Session 3

New Techniques

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New Techniques

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Abstract

Routine millimagnitude photometry may require a new approach to reduction of photometric errors. Such an approach is outlined in this paper; it stresses elimination of each error as close to its source as possible. The possibilities provided by modern technology are reviewed in this light. An engineering design group dedicated to photometry is a prerequisite and an on-site photometric technician may be necessary. In this concept, observers are mainly remote users of a database. Implied is the idea of *accurate* photometry necessarily developing into a single but multi-site astronomical facility (cf. VLBI) and the communal discipline that goes with it.

Introduction

"Techniques" is a pleasantly vague term. Reviewing 'New Techniques', I have chosen to capitalize on 3 decades of varied experience as a hybrid astronomer/engineer and I intend to put up for discussion a model for a different kind of photometric instrument system than you will be used to. I do not claim uniqueness for this model; the 'conversation piece' I shall present will be there to provoke further thought. It should be knocked down if it can't stand up, and major surgery may be required. But I hope there will prove to be some virtue in at least some parts of it, to help make some real progress towards *routine* millimagnitude photometry, which we all claim should be possible. 'New Techniques', therefore, I shall take as 'technology which does exist, but which most of this audience may not associate with the aims and practice of photometry'. My assumed role will be that of the systems engineer, translating system aims into requirements for the component subsystems. Development of those subsystems to the requirements is something I shall leave to an imaginary staff of specialized engineers. Hopefully, these imaginary specialists have kept me sufficiently well-informed of the state of their respective arts.

My own experience started in radiopolarimetry, then shifted to optical photometry and polarimetry with small telescopes, and finally included 10 years of the more hi-tech environment of equipment design for large telescopes. Technological areas which I judge to be of interest include telescope construction, autoguiding, filter design, detectors, on-line calibration facilities, optical fibre techniques and computer control.

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Actual implementation of most of the concepts discussed will require an engineering group covering optics, mechanics, electronics and software. This should not discourage us, at least not at this point: world-wide photometry is a large enough community to support 'somewhere' a central development laboratory for the benefit of all; it is a matter of wanting it badly enough.

The Story So Far

The design of many classical photometers has been dictated by a requirement of minimal cost. As a consequence, such photometers are extremely simple, consisting of little more than an entrance aperture, a filter wheel, a Fabry lens, a photomultiplier and the bare minimum of electronics. Recently, a computer has been added to this basic setup, and much effort has gone into automating and standardising the data collection and analysis. As a result, we now know a great deal about systematic errors of various kinds in our photometry and in many cases we know the basic causes. They are discussed in Young's papers entitled 'Improvements to Photometry' and in the proceedings of the two workshops with the same name. Examples of error mechanisms are (e.g. Young et al. 1991):

- Image motion translates into photometric errors at the photometer aperture, at the filter and at the detector; the details differ between photometers and depend mainly on where pupil and focal plane are re-imaged and on the type of component used.
- Change of ambient temperature affects filter passbands and detector properties.
- Filter sets in most cases do not fully sample the spectrum, so that transformations to other photometric systems depend on information which has not actually been measured.
- Filter bandpass shapes are generally suboptimal for successful transformations.
- Atmospheric dispersion causes relative image displacement as a function of wavelength and elevation, leading to elevation-dependent errors in measured photometric colours.
- Atmospheric extinction is more complex than is often assumed; the only good way to reduce its influence on the observations is to disentangle its spatial, temporal and wavelength dependences routinely by a suitable standard star strategy *applied systematically*.
- Humidity may affect the behaviour of optics (including those of the telescope), filters and possibly detector.
- Variable flexure of telescope and photometer affect their response.
- Magnetic fields (of the Earth and of local motors and solenoids) affect the response of photomultipliers.

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- Neutral-density filters are generally not sufficiently neutral for the wide bands used in photometry, therefore affect passbands.
- Stray light from the Moon or from within the dome can enter photometers that have been sealed or baffled insufficiently, or via insufficiently clean telescope optics.

In the 'classical' photometer I have sketched, there is often not much one can do to eliminate these defects, and the trend has been to take the photometer for granted and determine its properties by comparison with standards (stars, systems, seasons, etc). This approach seems to have reached its limit at an accuracy of perhaps 0.01 magnitude (in the best cases). Young (1992a and earlier papers in the series) points out possible improvements, but these are not all really simple to implement and one wonders whether *routine* improvement by an order of magnitude or more can in fact be achieved by simple means at all. Scientifically speaking, improvement by much less than an order of magnitude is not of interest: imagers and low-dispersion spectrographs, used in standardized fashion, will supersede classical photometers for such purposes; this trend has started already and it will continue now that the detectors are good enough and as spectroscopic observers become aware of photometric basics.

