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Richard R. Radick

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IN PURSUIT OF HIGHER PHOTOMETRIC PRECISION

Richard R. Radick

Air Force Geophysics Lab., Solar Research Branch

ABSTRACT: Classical differential photoelectric photometry, cluster photometry, and CCD photometry are three techniques that have been used in the pursuit of higher photometric precision. Each has its own particular strengths and limitations, each manages its error budget somewhat differently, and each is capable of achieving a photometric precision of a few tenths of a percent.

I. INTRODUCTION

Contemporary stellar photometry achieves a precision of about 0.01 mag (1%), routinely and without great difficulty. However, several areas of current astronomical interest, such as the study of stellar analogues of solar variability (the solar–stellar connection) or the study of stellar oscillations (astroseismology), require measurements with precision considerably better than one percent. Indeed, there are several photometric techniques capable of achieving measurement precision in the range 0.001–0.005 mag (0.1–0.5%). One of these, differential

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photoelectric photometry, is well established and widely practiced, and provides a useful benchmark for the evaluation of other newer or lesser known techniques. In addition to differential photometry, I will consider two of these other techniques here: cluster photometry and CCD photometry.

In the high precision regime, photometric measurements encounter a host of effects of instrumental origin, each capable of contributing to the overall noise budget at the level of 0.001 mag (0.1%) or more. Since many such instrument–specific effects are discussed elsewhere, (e.g., Young 1974; Djorgovski 1984), I will not attempt to review this vast subject here. Rather, I will simply assert that, with conservative observing procedures, and with proper equipment, calibration, and reduction techniques, it appears that total instrumental noise can be reduced to a tenth of a percent or so, a tolerable level that does not strongly dominate the precision of photometric measurements. Under such circumstances, two principal noise sources remain: (1) atmospheric noise and (2) photon noise.

Atmospheric noise arises primarily from scintillation and extinction. Generally, scintillation can be reduced to an arbitrarily low level (0.1%, say) simply by using larger telescopes or longer integration times (Young 1974). Extinction effects are generally more unpredictable, and certainly more difficult to compensate. For example, there is evidence that transparency fluctuations on time scales of minutes can adversely affect photometric precision at the level of several tenths of a percent (Radick et al. 1982; Kurtz 1984). Although some techniques offer better control than others, it is nevertheless impractical to try to compensate fully for such fluctuations in the context of single–star observations.

Unlike atmospheric noise, photon noise is strongly magnitude–dependent and quickly dominates the overall precision once the threshold determined by the constant noise sources is breached (see, e.g., Radick et al. 1982, Figure 1, or Gilliland and Brown 1988, Figure 5). Like scintillation noise, photon noise can easily be reduced by using larger telescopes or longer integration times. However, because of dynamic–range limitations, these strategies may not be fully available when area detectors such as CCDs are used: the effort to reduce photon noise for the fainter stars in a field can lead to saturation problems for the brighter stars.

Clearly, successful management of instrumental and atmospheric noise is necessary to achieve and maintain high photometric precision. Unfortunately, such measures alone may not be sufficient: a serious lack of suitably stable photometric references for high precision relative photometry is only now beginning to be recognized.

II. STELLAR VARIABILITY AS A SOURCE OF NOISE IN PHOTOMETRIC MEASUREMENTS

Stellar photometrists have long recognized that all stars are likely to be variable "at some level." We are now beginning to discover just what that level is: in certain spectral regions and among certain groups of stars, it can be distressingly high. For example, among relatively young stars such as those of the Hyades or Coma clusters, it appears that virtually all stars later than spectral type F8 (or so) are variable at a level of 0.01–0.03 mag (1–3%), about a factor of ten greater than the attainable measurement precision (Radick, Lockwood, and Thompson 1986; Radick et al. 1987). In fact, even among field stars, late F– to mid K–type are as likely as not to be variable at an amplitude of 1% or more (Lockwood and Skiff 1988). Variability on night–to–night, seasonal, and year–to–year timescales is observed. Giants are suspect, young stars are suspect, early–type stars are suspect, stars in the instability strip are suspect, M–type stars are suspect... indeed, it may be that late B– to early A–type dwarfs, mid F–type dwarfs, and some old late F– to K–type dwarfs are the only individual stars that are truly suitable for use as references for high–precision photometric measurements.

III. DIFFERENTIAL PHOTOELECTRIC PHOTOMETRY

Single–star differential photoelectric photometry is the "classic" high–precision, high–accuracy photometric technique. It is relatively simple in both concept and execution, it uses established, inexpensive technology, and it is well suited for automatic, digital data acquisition. It offers superb flexibility in tailoring integration times for scintillation and photon–noise control, and rarely encounters dynamic range problems. Data reduction is relatively uncomplicated and does not require large computers.

