

Earth- and Space-Based Light Bucket Intensity Interferometry Arrays

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Abstract

Recent progress has been made in the development of low cost, portable, meter-class light bucket telescopes, as well as low cost, lightweight foam glass and spin-cast epoxy mirrors. One of many astronomical applications of light bucket telescopes is stellar intensity interferometry, pioneered by Hanbury Brown in the 1960s. Major advances in detectors, electronics, and computers now allow much fainter sources to be observed; an opportunity being explored by several intensity interferometry experiments. Intensity interferometric arrays of three or more telescopes with much longer baselines could be used to obtain very high resolution images. Earth-based arrays with baselines of kilometers could be implemented in the near future. Space-based light bucket arrays with baselines up to 20,000-km and sensitivity down to $V \sim 20$ could split bright spectroscopic binaries in nearby galaxies, thus obtaining direct distances. X-ray binaries could also be split and probed for relativistic orbital effects. The very highest nearby 'strong gravity' regime, that of the galactic center, could be monitored for

last-time-of-light material as it enters the black hole at Sgr A*. Finally, the very granularity of space-time itself could be explored by mapping the increasing decoherence of light from cosmological sources with increasing baseline, due to the effect of the fundamental Planck scale of space-time 'smearing' out the fringes.

1. Introduction

A previous Society for Astronomical Sciences paper, "Light Bucket Astronomy" (Genet, Henden, and Holenstein 2010), overviewed the various uses that light bucket telescopes could play in astronomy. In this paper we review progress over the last couple of years in the development of two portable light bucket telescopes with apertures of 1.0 meter and 1.5 meters. We also review the progress made in two mirror technologies: foam glass sandwich mirrors and spin-cast epoxy mirrors.

We then consider just one of many astronomical applications of light bucket telescopes: stellar intensity interferometry. Pioneered by Hanbury Brown in the 1960s, major advances in detectors, electronics, and computers now allow much fainter sources to be observed. We describe several ongoing intensity interferometry "experiments." One experiment is using two single photon avalanche diodes (SPADs) sensors mounted on (non-light bucket) telescopes at Lowell Observatory as a minimal intensity interferometer "array." Another experiment is using two high-speed photomultipliers as the detectors. Currently undergoing lab and small telescope tests, the plan is to place these two detectors on the 1.0 and 1.5 meter portable light bucket telescopes, allowing the spacing and orientation of the two telescopes to be varied at will.

Finally, we consider how intensity interferometric arrays of three or more telescopes with much longer baselines could be used to obtain very high resolution images of selected astronomical objects. Earth-based arrays with baselines of kilometers could be implemented in the near future, while space-based arrays with baselines of tens of thousands of kilometers will take longer to develop but could feature relatively low cost light bucket space telescopes and ultra-high resolution.

2. Light Bucket Telescopes

Light bucket telescopes are non-imaging, on-axis flux collectors used in various areas of astronomy such as high speed photometry, near-IR aperture photometry, and spectroscopy. Genet and Holenstein (2010) explored applications of modern light bucket telescopes in the 1-m to 3-m aperture range. Specifically, they defined them as telescopes which are low-optical quality light concentrators used in

those areas of astronomical research where vast quantities of cheap photons are required, but not an image per se. Light bucket telescopes are low in cost and lightweight, and can be designed to be easily moved about and transported in small vans or on trailers.

Genet and Holenstein (2010) suggest that light bucket astronomy is advantageous in those situations where, compared to noise from the sky background, the noise from one or more other sources is dominant or, putting it the other way around, where 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.



Figure 1. This 1.0 meter portable light bucket telescope received the 2011 Riverside Telescope Maker's Conference (RTMC) award for innovation. Celebrating at RTMC, left to right, is Alan Keller, Chris Estrada, Reed Estrada, Russ Genet, and Joe Haberman.

A 1.0 meter light bucket telescope has seen initial operation (Genet et al. 2010). Requirements for this telescope included: (1) low cost, (2) use of readily available materials and manufacture using home shop construction tools and techniques, (3) a compact design that would allow transport in a normal sized sports utility vehicle or pick-up truck, (4) a lightweight structure to allow easy movement and transportation, (5) a robust design to withstand

the rigors of frequent transportation, (6) easy field set up with a thirty minute time goal from the time the telescope was unloaded to being ready for operation, (7) precise pointing and tracking, and (8) weather durability to allow extended outdoor unprotected operation.

