Multi-baseline bootstrapping at the Navy Precision Optical Interferometer

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ABSTRACT

The Navy Precision Optical Interferometer (NPOI) was designed from the beginning to support baseline bootstrapping with equally-spaced array elements. The motivation was the desire to image the surfaces of resolved stars with the maximum resolution possible with a six-element array. Bootstrapping two baselines together to track fringes on a third baseline has been used at the NPOI for many years, but the capabilities of the fringe tracking software did not permit us to bootstrap three or more baselines together. Recently, both a new backend (VISION; Tennessee State Univ.) and new hardware and firmware (AZ Embedded Systems and New Mexico Tech, respectively) for the current hybrid backend have made multi-baseline bootstrapping possible.

Keywords: optical interferometry, baseline bootstrapping, NPOI

1. INTRODUCTION

One of the perversities of stellar optical and infrared interferometry derives from the fact that we (usually) use our observing target as our phase reference. To do so, we need the fringe signal-to-noise ratio, $NV^2/2$, to be high enough to track the fringes.[1] (N is the number of photons in a frame, which at the Navy Precision Optical Interferometer [NPOI] is typically 2 ms, and V is the fringe visibility.) This requirement is not a problem when we observe circumstellar material or multiple-star systems, because those size scales are considerably larger than the stellar disk that provides the fringe-tracking signal. We can use baselines that are short enough to avoid over-resolving the stellar disk, yet long enough to resolve a disk or a double star.

The perversity is compounded, though, when we want to observe stellar surface features. In this case, a baseline that is short enough to avoid over-resolving the disk of the star is too short to resolve these features, and may even be too short to unambiguously constrain the degree of limb darkening.

For an example suited to the NPOI, consider a 5 mas diameter late K star at $m_V \approx 3.1$ (assume uniform surface brightness for simplicity), observed on a single baseline with 12 cm apertures, a wavelength range from 600 nm to 850 nm, a frame time of 2 ms, and 5% throughput. Reaching a fringe signal-to-noise ratio of 5 requires $V^2 \gtrsim 0.05$, which occurs inside the first null of the Airy pattern. The result is that we cannot expect to track fringes on this star with baselines longer than ≈ 25 m — but to observe any details of the stellar surface, ranging from limb darkening to spots, requires taking data at spatial frequencies a few to several times higher.

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There are several possible solutions to this problem. One is to track fringes in a long wavelength band, e.g., the H band, and to take data in the visual band, a technique sometimes called "wavelength bootstrapping." A second is to use a separate unresolved target, such as a laser guide star or a nearby reference star, that can be observed simultaneously with the target of interest. A third, "baseline bootstrapping," is the method that we discuss here.

The basic concept of baseline bootstrapping is simple: if you want to resolve a surface feature of ≈ 1 mas on our K star, set up a baseline ≈ 100 m long. Between the two elements that form this 100 m baseline, place three more array elements at equal intervals between them. Now you can track fringes on the four 25 m baselines thus formed. Knowing the fringe phase on each of these short baselines, you now know the fringe phase on the long baseline as well, which allows you to integrate the signal on the long baseline until the fringe shows up. The idea is not new; it was first suggested by Roddier in 1988.[2] The NPOI uses bootstrapping with three array elements: with the middle element as the reference station, we track fringes on the two short baselines to stabilize the longest baseline.

2. BOOTSTRAPPING AND THE NPOI

The NPOI[3,4] is a multi-element instrument intended for both astrometry and imaging, located at the Lowell Observatory's Anderson Mesa site near Flagstaff, Arizona. The astrometric array consists of four siderostats in fixed positions in a Y-shaped array with ≈ 20 m arms. The imaging array consists of 30 piers, laid out in a Y with ≈ 250 m arms, on which as many as six imaging siderostats can be placed. The arrays share a vacuum feed system and six delay lines. Astrometric and imaging siderostats can be used together.

The NPOI was designed for bootstrapping up to five baselines together, with imaging stellar surface structure as one of its imaging goals. In order to obtain the largest possible number of resolution elements across a stellar disk with a fixed number of array elements, the NPOI layout provides a number of configurations in which all of the short, tracking baselines are the same length. If all six elements were in a straight line, the highest-resolution baseline would be 5 times the length of the tracking baselines; instead, with three array elements along each of two arms of the NPOI imaging sub-array, the highest-resolution baseline would be slightly shorter, at ≈ 4.5 times that length. Equal-spacing configurations with two siderostats on all three arms or three siderostats on two arms are included in the design, with tracking baseline lengths from ≈ 5 m to ≈ 260 m.

Despite the design, equal-spacing bootstrapping with more than three array elements has not yet been implemented at the NPOI. One reason has been that an equal-spacing configuration has not been brought into use. Until the past year, we had brought into operation only two of the imaging-array stations, providing baselines ranging from 16 m to 79 m when used with the four astrometric array elements. A second reason has been the ancient 1990s-era firmware that provides delay-tracking information to the delay lines. Using the flux in the combined beams, that firmware calculates fringe positions only on baselines that include a common reference element, but is not fast enough to calculate corrections for a chain of baselines within the atmospheric coherence time.

