Light Bucket Astronomy

Russell M. Genet
California Polytechnic State University
4995 Santa Margarita Lake Road, Santa Margarita, CA 93453USA
russmgenet@aol.com

Arne A. Henden
American Association of Variable Star Observers
49 Bay State Rd., Cambridge, MA 02138, USA
arne@aavso.org

Bruce D. Holenstein
Gravic, Inc.
301 Lindenwood Dr. STE 100, Malvern, PA 19355 USA
bholenstein@gravic.com

Abstract

Light bucket astronomy uses low optical quality, low-cost telescopes advantageously in those situations where the noise contributed by the sky background is a small or nearly negligible source of noise. This situation can occur with bright objects, short integration times, narrow bandwidths, or high detector noise. Science programs well suited to light bucket astronomy include lunar and asteroid occultations, fast cadence/high precision photometry, near infrared diaphragm-limiting photometry, low to medium-resolution spectroscopy, and polarimetry. With an array of a half-dozen light bucket telescopes equipped with very high speed photometers, images of the surfaces of nearby stars could be obtained via intensity interferometry, a quantum-mechanical effect that occurs at sub-nanosecond timescales.

1. Introduction

Light bucket astronomy is one of several types of observational astronomy that use dedicated, mission-specialized telescopes, instruments, and operational approaches that foster unusually low initial and operational costs. Such low "life cycle" costs can have a number of benefits, including greater productivity (more science for the dollar), increased participation by more institutions being able to afford a research instrument (or timeshare in one), and making long-term synoptic research programs economically feasible.

An example of low life cycle cost is automatic photoelectric telescopes (APTs) such as the 0.8 meter APTs at the Fairborn Observatory. These are essentially identical, specially-designed telescopes with thin meniscus mirrors and permanently installed photometers. Operational costs are kept low through total automation and grouping telescopes together at one observatory. The 14 telescopes at Fairborn Observatory are kept in operation by one person, Louis Boyd. An example of an economical single APT is the AAVSO's 0.35 meter system at the Sonoita Research Observatory. Off-the-shelf hardware and software were assembled in a single day into a working, totally automatic system.

Could the low initial and operational costs achieved by APTs be extended to larger apertures (1-2 meters) and to other areas of research beyond conventional photometry? Achieving low operational costs with dedicated-mission, fully automatic operation has already been adequately demonstrated, and that these costs should not be very dependent on telescope size as long as the telescopes remain compact and lightweight. However, achieving low initial telescope cost for 1-2 meter telescopes is an issue.

Low-cost, lightweight mirrors can lead to low-cost, lightweight telescope structures that don't require 18-wheelers to transport or cranes to install. Members of the Alt-Az Initiative are developing various lightweight mirror technologies including foam glass composite, replica, and spin-cast epoxy mirrors (Genet et al., 2009). There are already some lightweight, low-cost mirrors such as the thin meniscus spherical plate glass mirrors used in flight training simulators that allow one to trade off optical performance for low cost and light weight. Telescopes that use these and other low optical quality mirrors are often referred to as "light bucket telescopes", and the research areas where they excel is what we term "light bucket astronomy."

Light buckets, with their unusually low areal costs (cost per photon), can outperform smaller but higher optical quality conventional telescopes when the sky background is a small or nearly negligible source of noise. This situation can occur when: (1) the object being observed is very bright, (2) the integration times are very short and hence photon arrival noise becomes important, (3) scintillation noise becomes a dominant noise source, (4) the bandwidth is very narrow or the light is spread out as in spectroscopy, resulting in significant photon arrival noise, or (5) noise from the detector is dominant, as it can be in the near infrared.

A number of science programs are particularly well-suited to light bucket astronomy. These include lunar and asteroid occultations, fast cadence/high precision photometry, near infrared diaphragm-limiting photometry, low to medium-resolution spectroscopy, and polarimetry. An array of a half-dozen light bucket telescopes equipped with very high speed photometers could, with their many two-telescope combinations, provide images of the surfaces of nearby stars via intensity interferometry, which is a quantum-mechanical effect that occurs at sub-nanosecond timescales.

2. Light Bucket Astronomy Region of Excellence

The major factors that influence the overall signal-to-noise ratio (SNR) of program object measures include the amount of program object and sky flux collected, scintillation, air mass, filter bandpass, and detector and readout noises. There is no substitute for estimating the SNR for the actual set of program objects, settings, and equipment expected. In order to understand some of the tradeoffs visually, Figure 1 displays figures of merit for the relative SNR for light bucket telescopes of 1.0-m and 1.5-m apertures relative to a 50-cm diffraction-limited Schmidt-Cassegrain telescope (SCT) as a function of program object brightness. A 50-cm SCT was chosen because we thought that its cost might be comparable to, or even more than, that of a 1- to 1.5-m light bucket telescope. Equation 20 of Holenstein et al. (2010) was used for the calculations.

