ARRAY POLARIMETRY AND OPTICAL-DIFFERENCING PHOTOMETRY

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ABSTRACT: Array detectors have improved the efficiency of optical polarimetry sufficiently for this technique to become part of the standard arsenal of observational facilities. However, we could gain even more: spatially-differentiating photometry can be implemented as an option of array polarimeters and low-noise, high-frame-rate array detectors will allow extremely high precision both in polarimetry and in such differentiating photometry. The latter would be valuable for analyzing many kinds of optical or infrared images of very low contrast; the essence of the technique is to use optical (and extremely stable) means to produce the spatial derivative of the flux image, in the form of a polarization image which is then presented to a "standard" array polarimeter. The polarimeter should incorporate a polarization modulator of sufficient quality for the photometric application in mind. If developed properly, using a state-of-the-art array detector and the most sensitive type of polarization modulator (stress-birefringence), optical differencing will allow levels of relative photometric precision not otherwise obtainable. With the optical differencing option taken out of the beam, the same instrument can be used for high-quality polarimetry.

1. INTRODUCTION

Large telescopes and their instruments (both imagers and spectrographs) are generally built in the first place for "detection of the faintest objects" rather than for "accurate (spectro)photometry of somewhat brighter objects", though the latter often is a scientifically equally valid use of a large telescope. This situation has meant that in many instruments array detectors operate close to undersampling and optics are kept as simple as possible, both features having disastrous consequences for high-precision photometry. Since some observers nevertheless try to use these basically unsuitable instruments for photometry, array detectors are in danger of acquiring a reputation of being unsuitable for photometric applications of the highest accuracy or precision.

There is, however, no proof for this assumption and it is in fact unlikely to be true. Like photomultipliers (PMTs) and unlike the grains of a photographic plate, the pixels of the array are not destroyed by being used as a detector, so we have the option of accurately calibrating our observation by auxiliary measurements. The massive parallellism and the lack of cascaded secondary-emission stages should prove an advantage over PMTs in well-designed instruments. The defects such as within-pixel gain variations (Jorden et al. 1994) appear to be no worse than for PMTs. With sufficient oversampling and properly designed electronics, therefore, arrays are likely to have better short-term gain stability than PMTs, and photometric instruments incorporating them should perform at least as well as the PMT (spectro)-photometers. The essence of good design is to optimize the entire instrument for stable use of the array detectors

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and to employ calibration in one form or another to extend short-term stability of each pixel to long-term stability of the entire calibrated array.

I have previously carried out, as an intellectual exercise, what one might call a "zero-order system design study" for the case of accurate all-sky spectro-photometry of relatively bright stars in a relatively faint sky (Tinbergen 1993). The main concern in that regime is to calibrate out the system gain variations, designing the entire system to take advantage of the short-term gain stability of the individual detector pixels. In the present paper I explore the regime of high-signal but low-contrast images; with ten-meter-class telescopes and high-QE detectors, this regime occurs more often than one might have supposed. The concrete question I shall examine is: "Can we eliminate a constant background signal to one part in 10^5 or even 10^6, to measure *accurately* the light from point sources as faint as one part in 10^3 or even 10^4 of the background?" Accurate polarimetry is one such situation and another would be a generalization of the chopping-secondary (infrared) and dual-feed (radio) photometric techniques; I shall show that such differential photometry and array polarimetry are intimately related.

The discussion applies to all kinds of images, both in the optical and in the near infrared: direct sky images, spectra, interferograms or hybrids such as long-slit spectra. The only basic requirement is the availability of array detectors and polarization components (polarizers, retarders). The precision one can actually attain will be a function of the properties of available components; examples of such properties are: readout noise as a function of frame-rate for the detectors, optical quality and achromaticity for the polarization components.

2. OPTICAL DIFFERENCING VIA POLARIMETRY

Suppose, for the moment, that we possess an array polarimeter which allows us to determine the *polarized flux* striking any pixel of our array. By inserting a properly-cut calcite plate into the optical beam just in front of an image plane, we can generate from any single flux image two separate half-intensity images of opposite polarizations (Fig. 1); these images will combine in the focal plane, with a slight shear (relative displacement). If, instead of measuring the total flux image, we analyze the *polarized flux image* (by using our array polarimeter), any constant background signal will have disappeared entirely, while a point source has been split into a positive and a negative source (Fig. 2). A constant gradient in the total flux background will show up as a constant signal in the polarized flux image. The separation of the positive and negative peaks, and the sensitivity to gradients, may be controlled by adjusting the thickness of the calcite slab. For infinitesimal thickness, the action of the slab is to spatially differentiate the image when going from total flux to polarized flux; since the slab thickness is always finite, the term "differencing" will be used.

