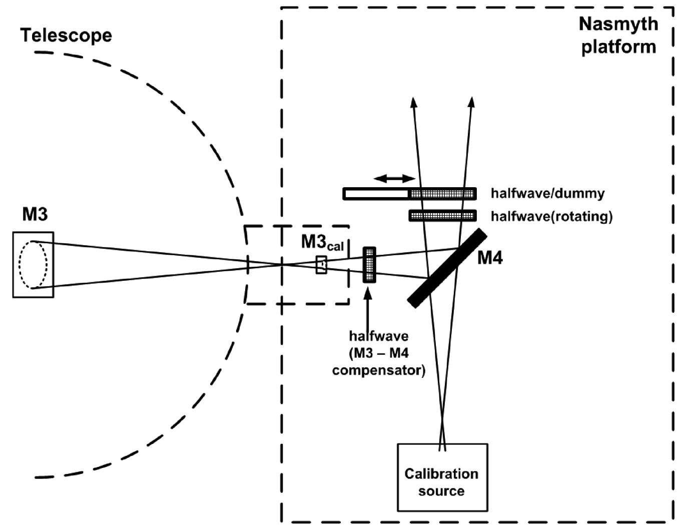

FIG. 9.—One possible layout at the Nasmyth focus. Calibration light may be injected either through $M3_{cal}$, which simulates M3 in the telescope, or just beyond M4, at the transition from telescope (polarization properties depend somewhat on elevation) to platform optics (polarization properties constant). The two half-waves just beyond M4 can serve as polarization switches or depolarizers. See § 8 and A2. The half-wave upstream of M4 is there to match M4 to M3, with regard to polarization; see end of § 5.

2. Having calibrated the polarimeter to check its proper functioning, the next earlier point of entry is just after M4 (see § 5), where the polarization has been restored more or less to "as from the sky." All that is needed to inject the polarization-conditioned beam here is to take M4 out of the beam (Fig. 9);
3. For a system such as that of Figure 9, injecting a calibration signal via $M3_{cal}$ will characterize the elevation and wavelength dependence of the half-wave retarder between M3 and M4 (see § 8 for details).

A convenient classical linear polarizer (A. Dollfus 1970, private communication; possibly traceable to B. Lyot) is a pair of thin, oppositely tilted transparent plates. Such a component does not displace the beam when inserted and its spectral dependence of polarization is predictable from that of the refractive index. Since surface microstructure or contaminants may modify the polarization generated, measurements through a Polaroid should be used as a check ($\equiv 100\%$) and, to check electronic signal processing, all measurements should be repeated at several signal levels. A convenient way to convert the linear polarization to circular is to use a superachromatic (§ A2.1) quarter-wave plate, or possibly an internal-reflection retarder (§ A2.2), though this requires a slow beam. A versatile laboratory polarimeter and computer modeling (§ A2.4) are essential to validate these calibration components periodically for routine use in the monitoring system.

[9] The tolerance for light-tightness may be relaxed if the laboratory calibration source is modulated (common practice in radio installations); conveniently, the frequency of such modulation could be chosen in the "atmospheric" range, so as not to interfere with those of the back-end modulator and the Nasmyth-focus polarization switch.

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