An alt-azimuth configuration was chosen for its compactness. The prototype was made from high density plywood, aluminum, and some steel. “Rapid prototyping” allowed major design changes to be made late in the construction and assembly process. The telescope’s 1.0 meter f/4.0 spherical, $\frac{3}{4}$ inch thick, slumped meniscus mirror weighs 70 lbs., and was donated by Display and Optical Technologies Inc. (DOTI). The telescope’s hexapod superstructure supports prime focus instruments.

The thin, low cost, spherical mirror had both spherical aberration and astigmatism that, without correction, would have produced an unacceptably large spot size many millimeters in diameter. On-axis spherical aberration was corrected, to a considerable extent, with a two-element corrector designed by Tong Liu (Hubble Optics) that utilized two low cost, off-the-shelf, 50 mm lenses from Edmund Optics.

Two approaches were taken to reduce the astigmatism, which was primarily along a single axis. One approach, suggested by Dave Rowe (PlaneWave Instruments), employed two low cost 70 mm eyeglass cylindrical lenses. The two lenses were oriented as an assembly to match the primary astigmatism axis of the mirror, while they were rotated with respect to one another to adjust the cylindrical correction power. The other approach utilized a cable and pulley warping harness along the principle astigmatism axis to physically bend the mirror into shape. Both approaches significantly reduced the astigmatism. The combination of spherical and astigmatic correction reduced the spot size to less than 1 mm.

Initial field trials used a high speed Luminera CCD camera. The telescope was recently transported to Holenstein’s East Coast observatory in the back of a Dodge minivan. Continued observations and hardware improvements are underway.

Based on lessons learned from the 1.0 meter telescope project, a 1.5 meter portable light bucket telescope was designed and fabricated by structural engineering students at California Polytechnic State University (Cal Poly). Computerized three-dimensional models were not only utilized in the structural analysis, but also in the CNC fabrication of the planar trusses used in much of the structure. Iterative structural analysis optimized the design by simultaneously solving for a high natural frequency with low structural weight.



Figure 2. A second, much-refined, all-aluminum 1.0 meter version of the portable light bucket telescope should see first light later this year. Yet to be installed are the drive motors, mirror and mirror cell, and hexapod superstructure for prime focus instruments.

Another DOTI slumped spherical meniscus mirror was donated to the project. Also $\frac{3}{4}$ inch thick, this mirror was a faster f/3. A 27-point wiffletree mirror support system was designed and fabricated by Donny Mott, following suggestions by David Rowe with respect to the pivot point of the mirror (in front of the mirror’s front surface) and providing adjustable forces on the six outer wiffletree triangles to reduce astigmatism. Following initial construction, the Cal Poly students evaluated the resonant frequency of the structure via accelerometers mounted at prime focus. Field trials should begin later this year.



Figure 3. The official rollout of the 1.5 meter portable telescope at California Polytechnic State University. Three structural engineering students, Mounir El-Koussa, Laura Rice, and Mike Vickery designed and built the telescope’s structure. The mirror is protected with a temporary coating of peel-off blue plastic



Figure 4: The Alt-Az Telescope Initiative, now in its seventh year, has done much to advance low cost light bucket telescopes and lightweight mirrors (www.AltAzInitiative.org). Above are participants in one of the Initiative's conferences, this one on Meter-Class Astronomy held in 2012 at Canada-France-Hawaii Telescope headquarters in Waimea on the Big Island of Hawaii.

3. Two Lightweight Mirror Developments

The development of lightweight, relatively low cost mirrors is proceeding along a number of fronts, including refinements in thin meniscus mirrors made from ordinary plate glass. Adjustable support systems have been designed for these thin mirrors. In this paper we summarize two developments: (1) foam glass sandwich mirrors, which are of much higher optical quality than mere light bucket mirrors, and (2) spin-cast epoxy mirrors which do not require any figuring.

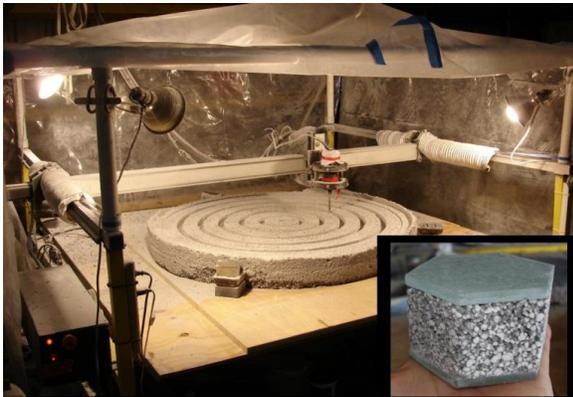


Figure 5. The foam glass core of a mirror being CNC machined prior to the fusing of glass faceplates. The inset is the raw material used to make the foam glass core.