The most important aspect of this differencing action is that it is entirely optical; it is therefore extremely stable and independent of detector properties. *Analyzing* the resultant polarized flux image will involve a detector within the polarimeter, but that is a different matter: "optical differencing" itself is a purely *optical* conversion of a total flux image into a polarized flux image with a different and possibly more useful structure (e.g. when faint point sources are the object of our scientific curiosity and the high background is merely a source of measurement error).

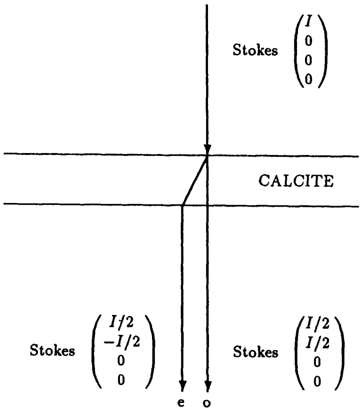

Fig. 1. Double refraction by a calcite plate (Schematic).

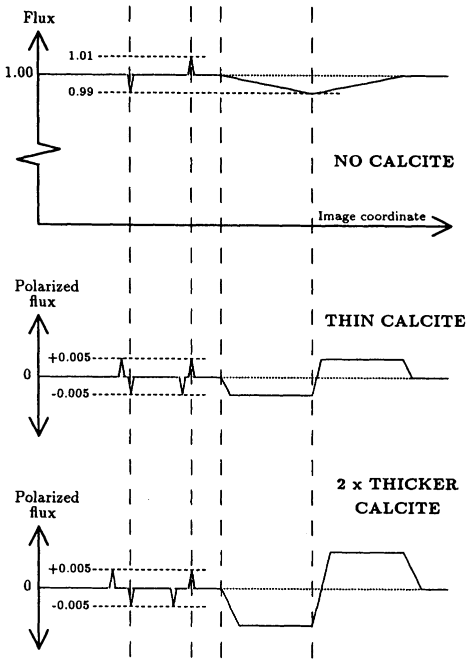

Fig. 2. Optical differencing: the flux and the polarized -flux images. The positive-polarization ray is the ordinary one in the calcite and is not displaced from the total-flux object: the extraordinary ray is assumed to be displaced leftwards.

3. PRECISION OF ARRAY POLARIMETRY

In this section I discuss available precision in array polarimetry. Give or take a factor of two, the same precision will apply to optical differencing.

"Classical" array polarimeters, whether of the direct-imaging type (e.g., Scarrott et al. 1983) or as part of spectrographs (e.g., Tinbergen and Rutten 1992), make use of a two-beam analyzer to produce two separate images of opposite polarization. These two images are both recorded and the polarization information resides in changes of the *flux ratio* of the images as the state of a polarization-modifying component is changed and a second pair of images is recorded. The most common polarization-modifier is a halfwave plate; this is rotated by 45 degrees to switch the linearly polarized part of the flux from one spectrum to the other, thus altering the flux ratio by an amount related to the degree of polarization of the input signal. When computing the degree of polarization from the two pairs of images, the assumption is made that the system gain for any pixel for any given exposure can be factored into a time-dependent but polarization-independent part (including scintillation and extinction noise) and a polarization-dependent but time-independent part (mainly the response of the instrument optics and detector pixels to the two separate beams of polarized light); this is explained in detail in Tinbergen and Rutten (1992). This basic assumption of "two-beam DC polarimetry" is very good, but at some level of precision it will break down, e.g. by sub-pixel-scale image motion as the halfwave plate is rotated or as a result of differential flexure of the instrument between the two exposures, or again by a difference in transmission for the two states of the polarization modifier (e.g. the Fresnel reflection coefficient depends on polarization and rotation of a halfwave plate will also rotate the weak polarization induced by this plate). Experience (partly with the PMT polarimeters) indicates that the assumption is robust to well below 0.1%, but that we shall be lucky if we routinely reach 0.01% in that way; this is two orders of magnitude removed from the goal I set myself in the Introduction.