Imagers using array detectors are in many ways *arrays of classical photometers* and to apply imagers properly we shall need most of our 'classical' experience, possibly augmented by such things as an accessible pupil for some of their filters and for shutters, by a telecentric beam for other filters and for detectors, and by compensation for field rotation during the exposure. Imagers are receiving attention from others and I shall not mention them often in this review. This is not to imply that they are unnecessary or 'not photometry'; imagers and spectrophotometers are complementary and several hybrids may also be necessary.

Plan of Attack

If it is not going to be simple to improve the 'classical' photometer, let us examine another possible approach, which is not simple either but has the virtue of being step-by-step rather than having to tackle many interacting effects at the same time. Let us try to specify a photometric installation, in which all the known causes of error are eliminated at source or as close to it as we can get, therefore as a first-order effect rather than as a second-order systematic error in the data. Let us attempt to reduce each cause of errors by a large fraction without introducing new errors and without interacting with the mechanisms that cause other errors. Isolate, decouple and eliminate at source will be the watchwords. At the end of that exercise, one should again use standards of all kinds, but hopefully to eliminate much smaller errors than in the classical case.

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My feeling is that, *for spectrophotometry as in imaging, we must learn to live with the array detectors,* both for the higher accuracy of colour information allowed by simultaneous measurements and for the multi-channel advantage which helps in observing standards sufficiently frequently to tackle the extinction problem systematically. We have learnt to live with photomultipliers, which at first sight are not particularly promising, either.

Image motion in the focal plane may serve as an example of how I intend to proceed. In the classical photometer, photometric errors may arise from light being spilt outside the aperture, from non-uniformity or angle-dependence of the filter passband, and from non-uniformity or angle-dependence of the detector characteristics. Rather than accepting image motion as a fact of life and spending great efforts and expense on reducing the (thoroughly mixed-up) secondary effects, let us see how well we can stabilise the position of the light source that serves as input to the photometer, using everything modern technology can offer and if necessary sacrificing a modest amount of light to gain much higher accuracy. The focal plane is the interface between 'telescope' and 'photometer' and the next section of this paper will concentrate on making the telescope deliver to the focal plane the kind of input a photometer works best with. Similarly, the section after that will concentrate on specifying a photometer that delivers an output signal suitable for recording accurately with an array detector such as a CCD.

Arguing backwards from the astronomical goals, we can make the following, logically more or less connected, series of statements:

— For astrophysical reasons, we require a system accuracy of 0.1% in N bands.
— To obtain this accuracy, measurements in these N bands must be simultaneous.
— If N is large, we are forced to use array detectors.
— For photometric stability, we need M pixels per band.
— Array detectors require that bands are defined *by optical means* and are spatially separated. The latter can best be implemented by a prism spectrometer, the former by a filter in the white beam (cf Walraven and Walraven 1960).
— Photometric stability demands a laboratory environment for the photometer.
— The photometer requires stable illumination of its entrance aperture.
— Such stable illumination requires compensation of atmospheric dispersion, it requires autoguiding and autofocus, and it requires an optical (fiber?)scrambler.
— Taming atmospheric extinction will require frequent short observations of standards all over the sky and a means of monitoring extinction *variations* near the object being observed.

These are the basic system requirements I have had in mind. The rest of this paper concerns the techniques for possible solutions. These solutions look suspiciously like very-low-resolution spectrometry. They are, in fact; the emphasis, however,

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will be on quantitative flux determination within a high-purity spectrum.

Telescopes

Since photometry is our business and photometers work best in a laboratory environment, we should attempt to satisfy that condition. We can either use a fibre to couple the telescope to a laboratory photometer, or design the telescope to give a stationary output. Fibres tend to have variable losses depending on bending or mechanical stress, so it may be best to avoid them for this application (but see Ramsey 1988 p. 285 and Heacox 1988 p. 300). A Coudé mirror train has atrocious photometric properties, partly due to the polarizing power of successive oblique reflections in a variable configuration. A feasible compromise is the Nasmyth configuration; this introduces only 1 oblique reflection and has the highly convenient platform, on which we can install our photometers horizontally and have the space to seal, thermostat and screen them. My idea of heaven is a 1-metre altitude-driven telescope on, say, a 10-metre azimuth platform. I would reserve one side for imagers, which must be mounted on large rotary bearings (almost of telescope-mounting precision); the other side would be reserved for the other main type of future photometer, the point-object spectrophotometers.