Foam glass mirrors, being developed by Aurigema, are a sandwich design of composite materials that result in a lightweight rigid optical structure. The thin float glass top face is slumped on a master mold to take the rough spherical shape of

the mirror's prescription. The center section of the structure is a cast-in-place foam glass aggregate composite material that is porous, lightweight, and very rigid. The rear face is also float glass. When these three components are brought together and fused, the resultant assembly can be machined and polished with conventional mirror-working practices and materials. The use of lightweight, low density ceramic foam as 80% of the mirror's volume allows an overall mass that is only 20% of a solid glass equivalent. A 1.0 meter mirror only weighs about 80 lbs. Preliminary tests show that figures can be generated with a $\frac{1}{2}$ wave RMS wave front error. Work still remains on achieving a thermally stable structure when using lower cost "plate glass" instead of more thermally stable but expensive borosilicate glass for the face sheets.

Epoxy mirrors are produced by employing a spin-cast method somewhat similar to that at the Arizona Mirror Lab, which is regularly used to form rough parabolic surfaces for glass mirror blanks (Hill, 1998). The spinning method is also used by Borra to spin liquid mercury mirrors (1982).

Our specially-formulated, thin epoxy naturally forms a parabolic surface when spun at constant velocity. Once it hardens, the mirror surface is ready for its reflective coating. Progress has been made as seen in the images below, although wavefront error is still high (10 waves RMS). Studies have shown that carefully made epoxy mixtures have RMS surface irregularities less than a few percent of the wavelength of visible light (Mollenhauer and Camping, 2002), so optical-quality polymer mirrors should be possible by spin-casting without any polishing or figuring. Given the flexibility of polymeric solids, the figure errors could be corrected by the mirror support which we are investigating. Spin-cast epoxy mirrors have, for some applications, a number of advantages over glass. For instance, the low f/ratios preferred for large instruments are no harder to make by this method (Laird, 2004).

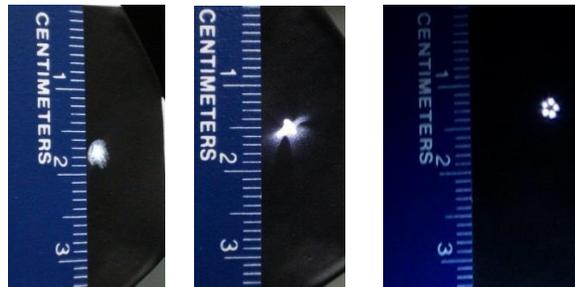


Figure 6. Optical improvements have been made by adding a stiff aluminum mold to hold the spinning epoxy.

The images in Figure 1 show the progress of the epoxy mirrors. A flashlight with 5 LEDs was placed 50 feet away from the mirrors and the resulting image of the LEDs was captured. The first image is from an early epoxy mirror while we were still proving the concept. This mirror was spun in a Rubbermaid container with a flat bottom. The center image is from a mirror produced in a polyurethane foam container that had a curved surface to match the spinning parabola. The final image is from a mirror spun in an aluminum mold, also with a curved surface. The 5 LEDs are now being resolved due to the stiffness and curvature of the container. Future improvements include using a carbon fiber mold to reduce the weight of the final mirror, manipulating the CTE of the epoxy in order to match the mold's CTE, and producing a low-shrinkage mirror with spiro orthocarbonate compounds.

4. Amplitude and Intensity Interferometers Contrasted

The highest resolution stellar interferometers in use today are Michelson-type optical amplitude interferometers. Amplitude interferometry baselines require strict ($\sim 10^{-8}$ meter) phase differences, and increase rapidly in both difficulty and cost with baseline length. Specifically, resolution of optical systems goes as λ/D , where λ is the wavelength of the radiation and D is the optical system diameter (baseline). Amplitude interferometers are limited by their size, which determines angular resolution, and in their ability to collect light, setting a limiting apparent magnitude of observable objects. All three parameters are constrained by cost as well as fundamental physics. Increasing baselines of amplitude interferometers rapidly becomes impractical: 400 meters appears to be the maximum baseline in the foreseeable future. The Navy Precision Optical Interferometer (NPOI) cost, with small 5 inch apertures, is on the order of \$50 million, and space-based missions with 2 meter mirror constellations (ESA's DARWIN, NASA's TPF-I, or SBI) are estimated to cost a minimum of \$5 billion.