If we wish to improve on this precision, we must do at least two things: we must ensure that the polarization modifier affects only the polarized signal and does not influence the total flux to any measurable extent, and we should complete our basic polarimetric measurement within a time short compared to all time-constants of unintentional changes in the opto-mechanical system (finally integrating over many such basic measurements to obtain an acceptable S/N ratio).

For PMT polarimeters, there is an almost ideal solution: the stress-birefringence modulator (e.g., Kemp 1969). This consists of a slab of isotropic material (often fused silica), which is periodically stressed mechanically to make it birefringent. The periodic birefringence is so minute (of order one part in 50,000 at maximum) that any influence on the total flux is below all practical limits of detection; also the angular acceptance of the component is very large, for the same reason. In the usual PMT application the device is mechanically resonant at a frequency of tens of kHz, so that the basic measurement (of the pair of fluxes from which the polarized flux is derived) is performed within a fraction of a millisecond and noise due to scintillation and varying extinction is eliminated entirely. PMT polarimeters of this kind have yielded a precision of about one part in 10^6, even without using the information in the second beam of the analyzer (the second beam is then used only to reduce photon noise by the square root of two).

Frame rates of tens of kHz are incompatible with astronomical array detectors, except when charge-switching is practical (e.g., Soucail et al. 1995). However, variants of the stress-birefringence modulator can be constructed to run at a few to a few tens of Hz; these will not be mechanically resonant, but that is not a necessary condition. New CCDs of the frame-transfer design exist which combine a readout noise of order 15 electrons with a frame rate of some tens of Hz; in the near infrared, the PtSi arrays are cited as combining three electrons readout noise with 3 MHz pixel rate (Ueno 1995). Such detectors will allow construction of stress-birefringence polarimeters with hundreds of thousands of parallel channels, one pixel for each (or, more probably, thousands of parallel channels with, say, 100 pixels each, to allow adequate oversampling in search of photometric stability). Such polarimeters will operate at a modulation frequency around 10 Hz, sufficiently high to eliminate almost all of the scintillation noise for large telescopes, even with a single-beam analyzer. A readout noise of about 15 electrons is acceptable: the corresponding noise-equivalent signal of about 200 electrons will allow the user an instantaneous dynamic range within the image from about 1000 electrons to saturation at a few times 100,000 electrons; with control of elementary exposure time (and therefore of modulation frequency) to suit the brightness of the image, such a within-image dynamic range will be enough for the regime we are considering.

A complete system including both optical differencing and an array polarimeter is shown in Fig 3. The only important component shown there but not discussed previously is the input depolarizer. This is needed to ensure exact 50/50 splitting by the calcite plate; it need not be a perfect depolarizer, a "time-averaging linear depolarizer" such as a continuously rotating halfwave plate (Tinbergen 1995) will suffice. The analyzer will generally be of the double-beam type, to use all the available photons and for elimination of "common-mode" noise (such as any remaining scintillation or extinction noise). The total system includes four optical components in addition to the basic spectrograph/photometer, so one must expect a light loss of some 10% even with good anti-reflection coatings on all surfaces; that is the price one has to pay for obtaining high photometric precision in very-low-contrast images. Design problems such as constructing a broadband system have not been mentioned here, but will determine the compromises one will have to accept in any practical system. The "calcite plate" is likely to take one of the forms illustrated in Fig 4, probably in the "Savart plate" modification.

Note: The reader may well wonder what is the reason to go to all the complications of depolarizing a signal, then polarizing it, then analyzing the polarization by what is in essence a differential photometer, in order to obtain differential photometry at the end. The only valid reason is robustness of the instrumental method and therefore of the astronomical results. I have mentioned before that optical differencing is extremely stable and robust. Modulation polarimetry, using a stress-birefringence modulator and a single detector (pixel) for the entire measurement, likewise has been shown (in the PMT case) to be very robust and capable of very high and repeatable precision. So the proposed rather roundabout method is a cascade of robust operational units, each doing that which it does best. Systematic and instability errors are eliminated by doing the basic polarimetric measurement with one detector pixel and within as short a time span as is compatible with the readout noise and the photon stream; the two-beam analyzer is only needed for further reduction of the photon noise and of any remaining common-mode noise.