The oblique Nasmyth reflection will cause photometric errors with polarized objects. The solution is to depolarize the light before it strikes the Nasmyth flat. A continuously rotating superachromatic halfwave plate is the right kind of depolarizer for this application (Tinbergen 1974); unfortunately, such components are small, so that we must bring the Cassegrain beam to a premature focus above the Nasmyth flat (cf. the design of LEST: Andersen et al. 1984, p. 15) and limit the focal plane field to a few cm (4 arcmin per cm for a 1-metre telescope and an F/10 beam, which is about the fastest beam such a depolarizer can handle; with 1-arcsec seeing, a 10-arcmin field will be about what even a very large CCD can handle for good imaging photometry). After the Nasmyth flat, we shall need re-imaging optics to produce the final, real, image in an accessible position on the platform. New UV-transmitting optical glasses make it worth considering refractive optics for this. A second depolarizer will be needed near this focus.

Frequent observations of standards all over the sky demand a fast-slewing and fast-settling telescope; of order 5 deg/sec is certainly possible and seems adequate for slewing, the transition from full slew speed to dead stop must not take more than a few seconds and modern computer drives can achieve that. The requirement of high slewing speed may determine the size of the Nasmyth platform (as may dome cost, of course).

We shall require atmospheric-dispersion-compensation prisms to produce a white focal-plane image. The best position for these is probably just in front of the secondary mirror, using them in double pass; this position will minimize polarization

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effects and consequent photometric errors with polarized stars.

We shall need a moving secondary mirror, under full computer control (Milone and Robb 1983). I envisage at least 2 functions for it: rapid switching from object to comparison stars and sky, and as a component of the autoguider system. Detailed considerations of allowable photometric errors will determine the maximum sweep allowed in each application.

With the telescope which we have just 'constructed' we can deliver a white, unpolarized image in the second focal plane. Unfortunately, this image moves around as the atmosphere does its worst, and our photometer is not going to like that. We shall have to install an autoguiding system. Excellent CCD autoguider cameras exist and can be expected to handle 15th, or even down to 17th, magnitude on a 1-metre telescope; they can also double as a monitor of 'local' extinction variations. The error signals from such a sensor will be separated into 2 or 3 frequency ranges. The slowest and largest errors will be corrected by driving the entire telescope, faster and smaller error components will drive the secondary mirror, and finally a very small optical element at the photometer input can be made to correct the highest frequencies and smallest amplitudes. Avoiding oscillations in such a system may not be easy, but a similar problem has been tackled successfully for the Mt Wilson interferometer delay lines (Shao et al. 1988, p. 360). Most of the time the autoguider will use an offset star to guide on, but for initial impersonal centering, and for cases where no suitable offset guide star exists, we need an option to use the object itself. This option can use all the flux for a fraction of the time, or it can use a 'neutral' fraction of the flux or a restricted wavelength range all of the time. Extracts from guide star catalogues must be on-line for quick selection of the most suitable star in the field. Clearly, the autoguider system is not trivial.

Since best photometric practice with fibre scramblers may be to defocus the stellar image by a controlled amount (Heacox 1988, p. 299), the CCD autoguider system should be constructed to auto*focus* the telescope as well (e.g. just before an integration); this function could in fact just be a computer algorithm: a 'focus run' to achieve best focus on the autoguider CCD, while the photometer input is permanently defocused by a fixed amount with respect to the autoguider.

Photometers

The prime requirement for the photometer is a laboratory environment. On the Nasmyth platform out in the open, this implies a sealed thermostated enclosure. Flexure is not a problem on the platform, but screening from local or the Earth's magnetic field may be necessary. The detector could be outside the thermostated enclosure, but will have its own temperature control. The entire instrument should be flushed with clean dry air at all times.

None of this poses any special problems and the list of requirements reads like

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the actual operating conditions of a recent large Nasmyth spectrograph. And indeed our photometer is going to look like a spectrograph; the fact that we do photometry will show in our detailed use of the detector pixels. For photometric stability in the face of any remaining instrumental drifts, each elementary channel will in fact be recorded on M pixels; M could be of order 100. In general we can expect to use a finite evenly-illuminated input aperture, which we shall image on to the detector (perhaps slightly out of focus) through a filter that defines the passbands and a prism that spatially separates them. Each pixel records a finite wavelength range; conversely each wavelength is recorded on a finite number of pixels. Stray light will have to be kept under stringent control; in this kind of system, it is like a red leak in a filter photometer, viz. it is light recorded in the wrong place for its wavelength, hence represents an error.