The sky background is 21-mag/arcsec^2. The 50-cm telescope uses a 20-µm (1 arcsec) focal plane diaphragm. The illustrated cases are for 100-µm (7 arcsec) and 400-µm (28 arcsec) diaphragms for each of the 1.0-m and 1.5-m telescopes. A relative SNR of 1.0 means that the two telescopes have the same photometric performance. Scintillation is calculated according to Young (1967) at a 1000-m elevation with an air-mass of 1.5. Amplifier and detector noise are modeled by an Optec SSP-5a with a Hamamatsu R6358 multi-alkali photomultiplier tube, B-filter.

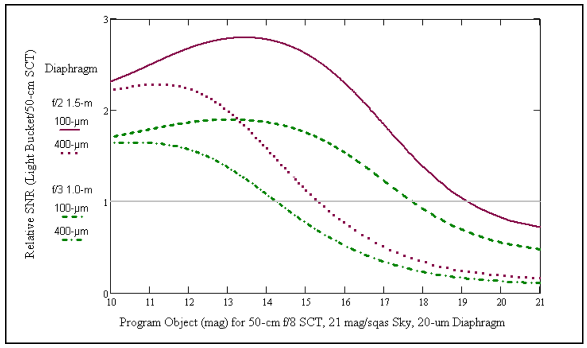

Figure 1. SNR of 1.0-m *f*/3 and 1.5-m *f*/2 light bucket telescopes divided by the SNR of a 50-cm *f*/8 diffraction-limited SCT as a function of the luminosity of the program object.

For very bright program objects, scintillation takes over and limits the relative performance to a value that approaches the expected value based on the relative sizes of the telescope apertures. The relative SNR for mid-brightness objects peaks at a value that approaches the ratio of the example telescope apertures. For faint program objects, the traditional telescope outperforms the light buckets depending on the size of the focal plane diaphragms. However, note that no allowance is made in the figure for program objects for which the diaphragm is unable to isolate the detector from nearby field stars or for errors caused by program object tracking problems (Holenstein et al., 2010).

The crossover point of 1.0 depends on the relative size of the focal plane diaphragms and the apertures of the light bucket telescopes. For mid-brightness objects the light bucket telescopes excel. For example, a relative SNR of 2 means that a 2-hour run with the SCT scope can be accomplished with the light bucket in one half squared, or one fourth, the time, i.e. 30-minutes.

Another way of looking at the situation in this example is that the productivity of the light bucket is four times higher than the SCT. Four times the number of program objects can be observed at the same SNR level as the SCT is able to obtain per unit of observing session. However, it is not just a question of the economics of observing time. In many scenarios, the more important factor is the SNR achievable in a set short integration time for fast changing objects. For example, if one wants to observe a flare star or cataclysmic variable with 10-ms time resolution, a factor of two or three improvement in the SNR achieved may make all of the difference in the interpretation of the observation results. Note that the relative SNR performance is insensitive to detector integration time because the noise increases for all telescope combinations at the same rate as the integration time is reduced (*i.e.*, all of the noise terms that add in quadrature are proportionate to the integration time).

Figure 1 is relatively easy to adjust for observing sites where the sky is brighter than 21-mag/arcsec^2. For example, in a suburban city location, the sky brightness might be 17-mag/arcsec^2. Since this setting is four magnitudes brighter, just subtract four from each value of the ordinate. So, 21 becomes 17-mag/arcsec^2, 20 becomes 16-mag/arcsec^2, and so on. However, this adjustment is only approximate for fainter objects due to the scaling relationship of the detector/amplifier noise.

3. Light Bucket Astronomy Research Areas

The Hipparcos catalog contains 118,000 stars brighter than visual apparent magnitude 7.3. The Tyco-2 catalog contains 2.5 million stars to about V ~ 11. For every magnitude fainter, the number increases by about 300%. As a result, there is rarely a shortage of interesting light bucket astronomy program objects at accessible apparent magnitudes compared to the sky brightness.

3.1 Lunar and asteroid occultations

High speed photometry covers, roughly, subsecond integration times. If objects are fairly bright, then photon arrival and scintillation noise are likely to be the dominant noise sources, not the foreground/background sky nor detector and amplifier noises. We discuss here just one of several high speed photometry programs that should be suitable for light bucket telescopes. Brian Warner (1988) wrote the classic book on high-speed photometry, an area where light bucket telescopes excel, while two more modern books are those edited by Don Phelan, Oliver Ryan, and Andrew Shearer (both 2008).

