CCD TIME-SERIES PHOTOMETRY OF ASTRONOMICAL SOURCES

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ABSTRACT: CCDs are essentially the only instrument available today for photometry at most observatories; they are also becoming more readily available to amateurs as well. Thus, obtaining good photometric data with these two-dimensional devices is something we all need to understand. The history of and recent developments in CCD time-series photometry will be reviewed with some comments on future directions.

1. BACKGROUND

The first reference to performing two-D photometry that I believe exists is in a paper by Nather (1972) in which he states, “Multi-channel detectors can be of real benefit in the photometry of faint objects...”, and, “the accuracy of the photometric measurement is limited by the amount of “sky” present in the [measurement] diaphragm,...the selection of a “virtual” diaphragm can materially improve the accuracy, if chosen to minimize the statistical error...” Well, that about says it all right there. It took a number of years for CCD technology and the rest of us to catch up with these principles, but we finally made it.

Howell and Jacoby (1986) presented the first detailed treatment of using CCDs for time-series photometry. They show in their examples that marginally cloudy nights, instrumental effects, and color terms are essentially neutralized and mostly avoided if one uses differential photometric techniques. Of course, on a CCD all objects have the same exposure time, so the S/N values varies with object brightness. Therefore, Howell et al. (1988) presented the necessary quantitative basis for working with unequal S/N value and the correct error analysis methods for such two-D differential measures.

There are many details of CCD photometric observations that are different from PMTs. These are not always intuitive but must be understood in order to gather meaningful, well understood data. Howell (1992) discusses the relative merits of two-D detectors over PMTs and Kreidl (1993) compares CCDs to PMTs for photometric observations of astronomical sources.

The history of and recent developments in CCD time-series photometry are reviewed with some comments on future directions. Many astronomical projects have built on these foundations and the current literature is full of uses for CCD time-series photometry. These range from variability of extragalactic objects (e.g., Miller et al. 1992) to rotation periods for comets in our solar system. Gilliland and Brown (1988, 1992) have made extensive use of differential techniques in their work with ensemble photometry in clusters where they have reached RMS precisions of millimags! The field of differential CCD photometry is certainly brightening!

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2. PHOTOMETRIC TECHNIQUES

For brighter, high signal-to-noise sources, the data collection and reduction processes are robust and use of even a marginally correct "CCD Eq." and almost any good software package for reduction can provide good photometric results and error assessment. For fainter, lower signal-to-noise sources or undersampled data, however, there are many factors that one must take into account to get correct answers *and* correct error estimates. Methods to deal with these types of sources both in terms of a proper "CCD Eq." for use before (to predict the outcome) and after (to provide proper error estimates) is necessary. One also has to be very careful in terms of the software used for data extraction and reduction. Sources with signal-to-noise values of 20 or lower can provide very accurate data sets through the use of specific techniques such as optimum data extraction techniques and growth curve (aperture) corrections.

Howell (1989) discusses in detail the method of optimum data extraction. Merline and Howell (1995) present a number of examples and reinforce the findings that the optimum radius for point-source extraction is near one FWHM (standard wisdom generally uses a radius of ~three FWHM) and that the optimum radius is in general, different for each point source. Fig. 1 shows the results for stars of various magnitudes: V = 18, 17, 16, 15 and 14 from top to bottom. The stars have a FWHM of 2.4 pixels and we see that the optimum extraction radius (i.e., the least magnitude error) occurs near one FWHM, but not at it exactly. Fig. 2 shows some examples of the resultant S/N ratio for optimum vs. standard aperture extraction for three cases. The three cases are listed on the figure as sequences of numbers corresponding to the following: telescope aperture in meters, f-ratio, detector read noise, detector dark current in electrons/sec, detector gain in electrons/DN, sky noise in electrons/sec, and pixel scale in arc sec/pixel. One can easily see that an increase of > two in S/N can be achieved through the use of the optimum extraction technique.