Since the input aperture and output light patches are of finite size, we cannot use detector windowing for the superior band definition we need. The solution is to use a filter in the white beam to produce a so-called channel spectrum, in which bright and dark bands alternate. If the filter is of the birefringent variety, there will be 2, 4, or even 8 beams with complementary bands; the resultant spectra are recorded side-by-side on the detector, and the edges of the detector readout windows are put within the dark bands; in this way, band definition is almost exclusively a filter function, and obtaining stable passbands is mainly a question of good temperature control rather than some uncertain mix of residual instrument flexure and spectral smoothing by the finite input aperture. The filters are the key to well-defined and stable passbands and are discussed in more detail in a separate section.

For stable results, the photometer requires stable, preferably broadly peaked, illumination of the input aperture. The telescope/autoguider system delivers a central 'point' source. This is surrounded by a field of much lower brightness, which nevertheless is essential to photometric precision. The central source has a stable average position, but a size determined by the momentary seeing. To match this signal to the photometer, we require a scrambler of some sort, a device that rearranges this changing light distribution into something more constant with time. The level of photometric accuracy which we can attain routinely may depend critically on the scrambler and some hard thought and experiment will be needed in this area. The best performance would probably be given by an integrating sphere, but its efficiency is prohibitively low. Fiber-bundle scramblers exist, but they transform small residual image motions into large (random) ones as well as the other way around, so they may not be the answer. A single fiber scrambles azimuthally but not radially (Heacox 1988). However, if one moves the fiber input back and forth along a diameter, radial scrambling is achieved, *in the time-average sense*. The attractive aspect is that, by controlling the pattern of motion, one has control over the shape of the light patch that serves as input to the photometer; one could thus compensate on-line for slow variations of seeing as detected by the autoguider . Such a device could be integrated into the final actuator of the

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autoguider system, merely by adding a periodic signal to one of the error signals driving the fiber input. Another way of introducing radial scrambling is to use 2 lengths of single fiber, linked by pupil-to-image conversion optics (Ramsey 1992 and Barwig et al. 1988). This provides a very uniformly-illuminated patch, but with sharp edges which we may not want and may have to remove by defocusing.

Another possible feature of the photometer is an option to observe several sources simultaneously, along the lines of Walker 1988. A really fast telescope reduces the need for a multi-object input, but for some programmes it will not be adequate to use the entire telescope or the secondary mirror to chop between object and comparison star, or one may need the optical efficiency of true simultaneity. Walker's data indicate that 0.1% precision can be obtained in practice, and there are likely to be enough pixels on the detector for multiple beams. Whether a multi-object input option is feasible will depend on the details of the birefringent filter. *Use* of the option may possibly conflict with the moving-fibre type of scrambler.

Detectors

To me, it is an article of faith that we must press the more sophisticated versions of the array detectors into service for photometry; their parameters have improved enormously. A very encouraging differential accuracy of 0.004 mag over a 3-magnitude range is reported by Penny and Griffiths (1991; see also Penny et al. 1992), for an imager; for a properly designed spectrophotometer using many pixels for a single output quantity, it must be possible to do much better than that. Gilliland et al. (1991; see also Gilliland and Brown 1988) reach a *precision* of 0.002 mag in *time variations* of each of over 100 objects within a repeated CCD frame.

The most troublesome property of CCDs for accurate photometry is likely to be their high reflectivity; recent trends to coat them for anti-reflection (to improve blue sensitivity) will help, but some hard thinking will be needed on how to stop the reflected light getting back to the detector a second time, often in a position where it does not belong (in other words: red and blue leaks!!). One of the problems is that the reflection is specular, leading to structured ghosts in instruments equipped with CCDs (e.g. Gilliland et al. 1991, fig 1), thus to highly local photometric errors. If a birefringent filter is used, the light striking the detector is likely to be 100% polarized and one may eliminate excessive reflections by a polarization trick as is used for computer terminal screens. If the light is not strongly polarized, this approach will lead to loss of half the light; in that case, a diffusing surface extremely close to the detector might be worth considering, to scatter the reflected light as widely as possible and thus to reduce the part that gets specularly reflected. Since reflection coefficients of spectrometer optics will be only a few percent per surface, reduction by a factor of 10 may be enough to make any structured ghost harmless, so that scattering over an angle of 3 times the angular extent of spectrometer optics

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may be very effective. Very interesting 'holographic diffusers' have been announced, which reportedly can be tuned during manufacture both to a specified wavelength range and to a specified angular width of the scatter diagram.