One of the most interesting areas for high-speed photometry is the interference (fringe) light curves produced when the Moon (or other solar system body) occults stars and data are obtained at millisecond intervals. Analysis of these fringe patterns can yield stellar diameters for nearby stars and discover new close binary stars with separations of just a few milliarcseconds (Nather et al., 1970; Beavers et al., 1980; Ridgeway et al., 1980; Feckel et al., 1980; Schmidtke et al., 1984; Peterson et al., 1989; Richichi, 1984; van Belle et al., 2002; Richichi et al., 2008; Richichi et al., 2009). Obtaining a decent number of photons for each millisecond interval requires a large photon gathering area, although only on-axis light concentration is required if a high speed photodiode or photomultiplier is used as the detector.

Deployed throughout the world today are members of the International Occultation Timing Association (IOTA) who use arrays of small telescopes (typically 0.1-m to 0.4-m aperture) to time lunar and asteroid occultations. A primary goal of the IOTA is to gain insight into the body occulting the background star rather than the star itself, although many new binary systems are discovered by IOTA members when the light curve exhibits a step function. Most regularly, the lunar limb profile and size, shape, and rotation rates of asteroids are routinely determined. Light bucket telescopes would enable occultation researchers the ability to study in greater detail the background objects that are occulted, as well as observing currently marginal occultation events.

Lunar occultations can be used to determine stellar diameters as well as the existence and orbital parameters for binary systems. The photometry needs to be high-speed (millisecond integrations) in order to see diffraction patterns from the lunar limb. To preserve the diffraction pattern, the maximum usable diameter for a single telescope is around 2-m, though results from numerous telescopes can be combined if appropriate corrections are made for relative telescope positions and timing offsets. Figure 2 provides an example of the theoretical light curve that would be produced by the lunar occultation of a binary system with various configurations.

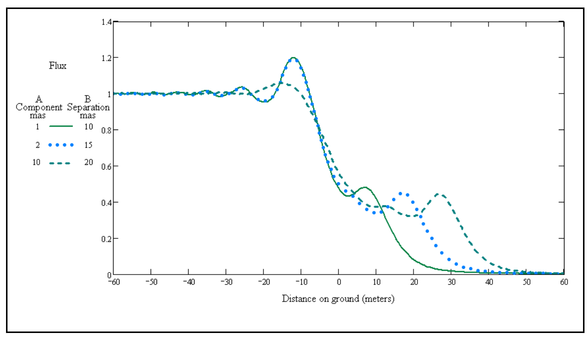

Figure 2. Theoretical diffraction pattern light curves (320-720-nm bandpass) for the lunar occultation of three stars, small with a 0.1-milliarcsecond (mas) diameter, medium 2-mas, and large 10-mas, each with a companion having 50% of the luminosity of the primary. Limb darkening is set to 1.0, and the location of the companions from the primary trails by 10, 15 and 20-mas respectively. The diffraction pattern sweeps over the ground in milliseconds.

It is apparent from Figure 2 that a great deal of information can be determined from the light curve, however many photons must be collected every millisecond in order to produce sufficient signal-to-noise ratio for positive detection and this requires a large photon gathering area, although only on-axis light concentration is required if a high-speed photodiode or photomultiplier is used as the detector. In addition, the diffraction patterns appear similar to scintillation. Some occultations are grazes where the star is occulted several times by mountains near a lunar pole. In this case, it's possible to co-add light curves to reduce the noise from scintillation. Most occultations, however, are not so favorably oriented. Several large scopes working along the occultation path may be needed to help rule out the scintillation contribution which may otherwise mask out interesting features in the program object signal.

The detection of new Kuiper Belt Objects (KBO/asteroids) requires high speed detectors, and big apertures to obtain a high signal-to-noise ratio. These devices will naturally be less portable than the devices used presently by the IOTA.

3.2 High-speed (fast-cadence) and High-precision Photometry

Fast cadence photometry is photometry of events where the changes in light level are fast enough to require shorter integrations than might otherwise be used, but not so fast as to require special high speed detectors and procedures, i.e., in the range of 1 second to 1 minute integrations. A fast cadence is required when the object being studied changes its brightness fairly rapidly and longer integrations would time-smear the details of interest.

An example is an eclipsing cataclysmic variable where the eclipsing star acts as a knife edge scanner cutting across the white dwarf or neutron star's accretion disk, thus revealing details of the disk's structure. Another example is an exoplanet transit where fast-cadence, high-precision photometric observations can yield high quality light curves from which very precise transit times can be deduced. Small, methodical variations in the transit times can reveal the presence of another planet in the system that advances or retards the transit timing due to the light travel time effect.