On the debit side, the accuracy of single–star differential photometry is severely exposed to degradation by extinction fluctuations and standard–star variability. In principle, a symmetric observing scheme (e.g., 1–2–3–3–2–1 for three stars designated 1, 2 and 3) will tolerate linear drifts in extinction, at some expense in duty cycle. However, it must also be appreciated that such a scheme is particularly vulnerable to extinction fluctuations with a characteristic time scale comparable to that of the observing sequence itself. Differential photometry is also inherently inefficient, since substantial time is spent observing comparison stars. This fundamental inefficiency is only aggravated by the likely variability of the comparison stars, since the direct way to guard against such variability is simply to observe more comparison stars, which reduces the efficiency even further.

Currently, the best differential stellar photometry is characterized by an rms dispersion of 0.002–0.003 mag (0.2–0.3%), on both night-to-night and year-to-year time scales (e.g., Lockwood and Skiff 1988). This is somewhat larger than what consideration of known noise sources leads one to expect, and suggests that our understanding of the error budget is not yet complete and accurate, despite recent efforts (e.g., Lockwood 1984; Lockwood and Skiff 1988).

IV. CLUSTER PHOTOMETRY

It is possible to overcome some of the limitations of classical differential photometry by observing relatively many stars (perhaps 50) in a localized field in rapid sequence, and using the ensemble average as the photometric reference. This scheme was implemented at Cloudcroft observatory during 1980–1982 (Radick et al. 1982; Radick et al. 1983), where it was nicknamed "cluster photometry." It achieved a night-to-night rms dispersion of about 0.004 mag (0.4%), i.e., not quite as good as the best contemporary differential photometry. We now realize that the Cloudcroft implementation of cluster photometry was more sensitive than differential photometry to transparency changes: essentially, it required constant extinction during the hour or so it took to observe a field. A symmetric observing sequence would perhaps help alleviate this defect. On the positive side, cluster photometry is much more tolerant of variability of individual stars: the ensemble average will fail only if several stars within the ensemble vary in phase, which must be extremely unlikely. Furthermore, since there need be few, if any, comparison stars as such, cluster photometry enjoys a considerable advantage in efficiency over classical differential photometry.

V. CCD PHOTOMETRY

Recent experiments aimed at achieving high precision using CCDs as photometric detectors have been encouragingly successful (e.g., Gilliland and Brown 1988). CCD photometry offers excellent extinction control in principle, since both program and comparison stars can be observed strictly simultaneously. Indeed, observation through one magnitude of variable cirrus, conditions that would be deadly to classical differential photometry or cluster photometry, degrades the precision of CCD photometry only by a factor of two or so. The technique easily and naturally preserves the principal strengths of cluster photometry, namely, high overall efficiency and the ability to suppress stellar noise through ensemble averaging.

CCDs are known to suffer from a wide range of defects that can limit their photometric precision (e.g., Djorgovski 1984). Gilliland and Brown (1988) developed a very careful and elaborate procedure, which they call HAOPHOT, that corrects CCD data for overscan, bias, dark level, deferred charge, and gain. They were able to achieve a differential photometric precision of 0.0014 mag (0.14%), relative to an ensemble average. Since their observations in effect spanned only a single night, the stability of the technique on longer time scales remains uncertain. The dispersion of the measurements can be modeled successfully by an error budget that includes only scintillation and photon noise. Therefore, it seems reasonable to conclude that the procedures of HAOPHOT reduce the total instrumental noise to about 0.1%.

High-precision CCD photometry does have some limitations. Data reduction is exacting, and requires access to considerable computing and image-processing power (for example, Gilliland and Brown used a CRAY-XMP). Although it is desirable to work in the regime where the total photometric error is not strongly influenced by photon noise, i.e., in the "scintillation regime" (see Radick et al. 1982, Figure 1, or Gilliland and Brown 1988, Figure 5), the scintillation regime for CCD photometry is narrower than for photoelectric photometry, spanning perhaps only two magnitudes or so. This is because CCD photometry with ensemble averaging offers only limited flexibility for tailoring integration times, and because CCDs have restricted dynamic range. Basically, one must avoid overexposing the brighter stars in the field while still adequately exposing the fainter ones. These restrictions are best met by seeking fields containing sizable numbers of comparably bright stars. Since CCD fields are also relatively small (typically a few arcminutes), this means in practice that the relatively dense agglomerations of stars provided by distant clusters offer the most attractive target for CCD photometry with ensemble averaging. Of course, such distant stars are also faint, making them relatively difficult targets for supporting observations such as spectroscopy.

VI. SUMMARY

A number of photometric techniques currently in use appear to be capable of achieving a level of precision and accuracy that is largely determined by fundamental sources of noise such as scintillation, extinction fluctuations, and photon noise, rather than instrumental sources. This level is about 0.001-0.003 mag (0.1-0.3%), and depends somewhat on technique. Techniques which use ensembles of stars as the photometric reference are less prone to imprecision arising from intrinsic low-level stellar variability, which is now known to be widespread.

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