One thing we must **NOT** do is to focus the spectrum sharply on the CCD and match the optical resolution to the size of one pixel. In such a case, we would produce both undersampling by a factor of at least 2 *and* the worst possible band shape (Young 1992b). Instead, we should spread the light for one channel (predefined in wavelength content by the filter) into a fuzzy patch of M pixels by judicious means such as size and shape of the photometer input light distribution, or defocusing the spectrometer part of the photometer. A value of M of 100 might be sufficient: reduction of errors by a factor of 10 by averaging, from the 0.004 mag quoted above for an imager (which did use some degree of pixel averaging itself).

In my other paper I shall argue that we may need some 1500 photometric channels, each of about 10 Angstrom width, to cover the optical range. This would mean 150000 pixels for recording the channels themselves and large chips will be needed to accommodate some dark space in which to put the *spatial* band limits. Such large chips may take of the order of a minute to read out, so arrangements must be made to read out only those pixels that contain photometric information. The maximum signal in 100 pixels will be of order 25 million electrons; with several tens of 10-Angstrom channels finally going into one intermediate-bandwidth photometric quantity, it seems we can accommodate a dynamic range of order 1000 with photon noise of 0.1% or better throughout and with a single exposure. Given that narrow bands will allow extensive use of neutral-density filters and that exposure times can vary from 1000 seconds down to where scintillation noise becomes prohibitive, such a dynamic range seems ample.

A point of some concern with CCDs is of course the stability of the gain and of the departures from linearity. We have lived with deadtime corrections for photomultipliers and can live with similar corrections for CCDs, as long as they are stable. In photometers such as I have sketched, a particular pixel will always be exposed to a narrow spectral range only, and very much the same mixture for all sources (ignoring stray light for the moment); this will help to obtain the desired *stability* of any imperfections that may be present. Actual data are hard to find; since for most purposes 1% is considered highly linear, measurement noise tends to be at that level. However, ignoring the noise in the published data, linearity better than 1% and stability better than 0.1% seem to be realistic. Linearity can be tested on-line by timed exposures to a well-stabilized lamp in the calibration system (see separate section) and by observing sources of different flux levels (can be lamps, too) both with and without a neutral density filter. Such tests will have to be done in extenso and reduced both in an absolute and a relative way. Gain stability may be more difficult to test. Comparison with calibrated diodes illuminated by the same stabilized lamp should allow sufficiently accurate interpolation between reliable standard-star sequences. The problem is likely to be much less

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serious than it ever was with photomultipliers and their nth-power dependence on supply voltage; we now have a million detectors all tied to the same supply and we are mainly interested in relative gains, since absolute detector gain variations mimic things we have little control over, such as thin cirrus, aging of mirrors and minor dewing of optical surfaces (telescope mirrors, for instance; KenKnight 1984).

We should realise that, by using array detectors to record our data in much more detail than we shall finally need, we have extra design freedom to improve our 'instrument'. For instance, by reducing the weight of data from outlying pixels, we can trim the wings of the passbands to achieve the log-concave-downward condition expressed by Young (1992a). At another level of resolution, we have the freedom to shape our scientific passbands as we like (my other paper). Yet another example: the recorded data are a first-order approximation to the spectrum of the source; if we have calibrated, for each wavelength, the level of scattered light into other channels than intended, we can correct for such scattered light afterwards, as long as the scattering function is smooth and the level is sufficiently low for the iterative correction procedure to converge. These examples emphasize that it is premature to predict the limit of CCD performance in such untried applications, but there does seem to be plenty of room for optimising to something practicable. Needless to say, the technology of CCD applications will need years of accumulated experience before it can be called mature; photomultipliers took decades. But at least the basic building blocks are available and we know more or less what we wish to find out about their detailed performance; the engineers can take over.

At my request, an instrument designer experienced in CCD optimisation has commented: *"A) for a thinned CCD, 450 to 850 nm is the best range and pixel-to-pixel response variation will be of order 1%; possibly more in the UV (surface cleanlinesss etc). B) temperature stability of gain and Q.E. can be made 0.1%. C) linearity is routinely better than 1%, while 0.1% is probably attainable with care. D) an LED internal to the cryostat, used with multiple standard flashes is excellent for checks of stability and linearity to better than 0.1%"* (Jorden 1992).