Some light buckets can produce slightly fuzzy images over a somewhat restricted field of view. This can be sufficient for fast cadence, high precision photometry of somewhat brighter stars. Here CCD camera integration times are a generous (compared to high speed photometry), 1 to 10 seconds, and the field of view is large enough to include nearby comparison and check stars.

Compared to the observatory site where the typical atmospheric seeing may be one to three arcseconds, a light bucket telescope will be optics-limited. If the best imaging of a fast 1.5-m light bucket telescope is 10 arcseconds, this would produce point spread functions with perhaps 12 pixels full width half maximum (FWHM). Photometry with a CCD detector on such a telescope will give the same results as a diffraction-limited telescope of the same size if the field is not crowded and poor seeing does not hurt. This type of photometry benefits from using broad-band filters where sky brightness dominates. A fast cadence requires a large light-collecting aperture. The large aperture of the light bucket helps high precision (e.g. for eclipsing binaries and exoplanet research) because scintillation scales as $D^{-2/3}$ according to the atmospheric model of Young (1967).

3.3 Near IR Photometry

Near infrared (NIR) aperture photometry is another area where on-axis light bucket telescopes should shine (pardon the pun). NIR cameras are expensive, and are likely to remain so for quite some time. Their complex electronics and liquid nitrogen cooling also makes them difficult to support. On the other hand, "one pixel" aperture NIR photometers use low cost InGaAs photodiodes and thermoelectric cooling. The Optec J/H band SSP-4 photodiode photometer costs only $3,000. As part of the Alt-Az Initiative, Greg Jones and August Johnson are developing very low noise J/H/K band photodiode photometers.

Near IR photometry may be an attractive candidate for light bucket astronomy for several reasons. Some of the stars that might be observed are very bright, although backgrounds are also bright and may vary considerably. Detector noise can be significant, especially for thermoelectrically cooled detectors. If a fast cadence or high speed is required, then the same logic as mentioned earlier for optical wavelengths also applies.

Lunar occultations used to determine stellar diameters are an interesting case of high speed NIR photometry where the targets, large diameter late type stars, are very bright in the near IR, while the background (scattered light from the Moon) is relatively faint in the NIR in comparison to visual wavelengths.

3.4 Spectroscopy/Very Narrowband Photometry

With light spread out in a spectrum, spectroscopy benefits from numerous low-cost photons. At typical "small" telescope locations, seeing is usually several arcseconds. An on-axis spot size of 50 to 100 microns can fiber-feed a medium- resolution spectrograph to obtain time series spectra. Spectroscopy (or spectrophotometry) of relatively bright objects, especially of objects changing the relative brightness of specific lines fairly rapidly, could be appropriate for light bucket telescopes. Very narrow band photometry of variable stars might be of interest.

3.5 Polarimetry

Polarimetry can be a high-sensitivity probe to identify asymmetries in the systemic environments of program objects (Clarke, 2010). Asymmetries can originate from binarity, limb darkening, stellar dark and bright spots, Rayleigh/Thompson scattering in stellar atmospheres, Mie scattering from multiple particles types in dust shells, and interstellar birefringence and other sources.

3.6 Stellar Intensity Interferometry

Perhaps the ultimate in high-speed photometry is stellar intensity interferometry. The pioneer in this field was R. Hanbury Brown, an Australian astronomer who used two large aperture moveable light bucket telescopes on a 188-m circular track to measure stellar diameters for 32 nearby stars (Hanbury Brown, 1974).

In the decades since Hanbury Brown's pioneering work, not only has the quantum efficiency and speed of detectors greatly improved, but very high-speed digital correlators are now possible. A revival of stellar intensity interferometry by use of Cherenkov telescope arrays has been contemplated (LeBohec and Holder, 2006; LeBohec et al., 2008) and a workshop on modern stellar intensity interferometry was held in Utah (LeBohec, 2009). Also, note that modern equipment might also be used to look for natural lasers in, for example, hot systems such as Eta Carinae through photon-correlation spectroscopy (Dravins and Germanà, 2008).

4. Conclusion

Light bucket astronomy is in its infancy. How rapidly this field progresses will critically depend on the development of unusually lightweight, low-cost, low optical quality mirrors and the matching telescopes and attendant instruments. Efforts by the Alt-Az Initiative are spurring development of the enabling technologies and techniques, including new mirror types, instruments, mounts, transportability options, automation methods, and identifying attainable scientific goals.

5. Acknowledgements

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