One of the most interesting uses of light buckets was that of R. Hanbury Brown (1956, 1974) by directly measuring the diameters of 32 stars at his observatory in Narrabri, Australia. He pioneered intensity interferometry, a technique for measuring a second-order quantum temporal correlation of photons arriving from the program objects. Unlike amplitude interferometry—which requires combining coherent light beams from high optical quality telescopes with path-lengths control in fractions of a micron—intensity interferometry uses two or more

low quality light buckets, does not require combining light beams coherently, and the positions of the telescopes only need to be known—not controlled—to centimeters. Fast electronics, as opposed to high-tolerance optical assemblies, can dramatically improve an intensity interferometer's signal to noise ratio (SNR) over the past devices.

Stellar intensity interferometers work by pointing all of the telescopes comprising the device at the same source. The outputs of high-speed detectors at each telescope are correlated electrically or digitally. The correlation of detected fluctuations from a stellar source, for instance, falls off with the apparent diameter of the source or by increasing the baselines separating the telescopes.



Figure 7. Hanbury Brown's first stellar intensity interferometer consisted of a borrowed pair of anti-insert hyphen-aircraft searchlights. After proving the technique worked on Sirius, Hanbury Brown and associates constructed the pictured 6.5 m aperture light buckets and deployed them on a circular track 188 meters in diameter for his main series of observations.

Hanbury Brown operated the Narrabri two-telescope interferometer shown in Figure 7 using photomultiplier detectors and electrical correlators. At the time, individual photon detection and coincidence counting correlation equipment was prohibitively expensive and performance was a limiting factor preventing their use. Hanbury Brown's (1974) Equation 4.54 for the signal-to-noise-ratio (SNR) of a pulse counting stellar intensity interferometer may be used to probe the performance of a modern instrument:

$$SNR_{pulse\ counting} = \frac{1}{2} (N_1 N_2)^{1/2} \tau_0 \left[\frac{T_o}{2\tau_c} \right]^{1/2} |y_{12}(B)|^2, \quad (1)$$

where N_1 and N_2 are the pulse counting rates from the two telescopes, τ_0 is the coherence time of the photon flux from the star, T_o is the observing period, τ_c is the resolving time within which two pulses are counted as having arrived at the same time, B is the baseline, and the $|y|^2$ correlation term ranges

from 0 to 1 and measures the mutual coherence of the flux detected at the output of the two detectors.

First order independence of the SNR from the optical bandwidth can be seen in the counts, N , which scale directly, and in the coherence time, which scales indirectly with the optical bandwidth and thus cancels out the dependence. One conclusion from Equation 1, however, is that using a narrow optical bandwidth will reduce the peak counting rate requirement of the electronics. In fact, Hanbury Brown rejected the pulse coincidence counting technique in favor of electrical correlators because he figured that, with his pair of 6.5 m aperture mirrors collecting flux from a zero-magnitude star, he would require matched optical filters just 0.02 nm wide.

Hanbury Brown's approximately 2.5 magnitude star observation limit was obtained with a pair of 6.5-m light buckets, an optical bandwidth of 4 nm, photomultipliers with a quantum efficiency (QE) of 20%, and an overall electrical bandwidth of 60 MHz. A modest one-channel modern device with a pair of 2.4 m light buckets, 4 nm filters, solid state detectors such as silicone PMTs or SPADs operating with 2 ns resolving time (i.e. the bin width), 70% QE, and a high-speed NVIDIA graphics card correlator would have about equivalent performance and yet would be much smaller, easier to operate, and orders of magnitude less expensive to acquire and operate. Even better performance is possible in a single channel device by pushing the bins and path length differences to the picosecond range. However, a balance is needed between N (which is proportionate to the telescope collection area) and the average number of detected photons collected per bin. Otherwise, if the bins are too sparsely populated, the coincidences detected will be few and lost in secondary noise sources (for example, a flux of 10^6 detected photons/second with a bin width of 1 ps will produce just 2 coincidences/second).

As discussed in Genet and Holenstein (2010), when multiple channels and path lengths are measured simultaneously, the following formula describes the overall signal-to-noise ratio (SNR) of the system:

$$SNR_{Overall} = \left[\binom{N_{Array}}{2} N_{Channels} \right]^{1/2} SNR_{One Channel} \quad (2)$$

where N_{Array} is the number of elements in the array, and $N_{Channels}$ is the number of simultaneous channels measured, and the noise is modeled as adding in quadrature. Using Equation 2, the overall SNR improvement of using 100 optical channels and a small array of seven 2.4 m telescopes would be an ability to operate four or more magnitudes fainter than the equivalent single channel device. Each additional magnitude enables one to observe about 300% more stars. So, the modern device specified

would be able to observe hundreds of more stars than Hanbury Brown measured. Note, however, that Cherenkov radiation from charged particles striking the Earth's atmosphere will produce spurious correlations in the intensity interferometer. Hanbury Brown predicted that noise from Cherenkov radiation would mask the stellar intensity correlations at about 6th magnitude for his device. However, his photomultipliers imaged an area of the sky which was 15x15 arc minutes. Modern light bucket telescopes are readily able to isolate much smaller regions of the sky, thus making Cherenkov radiation an insignificant issue for modern systems.