Filters

A simple prism spectrometer is sufficient to disperse a white beam into a spectrum fit for a CCD. In order to avoid problems of residual wavelength shifts in this spectrometer, it is very desirable to incorporate into the white beam a multi-band filter producing alternating bright and dark regions in the spectrum of that 'white' beam. The spectrum on the detector will then consist of isolated bright patches; these patches may move around slightly as conditions change, but their wavelength content remains constant, as defined by the filter passbands. To the extent that the

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detector spectral response is constant from one pixel to another, no photometric errors will result, as long as the boundaries of the readout window for a particular patch remain within the dark region. A Fabry-Perot etalon is an example of such a multi-band filter, but for several reasons it is not suitable. Filters based on the spectral dispersion of birefringence are much more promising. Applications known to astronomers are by Lyot, Šolc and Walraven; each of these designs is capable of further development. What such filters have in common is the possibility to conserve all the light by using beamsplitting polarizers: the light that is rejected by one beam is shifted into the other beam, of opposite polarization. One can pass both those beams through the spectrometer and record them both with one array detector (Wizinowich 1989); by using the correct polarization and passing the prisms at the Brewster angle, one can construct extremely efficient systems (Walraven and Walraven 1960). The passbands are all of the same shape (on a linearized birefringence scale), all of them being determined in the same way by material constants, thickness of crystal slices and position angle of the components. Since one hardware filter determines all the passbands, care in stabilizing the operating conditions of this filter is well-spent indeed and calibration is a matter of determining a small number of parameters. By changing the position angle of components in the filter, one can move all the passbands in synchronism; this feature allows creation of passbands separated by half their FWHM, the separation that is required for fully sampling the spectrum at the resolution determined by the bandwidth.

Two developments of the basic filters are of great interest. Ai Guoxiang and Hu Yuefeng (1985, p. 10, 11) describe adaptations of the Lyot filter that can produce, in 4 or 8 beams, multiple passbands separated by wide dark regions. The efficiency is not far from 100% if one uses both beams from the entrance polarizer. In a series of papers, Ammann and associates (Yarborough and Ammann 1968 is the best reference to start with) present a synthesis technique (with experimental verification!) for arbitrarily-shaped passbands by filters similar to Šolc's. Again, the efficiency is close to 100%. For bandwidths of order 10 Angstrom, these two types of filter are more suitable than Walraven's; the choice between them must be resolved by detailed engineering considerations of passband shape, sidelobe level, maximum size of input aperture, adaptability to multiple output beams, etc. It seems likely that Young's (1992a) conditions for good transformability can be met well enough by either type (see also section on Detectors: 'trim the wings' etc).

Calibrations

Calibration is going to be much more important than with classical photometers and the main reason is that there is much more opportunity for it. For classical photometers with relatively wide passbands, calibration with one source will not be of much use for a source with a noticeably different spectrum. If, however,

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our instrumental passbands are narrow compared to spectral variations of some of our sources, we can usefully observe those sources to monitor relative channel sensitivities with time; for short timescales we can use stable lamps, for longer timescales we may have to refer to groups of selected standard stars. The aim of calibration is to relate the changing channel sensitivities and central wavelengths of our actual instrument to those of a virtual instrument with absolutely constant properties; this virtual instrument may be a similar instrument somewhere else or the same instrument at some other time. If we can do that consistently, we shall no longer be plagued by transformations from instrumental to standard systems, at least not at the stage of using the data for a scientific purpose. The traditional difficulties of absolute calibration remain, but fortunately most of our work can be done without such absolute calibration.

Several kinds of calibration will be necessary. Some of these can be carried out once in a while, others could be quick online checks or necessary monitoring. An extremely important matter is that beams from lamps should resemble beams from the telescope. They should therefore have the same focal ratio, and proceed from a pupil at the same distance and with the same central obstruction. The most likely way to achieve this is to inject the light by a flat mirror introduced just downstream of the secondary mirror and mount the pupil and beam-defining optics on the side of the telescope. This optical system should be fed by fiber (bundle) from a sealed and screened 'lamp laboratory' on the Nasmyth platform. To ensure that the lamps and fibers have constant, or at least known, properties, there will need to be calibrated diodes inside the photometer; these diodes will most probably be the best final reference components (Borucki et al. 1988). With lamps and diodes protected from environmental effects and the transmission path calibrated out, we have probably gone as far as we can with terrestrial sources. To include the telescope mirrors and for the very highest accuracy over long time periods, nature probably still provides the best reference; if a select group of stars (cf. Lockwood and Skiff 1988, p. 201) all give the same results, one must conclude that those stars are stable or be very sure of an alternative explanation.