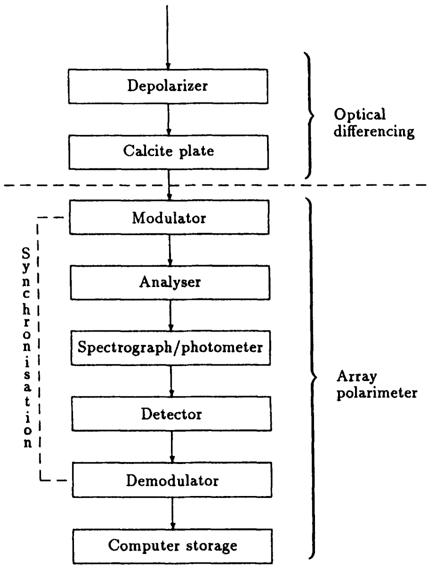

Fig. 3. System Layout.

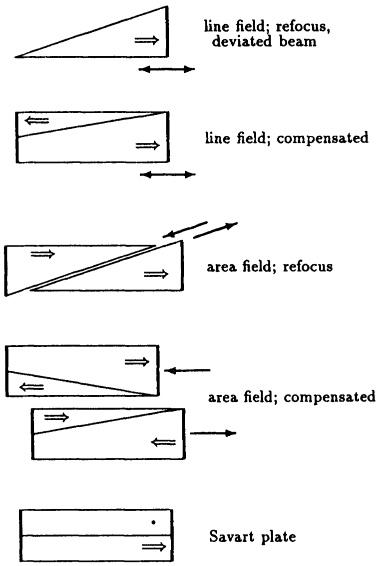

Fig. 4. Compound calcite plates (schematic only

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4. APPLICATIONS

In this section I explore the potential use of optical differencing; polarimetry is sufficiently well-established to fend for itself. The context is provided by the ten-meter-class of new telescopes, which in many cases provide photon streams sufficient for very high precision indeed on relatively bright objects. The main question will be: what in the present context is meant by "relatively bright"? To me, at any rate, the apparent answer was a surprise; my hope is that appearances do not deceive.

Supposing we can eliminate systematic and instability errors by the techniques discussed, photon noise will be the determining factor of the precision obtained. We are used to 1% precision being called "high" in astronomy, but that is because of our preoccupation with "detection of the faintest objects". A precision (or at least S/N) of 0.1% is common in (spectro)photometry of brighter objects and 0.01% precision is the norm in PMT polarimetry. Large telescopes used on bright objects collect enough photons for all these applications; we may ask ourselves how much further we can go. To put this into perspective, consider the largest practicable signal in stellar astronomy: a zero-magnitude star being observed for six hours by a ten-meter telescope, using a 6000 Å bandwidth and an instrument of 0.5 overall quantum efficiency. The number of photons detected would be of order 3×10^{16} and a precision of better than one part in 10^8 would be possible. We conclude that, even if we set our sights on a precision (very high for astronomy) of one part in 10^6, we still have a reserve factor of 3×10^4 or 11 magnitudes for fainter objects, narrower bandwidth or shorter integration times. This shows that sufficient photons can be collected for a number of applications, but that the largest telescopes will be essential in many cases.

To start with, let us estimate the limiting magnitude for detection of point sources in broad daylight, assuming blue sky to be absolutely uniform and assuming one arcsec seeing. Blue sky is of order of one fourth-magnitude star per square arcsec, which leads to a signal of order 6×10^{14} detected photons and a photon-limited precision of one part in 2.5×10^7. Such precision in measuring the signal from blue sky corresponds to a limiting (one sigma) point-source magnitude of 22. If we reduce the precision to one part in 10^6, we still reach a one-sigma limiting magnitude of 15, now in about 40 seconds if we retain the very wide bandwidth; obviously, other choices can be made.

A similar rough calculation leads to a one-sigma limiting magnitude for point-source detection during full moon of 28.5, using a precision of one part in 10^5. Using the same figure for precision for the analysis of a spectrum with relatively few and shallow lines (absorption or emission), one estimates that a 0.001% band of 30 Å width will still be one-sigma detectable for a tenth magnitude star. Time variations of period 100 seconds of a 0.001% absorption band could be investigated in stars of magnitude four.