5. Recent Intensity Interferometry Developments

A January 2009 workshop, organized by Kieda and LeBohec (2009), and held at the University of Utah, marked the revival of intensity interferometry. Working with others (Dravins 2013), Kieda and LeBohec are considering how the planned Cherenkov Telescope Array (CTA) of dozens of 6 meter telescopes could also be used for intensity interferometry, especially on moonlit nights less favorable for observing faint Cherenkov radiation showers.

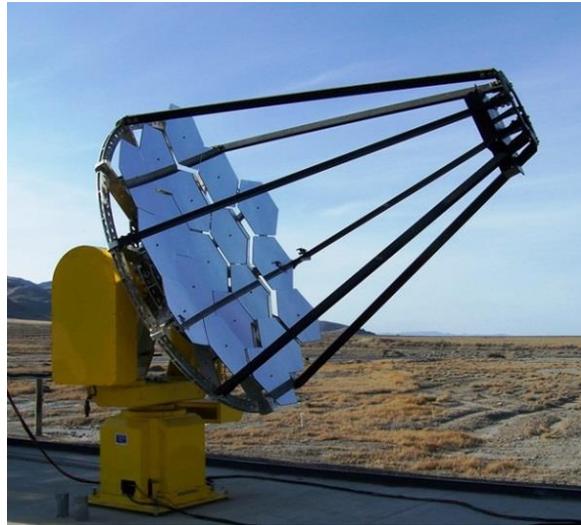


Figure 8. One of the two 3.0 meter telescopes at Starbase Utah used in intensity interferometry experiments. The large object at prime focus is a small optical bench used to mount components.

In order to test these ideas, Kieda and Lebohec have built two 3.0 meter light bucket telescopes at Starbase Utah that they use in their experiments. They have developed technologies for high speed digital recording of time-tagged photons, as well as approaches to ex-post-facto digital correlation. The

digital correlator employs a 500 MHz National Instruments-based, 8-bit streaming digitizer system combined with a front end VEREX-5 FPGA processor and high speed (800 Mb/Sec) 12 TB disk drive capable of recording multiple hours of continuous streamed data from a photomultiplier tube or SPAD light sensor.

The light sensor data is time tagged to a PXIexpress backplane which is synchronized to a GPS clock. Laboratory tests of the system indicated a current ability to record relative times between widely separated stations to an accuracy better than 10 nano-seconds on hour-long durations. Correlations between photon streams can be performed with narrowband digital filters in order to eliminate cellphone noise for the data streams, and enhance signal-to-noise. Kieda is continuing to work with National Instruments on the development of a 'white-rabbit' synchronization board that should be able to provide synchronization of widely-spaced (100m) telescopes to absolute timing better than 0.5 nano-seconds. The development of the technology to perform high-resolution synchronization across a widely spaced array of telescopes will enable the realization of the capability of large telescope arrays (like CTA) to perform high resolution imaging of stellar surfaces and orbiting binaries.

Horch is working toward an "intensity interferometer in a suitcase." The interferometer's sensors consist of two SPAD detectors made by the SPADlab (www.EveryPhotonCounts.com). Real-time digital correlation is performed with a Picoquant Picohartp 300 timing module.



Figure 9. The Picohartp 300 (left) is shown connected to the two SPAD sensors at Horch's lab at the University of Southern Connecticut.

This interferometer is easily transported to a two-telescope observing location as airline check-in luggage. Initial intensity interferometry runs have been made at Lowell Observatory. The SPAD

detectors were mounted, along with focusing optics and narrowband filters, on two telescopes, while the Picohartp real-time correlator was placed on a small table halfway between the two telescopes. The SPAD detectors exhibited temperature sensitivity, actually stopping operation when it got cold.



Figure 10. The photometers are shown mounted on the 1.0 and 1.8 meter telescopes on Anderson Mesa at Lowell Observatory (left and right, respectively).

Coauthor Christensen, with Rodriguez and Genet, is also developing an easily transported two-sensor intensity interferometer. Rather than using SPADs, they are using high speed photomultiplier tubes (PMTs). While not as high speed as SPADs, PMTs have a larger surface area amenable to the large spot sizes typical of light bucket telescopes. Design and construction of a pair of photometers (pictured in Figure 11) are ongoing.