The most basic calibration will be to scan through the passbands with a monochromator source of considerably higher resolution, as a check that they are indeed of the shape intended. This very time-consuming procedure will need to be speeded up by multiple output slits in the monochromator. We also need to know scattered-light levels. These can be determined by tuning the monochromator to the central wavelength of each channel in turn and reading out *all* channels every time. For this purpose, we shall have to be very sure that the monochromator delivers just one wavelength; order-sorting and other blocking filters will be needed, even with a double monochromator.

A continuum source, stabilized by reference diodes as above, will be needed for routine (several times per night) calibration of channel sensitivities. This takes very little observing time, since the lamp is a bright source and there is no scintillation.

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For routine checking of wavelength stability, a temperature-stabilized solid Fabry-Perot in the beam of this continuum source may be the best component. The multiple transmission bands of this filter will lead to a characteristic pattern of outputs of the photometer; any wavelength drift of the photometer will lead to an equally characteristic change of that pattern. Fewer than 10 parameters determine F-P, transmission optics, birefringent filters and detector, whereas measurements will be available in hundreds of channels. By methods similar to determining a pointing model of a telescope from measured apparent positions of standard stars, it should be possible to disentangle drifts in the several component systems. This type of measurement will also take very little time from the observational programme.

Any neutral-density filters used in the photometer will have to be calibrated regularly. With narrow passbands, this is an accurate and not very time-consuming procedure. It can be combined with the detector linearity check and could be carried out on the continuum lamp in the daytime, as a check on occasional determinations on standard stars.

Computers, Automation and Organisation

The installation I have sketched contains many automatic processes that are essential to its functioning. These will have to be computer-controlled. The trend is to use dedicated computers for single well-identified functions. One expects to have at least the following computers in some sort of hierarchy:

— System	has overall control, serves local observer and engineer
— Telescope drive	includes on-line extracts from star catalogues
— Autoguider	reads autoguider CCD, computes errors, checks focus
— Photometer	controls temperature, ND filter wheel, etc
— Detector	controls shutter, reads out CCD windows
— Communications	serves remote observer and remote archive

There are two separate reasons to organize actions through computers. One is ease of operation, or impossibility of doing the same thing manually. Examples are autoguiding, autofocus, auto-guidestar-selection and CCD readout. The other reason is that some activities are too important to leave to individual observers. Examples of this type: scheduling of standard star observations sufficiently frequently for good extinction handling, and calibration by suitable lamp exposures. Except for very specialized programmes, it is to be expected that the observer will be remote, entering his wishes into a scheduler programme running on the system computer and receiving messages that tell him when his observations have arrived at the archive. To achieve good photometry, standardized operation is essential and cannot be left to observers' social conscience: one's own programme is always more important than someone else's calibrations. For the benefit of all, the scheduler (or

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whoever controls its parameters) must firmly resist any attempt by observers to get more than their fair share of programme star observations.

Conclusion

I have outlined what kind of instrument development seems necessary to me, if we are to profit from our knowledge of the causes of photometric errors. The approach has been that of modularity, allowing gradual buildup and enhancement of the installation, and effective detection and diagnosis when things go wrong. Once a satisfactory instrumental system has been achieved, standardization of the observational process and routine calibration will be basic to the approach. As I argue in my other paper, instrumental bandwidths could be as narrow as 10 Angstrom. The standardized observations will be stored in a data-base. The data-base contains the raw measurements, with all auxiliary data that could be relevant; it also contains a version of the photometric data corrected for *known* instrumental drifts and scattered light, and transformed to outside-atmosphere by standard extinction handling. The individual observer will take observations from this standardized observational machine and put them to his own creative use by synthesizing his own scientific passbands and creating his own photometric system from scratch, using the standard star observations in the data-base which are immediate public property. It is by such methods that I feel we can *routinely* achieve millimagnitude photometry and perhaps beyond; the classical method of 'build it cheap and see what it does' will only achieve such accuracy now and then, by luck or extreme hard work.