DaCosta et al. (1982) first discussed the use of growth curves for the reconstruction of stellar profiles in the case of low S/N objects. Howell (1989) talks about growth curve usage for faint and crowded stars and Stetson (1990) discusses an implementation of using growth curves to get better results from faint and crowded stars in clusters. The basic idea is one of obtaining growth curves for brighter point sources in a given CCD frame (essentially another version of 2-D profile fitting but with azimuthal averaging), and then using these curves to guide fits for the fainter, not well detected point sources. See Stetson (1990) for further details.

The CCD equation itself (listed in many places, including typical observatory users manuals) has also been re-examined to look for further improvements that might be made in observational predictions and in error analysis (e.g., Newberry 1991). Merline and Howell (1995) present a detailed look at this equation and the errors involved and they discuss some generally overlooked terms. These include terms for the error contribution due to the detector gain and the effect of the number of background pixels used.

An area that is getting more attention these days, especially as some older telescopes are being outfitted with CCDs, is that of undersampled data. Generally this is only thought about in terms of data from satellites and spacecraft (e.g., HST/WFPC, Holtzman 1990). Buonanno and Iannicola (1989) provided an initial look into the case of undersampling for ground-based data as well. Generally this problem is encountered for large field-of-view telescopes, such as

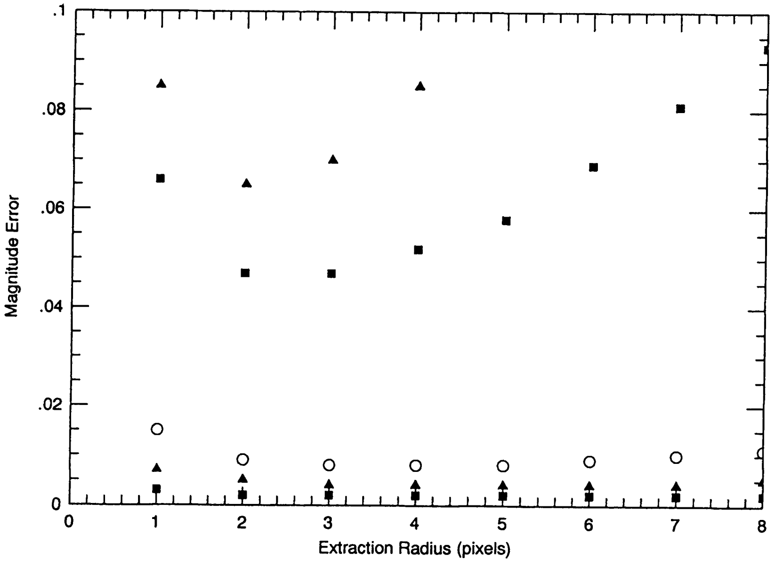

Fig. 1. Magnitude error as a function of Extraction Radius.

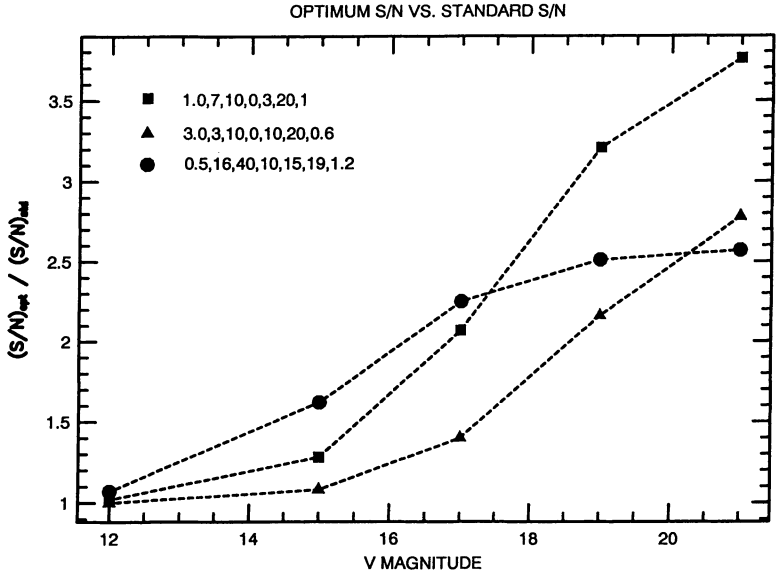

Fig. 2. Optimum S/N vs Standard S/N as a function of magnitude.