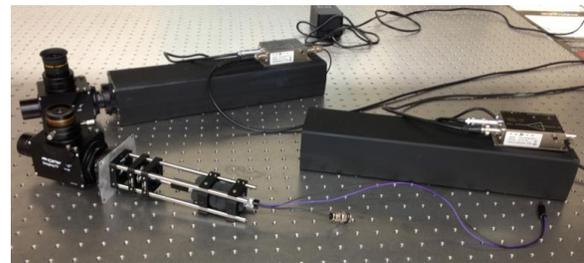


Figure 11. Photometers for intensity interferometry studies. A flip mirror is used to center the object along the optical axis. This is followed by an aperture to reduce night-sky background, a Fabry lens, a blue filter, and a photo-multiplier. A battery powers the HV supply built into the case, while a high-speed amplifier is screwed onto the outside. Signal cables are then run to an external 2-channel digitizer controlled by LabView.

Initial engineering tests to calibrate and validate the instruments are promising. A proof of principle laboratory test using a pseudo-thermal source is shown below. A pseudo-thermal source is created by shining a laser on a piece of ground glass that is rotating. The resulting speckle pattern is projected onto a beam splitter that directs 50% of the light to

one PMT and allows 50% of the light to continue on to another PMT. A pinhole in front of each PMT is used to sample the same speckle. Figure 12 shows that as the location of one of the PMTs is moved, the cross-correlation between the signals decreases as expected.

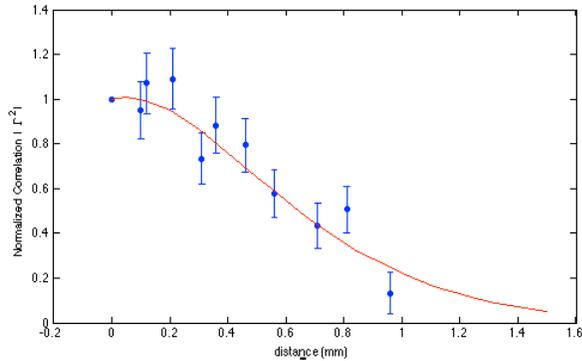


Figure 12. Cross-correlation of a pseudo-thermal source measured with a pair of photometers in the lab. The x-axis is the transverse location of one of the photometers with respect to the other.

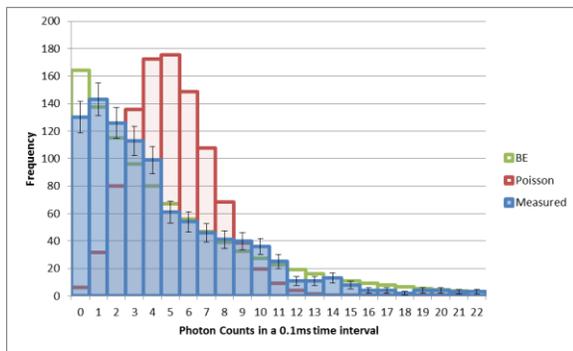


Figure 13. Frequency distribution of the number of photons arriving at the detector in a 0.1 ms interval from a pseudo-thermal source and theory curves for the expected Poissonian and Bose-Einstein (BE) distributions.

In order to test the characteristics of light from a thermal source, such as a star, and the feasibility of photomultiplier tubes for use in intensity interferometry, an experiment was setup to mimic the intensity fluctuations from a star and characterize the photon counting statistics as recorded by the PMT. This proof-of-principle test demonstrates the detector’s ability to measure light coming from a pseudothermal source. A He-Ne laser directed at a PMT was placed behind a rotating ground glass; the rotating ground glass diffracts the laser light and causes it to fluctuate as the glass rotates, creating a pseudo-thermal source. The PMT then recorded the quantity of photons that struck the detector at intervals of 0.1ms in 1000 trials. The figure shows the result of the experiment as a blue (lower)

histogram as well as theory curves for the expected Poisson and Bose-Einstein distributions.

The distribution of the photons demonstrates that the pseudo-thermal source does not behave as a coherent light source. Rather the light measured by the detector is more Bose-Einstein with a slight Poissonian influence that can be seen in the bin where no photons were recorded. Here the expected frequency for a pseudothermal source falls below theory; this can be attributed to the imperfections in the ground glass indicating that the source is not perfectly pseudothermal.