The amount of modern technology implied may seem frightening, particularly to those who have used similarly complex installations at large telescopes and have lived through numerous partial breakdowns during observations. Experience shows that such installations become spectacularly more reliable, the more they are left undisturbed and used only in standard ways. Designing for maximum reliability rather than for maximum flexibility will also help. However, an on-site 'photometric assistant' may be a necessary condition for success.

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Discussion

S. C. Russell: *In your ideal photometric telescope, where you are intending to focus within the telescope anyway, could you not do away with the mirror and depolarizer and collect the light near the focus with the fibre image scrambler?*

Tinbergen: Yes, that could work for the single object photometers. I envisage that the telescope might be needed for several different jobs - uncrowded fields, medium crowded fields and crowded fields for instance; imagers and single-object spectro-photometers are the two extremes. For imagers the Nasmyth flat is needed.

S.C. Russell: *So you envisage telescopes that can do many jobs rather than one job well?*

Tinbergen: Yes, if we are to ask for dedicated and expensive photometric telescopes to be built, they would have to be able to perform many jobs. It is hardly likely funding would be approved for five telescopes to do five particular jobs. Besides, we don't *know* yet quite how well fibres can perform; with a Nasmyth flat, conventional optics remain an option.

D.L. Crawford: *We definitely want to go in this direction, most likely as fast as we can, and where we can. We will also be using 'classic' photometers (all we can afford, or what we need). I have been promoting a 'law' or 'goal' where the telescope costs less than the instrumentation which cost less than the software for analysis.*

Tinbergen: In easy steps, most of this is possible, I'd say. The telescope and drive mechanics would be exceptions, but are receiving attention (see Genet's review). With reference to your second point: compared with solar physics; we are growing up, too!

D.L. Crawford: *Please also add the Site (atmosphere) to your list, at the top end. Quality of the site (clear, photometric, stable, dark skies) is a quite important aspect to all this, of course, including site preservation.*

Tinbergen: I know. La Silla (photometric), versus La Palma (spectroscopic), criteria were paramount in their selection.

A. T. Young: *A problem you did not mention with fibres is that of coupling light, in and out. With a 100 μ fibre, a defect or dust speck just a few microns across is photometically important, at the millimagnitude level. I think this is one reason why people have had difficulty in using fibres photometrically, in addition to the bending-loss problem you mentioned.*

Tinbergen: Is a 1mm fibre more difficult to keep clean than a 1 mm diaphragm? I am hoping that multi-fibre components with low input loss can be produced. Mantel (MEKASPEC project) mentions 85% transmission for uncoated end faces - about 7% short of perfection. The trick is precisely that of removing the cladding at the input end. However, I do not wish to pretend that engineering development is unnecessary.

R.M. Genet: *Many of the telescope features, 1-metre alt-azimuth autoguide, fast slewing, autocentreing, fast secondary motion, etc., are being applied at Autoscope. We are currently building a 1-metre alt-azimuth telescope for the University of New Mexico to be placed at*

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the Apache Point Observatory.

Tinbergen: I am very pleased to know I have companions along this route and engineer too. I can't believe my luck.

E. F. Milone: *On an aspect you haven't fully covered, but to which you alluded, — time re olution; there is the binning problem, which presumably requires additional time to correc The read-out time is another problem. On another point - the limited size of CCD chi may well limit the precision attainable if there is no suitably bright (and colour-matche comparison star in the frame (see Schiller and Milone, 1990).*

Tinbergen: I was referring to software re-binning on conversion to wavelength scale. Thi is a transformation in the photometric sense, with rectangular bands under sampling th spectrum by a factor of two; the worst of all, according to Young (these proceedings). does not concern my main argument, but was an aside on an illustration not reproduce here. Your second point concerns imagers, which are not the optimum way of using CCD for accurate photometry. In the narrow-band spectrophotometry I propose, in my othe talk, colour-matching is not necessary. A fast telescope is a more important point (cf. co ment after Genet's review).

A. J. Penny: *In addition to your dedicated 1-metre telescope, it would also be cost effecti to have an additional 0.5-metre telescope dedicated to monitoring the extinction over t sky during the night.*

Tinbergen: Yes, an extinction monitor will always be useful. Considering Young's co ment, and Genet's figures for the slewing speed and settling time of a 1-metre telescop primary extinction data could best be derived from observations by the prime instrumen Monitoring extinction variations of stars very close to the object might be done in say broad bands. Perhaps the autoguider CCD could perform this task.

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