CCDs used in Schmidt telescopes. The term undersampled can be defined by the following parameter:

$$r = \frac{FWHM}{p}$$

where *FWHM* is the full-width at half-maximum of the point spread function and p is the pixel size, both in the same units. For the sampling parameter $r \leq 1.5$, errors are highly likely to be expected in the photometry from use of standard analysis techniques. Most popular software packages for CCD reduction are NOT prepared to deal well with undersampled data. Astrometric and photometric errors tend to track each other and, for CCD data with poor sampling, Gaussian fits, for example, are no longer valid, partial pixel handling by the software becomes critical, X,Y moment determinations for centering are suspect, and detection and differentiation of low S/N point sources is difficult. Further work in the area of undersampled data is needed.

3. CONCLUSIONS

The future of CCD photometric observations is only limited by our imagination and how well we can make use of software to perform real-time functions at the telescope and reduction and analysis of the resultant images. The next few years will be a golden time in working with CCDs. For example, Fig. 3 shows a simulation from Howell (1995) of the possibility of relatively easy detection of transits of extra-solar planets from a ground-based telescope. This figure shows a typical M2 star of 15^{th} magnitude being transited by three solar system sized giant planets. To give you an idea of what the x-axis scale might be, a Jupiter-Sun transit viewed from outside our solar system would take about 30 hrs. Large CCD mosaics are already collecting more data in a few nights of observing than many years of single CCD observations combined, with the data collection, reduction, and analysis is becoming routinely automated. Also, the promise of CCDs in space or on the moon allows for a new horizon of photometric possibilities (Granados and Borucki 1994).

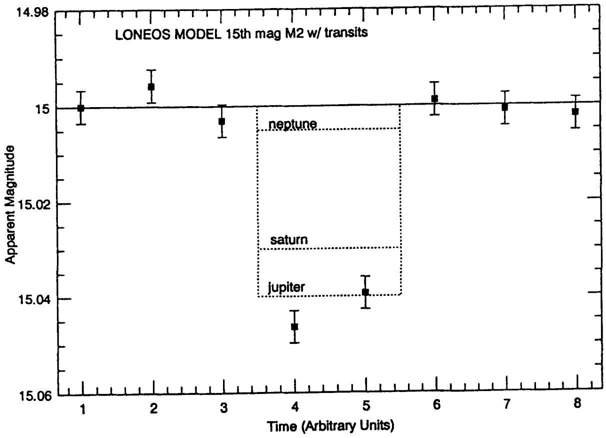

Fig. 3. Apparent Magnitude vs time.

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DISCUSSION

JEDICKE: Is the MACHO data suitable for detections of Jupiter-like objects around stars in the Magellanic Clouds?

HOWELL: It may be and I am currently working with that group on such possibilities.

JEDICKE: How will you account for the undersampling of the LONEOS data in photometry intended for discovery of Jupiter-like transits of other stars?

HOWELL: The pixel size will be 1.8 arc sec and the seeing is typically 1.6 arc sec, so the data will be marginally undersampled. Techniques to deal with these types of data have been developed for other projects and include optimum aperture extraction.

TANCREDI: What is the typical transit duration of a Jupiter-sized planet?

HOWELL: For the Sun-Jupiter system viewed from a star, the transit time across the Sun's equator would be 30 hours.

CRAWFORD: In the result of finding one or two Jupiters per year, what one specific assumption of how many telescope hours, field site, etc?

HOWELL: That number is based on using the assumptions (best current guesses) of a Schmidt with a mosaic of four 2048 x 2048 CCDs, covering 1000 sq. degrees/night.