6. Long-Baseline Intensity Interferometry Arrays

We envision two futures for long-baseline, light bucket intensity interferometry arrays: one on Earth and the other in space. Time-tagged photons allow data reduction after the fact—somewhat similar to long-baseline radio astronomy. This opens the door to multiple optical telescopes with long baselines. Earth-based kilometer baselines could provide images of exoplanet transits, binary stars, and stellar disks. Horch has proposed using multiple Dobsonian telescopes around the Southern Connecticut University campus and two large telescopes at Kitt Peak National Observatory.



Figure 14. Mounir El-Koussa, after graduation from Cal Poly, redesigned the 1.5 meter portable telescope into a 2.4 m portable telescope. An array of six of these telescopes is shown above, although an intensity interferometry array would have wider spacing and would not be placed in rows.

By placing arrays in space, very long baselines could be achieved. A 20,000 kilometer baseline would yield nano-arcsecond resolution. With space light bucket telescope intensity interferometry arrays, one could split low- and high-mass x-ray binaries, image black holes and quasars, and explore quantum gravity.

Space-based intensity interferometry arrays recording time-tagged photons with low cost, loosely coordinated satellites could enable ultra-long baseline astronomy and astrometry missions that would improve current approaches to high resolution

astronomy by a factor of 1000 at a minimum. Ritter estimates that this could be done at just 5% of current NASA Flagship Mission costs. Advances in fast optical detectors, along with inexpensive, lightweight, low optical precision large telescopes, presents the tantalizing possibility of performing ultra-long (>megameter) baseline ultra-resolution (<nano-arcsecond) space-based optical intensity interferometry in the next 20 years with a free-flying array of space light bucket telescopes that would combine, non-asynchronously, temporal intensity correlation technique enabling nano-arcsecond astronomy and astronomy.

An array of three or more coordinated satellites, measuring intensity at GHz bandwidth with inexpensive, low optical quality, large area mirrors—where baselines for phase closure only need to be known to a few cm—could be implemented with flyers coordinated with LIDAR and corner cubes. Time tagging asynchronous temporal correlation in conjunction with relaxing the baseline differential constraint enables intensity interferometry with, literally, astronomical baselines. Combining picosecond (and eventually faster) detector and electronics with asynchronous data post processing requires only a simple radio link. Inexpensive light bucket telescopes will enable missions with a factor of 1,000 to 1,000,000 times the resolution of the James West Space Telescope.

A “Path for Progress” is dictated by Hanbury Brown’s (1974) Equation 4.30 for the SNR of an intensity interferometer which uses electrical correlators, recast as a function of stellar magnitude:

$$SNR = 2.512^{-m} F_0 A \eta |\gamma_{12}(B)|^2 \left[\Delta f \frac{T_0}{2} \right]^{1/2}, \quad (3)$$

where m is the magnitude of the star observed, F_0 is the photon flux of a zero-magnitude star per unit bandwidth and unit of area, A is the area of a collector, η is the optical system efficiency (optical transmission x detector quantum efficiency x correlator efficiency), B is the baseline, $|\gamma|^2$ is the mutual coherence, Δf is the detector bandwidth, and T_0 is the integration time.

Increasing Δf and η (bandwidth and efficiency) — SNR is proportional to both detector quantum efficiency and the square root of detector bandwidth. Hanbury Brown’s original Narrarbi instrument had optics, phototubes, and an electrical correlator operating with $\eta = 0.08$ and $\Delta f = 60$ MHz. Now commercially available Single Photon Avalanche Diode (SPAD) detectors have quantum efficiencies of 0.7, and high-efficiency signal correlators with $\Delta f = 100$ GHz are also available, making possible η ’s above 0.5. These factors alone can provide an overall gain in SNR of over 250, assuming the overall opto-

electrical path length tolerances are held to under 1 mm and 10 ps. If the same interferometer that Hanbury Brown and Twiss used in the 1950s were operated today with modern electronics and medium-quality light bucket optics, its limiting magnitude would be 6 magnitudes fainter than the old device, or about $V = 8.5$; this compares favorably with NPOI. Large format, fast SPAD arrays also significantly reduce pointing requirements and detector dead time.

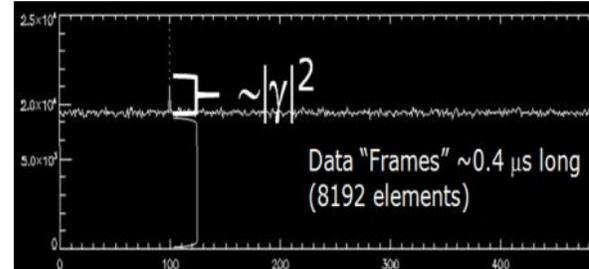


Figure 15: Our conservative simulation of a two-telescope arrangement, 400 second exposure of a point source giving a 1 MHz count rate on each SPAD with a 0.1-nm filter width, resulting in a signal-to-noise ratio of 10.