A precision of one part in 10^4 used in direct imaging during a really dark night leads to a one-sigma limiting magnitude of 31 in one arcsec seeing and much deeper if the optical differencing technique can be combined with wavefront reconstruction. Other examples can easily be worked out for spectroscopic applications, such as faint interstellar absorption bands, Doppler or Zeeman profiles of stellar or interstellar lines of very low optical depth, etc.

A precision worse than one part in 10^4 does not seem to me to need optical differencing.

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Drift-scan techniques should be able to fill the range between one part in 10^4 and one part in 10^3, while conventional flatfielding seems able to cope with precisions worse than one part in 10^3. Since drift-scanning and optical differencing are both one-dimensional techniques, a combination may be both feasible and useful.

Natural applications of optical differencing would be detection of one particular very faint fringe within the grey mist of an interferogram, and sky-line subtraction to very high precision in spectroscopy. Using double-beam analysers to allow much slower modulation and readout, the mid-infrared range with its high thermal background could be a natural application, too; the polarimetric components, to the extent that they are non-lossy, could stay outside the dewar for convenience of operation (cf., Hough et al. 1994 for near-infrared). Speckle methods could conceivably be combined with optical differencing (see discussion at the end of this paper, on confusion).

Having considered photon noise in the final image accumulated in the computer, we need to consider it for the individual images read out from the detector. The minimum signal is taken to be 1000 detected photons per pixel (which may be a superpixel, using binning) per readout. To take the blue sky example: with the 6000 Å bandwidth, the signal is of order 3 x 10^{10} photons/sec, so narrower bandwidths are no problem whatsoever (essential, in fact). The darkest night-time sky, however, is marginal even for a bandwidth of 6000 Å: 6000 detected photons/sec, allowing at most a 6-Hz frame rate and 3-Hz modulation rate; dual-beam analyzers will often be essential in that application, unless readout noise at about 10-Hz frame rate improves even more. For a typical spectral application of 30 Å bandwidth, a 15^{th} magnitude star still yields 10000 photons/sec, allowing a ten-Hz frame rate.

Scintillation noise is unlikely to be a serious issue. Young (1967) states that for (at that time) "large" telescopes the crossover between scintillation-dominated and photon-dominated noise occurs at 8^{th} to 11^{th} magnitude; since we are concerned only with the residual high-frequency tail of the scintillation power spectrum, the crossover magnitude in our case will be brighter. In addition, as stated above, scintillation noise is "common-mode" for the two beams of a dual-beam analyzer and can be eliminated; actual experience with a ten-meter-class telescope (and its central stop, which determines the high-frequency tail of the scintillation power spectrum) will be needed before such matters of detailed design can be decided.

5. CONCLUSION

I have discussed how frame-transfer CCDs and PtSi arrays may be used to extend the realm of photon-limited precision to situations of very low image contrast. The essential ingredient is adequate very-short-term stability of the gain (detected electrons/photon) of the individual pixels of the array; by sufficiently fast modulation, such short-term stability can be exploited to obtain polarimetric and differential photometric precision. We do not know what the operational very-short-term photometric stability of array detectors is; we suspect it is very good indeed and measuring it seems feasible, to say the least. If we can design instruments that exploit the short-term stability, it seems likely that both polarimetry and optical-differencing photometry can be implemented to levels of precision beyond the reach of any other method. Certain high-precision areas of optical/infrared astronomy would thus become accessible, particularly with the large signals provided by ten-meter-class telescopes. With large telescopes, many such programs could be carried out near full moon or in the daytime, so they would compete only marginally with other programs and the scientific significance of large telescopes would benefit.

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DISCUSSION

PHILIP: This technique could be used to detect faint members of open clusters, but I imagine that in a globular cluster the images would be too crowded.

TINBERGEN: That is correct. The proposed technique eliminates a high constant background but can do nothing for confusion (it could be operated with wavefront correction, however). If in confusion limited situations one uses CLEAN, the "±" PSF is no worse than a single peak, I suspect; one does give up the constraint that the image must be positive everywhere.

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