Increasing A (area of the collector) — Large, yet inexpensive flux collectors require light buckets, not mirrors polished to a millionth of an inch. Ultimately, the mirror figure is determined by the detector spot size needed and pointing accuracy. Fortunately, large fill factor SPAD arrays are in development. A 1000 pixel detector already exists, providing more surface area (detectors cost less than telescopes so it is reasonable to push in this direction). In order to overcome current low fill factors, approaches such as remapped fiber bundles as well as lenslet arrays could be used. Intensity interferometry has, to first order, a constant SNR with optical bandpass; extremely narrow band imaging can achieve the same limiting magnitude as wider bandpasses. We envision a dispersion instrument where we use multiple bands to improve correlation efficiency. Light buckets are inexpensive, and even current membrane technology as well as more advanced photoactive membranes like Ritter’s are on the horizon to reduce satellite pointing requirements and increase flux correction.

Increasing B (baseline) — In intensity interferometry, spatial phase coherence is not required. The limitation will ultimately be the SNR as baseline increases. SNR, which goes as NV^2 (N = number of photons, V is visibility) for extended objects, will drop with baseline. However, for compact hot sources, V will be high for even very long baselines: exactly the sort of interesting physics regime that has not been probed.

As intensity interferometry uses a 2nd order quantum temporal correlation, no fixed baseline

needs to be maintained. One only needs to measure the electro-optical path length to somewhere between a millimeter and a few centimeters, less with more computer memory. Loosely coordinated constellations of satellites with simple LIDAR/corner cube systems would suffice. In ground-based tests, rather than using an expensive micron measuring interferometric laser tracker as would be the case in amplitude interferometry, in intensity interferometry one could simply use a measuring tape.

Is there any limit to the baselines that could be achieved? We plan to examine the theoretical maximum baseline by exploring the decoherence issue. The arrival of correlated photons at two stations on Earth is de-correlated in time by atmospheric fluctuations, as it is in amplitude interferometry. Radio arrays compute atmospheric phase delay and compensate. In contrast, in the optical, the corrugation of the wavefront amounts to variations in the direction of the Poynting vector of 10^{-5} m at most, so arrival times differ only by $\sim 10^{-14}$ seconds are easily covered in a bin of 50 ps. Interstellar media can produce a phase shift, e.g. Faraday rotation, as well as an effective refractive index shift near absorption lines. Staying away from the galactic plane and absorption lines can increase the SNR. Ultimately NV^2 becomes baseline dependent as, at some point, everything is resolved. We aim for unparalleled resolution: A million-fold resolution improvement is our ultimate goal.

Increasing Channels and Array Elements —

As discussed following Equation 2, multiple optical channels and array elements will increase the overall performance of the intensity interferometer. Rather than attempting to observe fainter objects, the extra sensitivity provided by the multiple channels and elements may be used to reduce the long integration periods required by Hanbury Brown from multiple hours per datum to minutes or even seconds.

7. Unique Discovery Space

The very long baselines possible with separated-station intensity interferometers have the potential to open up entirely new vistas in astronomy. For a ground-based prototype, if the discussed advances from modern electronics enable sensitivity to $V < 8.5$, a 20-km baseline should be fairly straight forward to realize. Such a demonstrator could easily obtain the first direct measurement of the size of a white dwarf, Sirius B, at an angular size of ~ 1 -microarcsecond (Holberg et al. 2012). A few high-mass X-ray binaries (eg. SS Cyg-like systems) would be sufficiently bright and have reasonable separations of ~ 10 s of microarcseconds (Tomsick et al. 2005) for

exploration of these strong gravity laboratories by an intensity interferometer prototype.

For a putative space-based facility, with baselines up to 20,000-km and sensitivity down to $V \sim 20$, further exotica present themselves for investigation. Direct distances to nearby galaxies in the Local Group should be possible by splitting bright spectroscopic binaries. Dozens of X-ray binaries could be split and probed for relativistic orbital effects (Unwin et al. 2008). The very highest nearby ‘strong gravity’ regime, that of the galactic center, could be monitored for last-time-of-light material as it enters the black hole at Sgr A* (Eisenhauer et al. 2009). Even the very granularity of space-time itself could be explored, by mapping the increasing decoherence of light for cosmological sources with increasing baseline, due to the effect of the fundamental Planck scale of space-time ‘smearing’ out fringes (eg. Lieu & Hillman 2003).

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