Both of those limitations are being eased. Within the past year, two stations have been brought into operation (E07 and W04; see Fig. 1), stations E03 and N03 have been prepared for operation, and preparations at stations N06 and N07 have been nearly finished. (In addition, two more stations, E10 and W10, have been prepared; using them will require supplemental delay lines that are in place, but not yet integrated into the array.) The impact of these additional stations for stellar surface imaging is described by Jorgensen elsewhere in these proceedings.[5]

The back end of the NPOI is also being improved. The current beam combiner (we will refer to it as the "hybrid" combiner) takes the six input beams and produces three output beams, each with light from four of the six inputs, and disperses each of them into 32 spectral channels covering the 450 nm to 850 nm band, using avalanche photodiodes in photon-counting mode as detectors. The electronics constraints limit us to using only one third of these channels; we usually choose to use 16 channels from each of two output beams. One of us (A. J.) is implementing a replacement for the data acquisition electronics based on field-programmable gate arrays (FPGAs) that will use all 32 channels on all three output beams, also described in these proceedings.[6] The FPGAs are installed in a computer that can calculate the delay corrections for bootstrapped baselines.

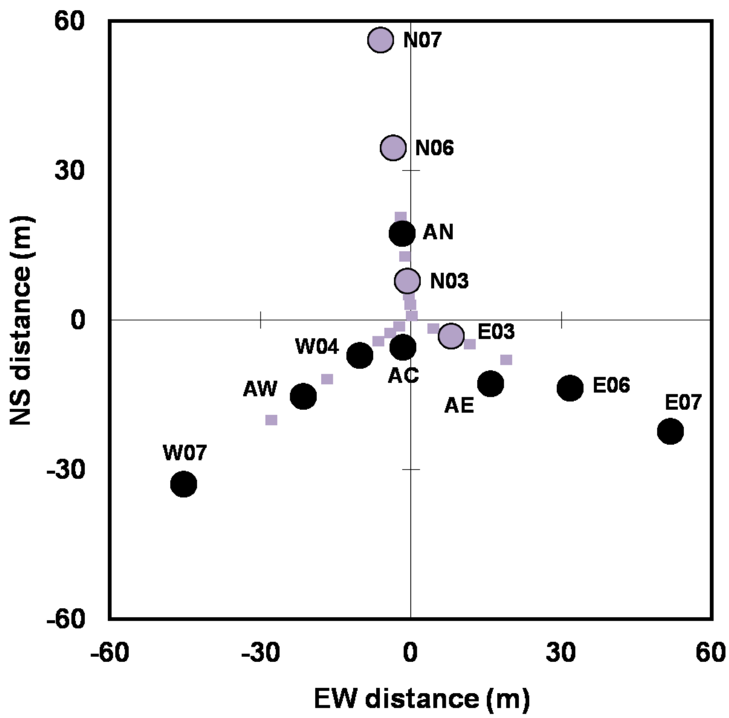

Figure 1. Available stations after current upgrades. Filled black circles indicate the stations available as of mid-2013 plus those stations that have been brought into operation recently (E07, W04). Filled gray circles indicate stations that are currently being added. The small gray squares are station locations not yet in use. Stations E10 and W10 are also nearing operational status, but at 250 m from the center of the array are beyond the borders of the figure.

In addition to the improvements to the hybrid combiner, another of us (M. M.) has developed and installed a six-input beam combiner, the Visible Imaging System for Interferometric Observations at NPOI (VISION)[7] that is very similar to the MIRC[8] combiner at the CHARA array. VISION spatially filters the incoming beams with single-mode fibers. The fibers are laid side by side with nonredundant spacing, producing 15 distinct fringe patterns across the image on the detector. The image is spectrally dispersed vertically.

3. SOME PRELIMINARY RESULTS

Both the hybrid combiner with updated electronics and the VISION combiner have the capacity for baseline bootstrapping with a chain of baselines, and both combiners are in the process of being commissioned as of May 2014. An example of a fringe power spectrum in preliminary data from VISION is shown in Fig. 2.

Meanwhile, we are using observations with the hybrid combiner to assess the impact of bootstrapping on the fringe phase signal-to-noise ratio. We used baselines E6–AE (16 m) and AE–AW (38 m; see Fig. 1) to track fringes and to bootstrap the 53 m E6–AW baseline. The target was Spica, a B star with $m_V = 0.97$, a companion about 2^{m} fainter in a 1.54 mas orbit, and an angular diameter = 0.9 mas for the primary.[9] Since $B/\lambda \approx 2.5$ mas for the E6–AW baseline, $V^2 > 0.75$, making Spica a good candidate for demonstrating bootstrapping.

Figure 3 shows the results of that investigation, plotting M, the number of frames needed to reach 0.3 radians of phase noise, against the fringe amplitude signal-to-noise ratio, $NV^2/2$. The tracking baselines (open circles) when used alone approach the photon-noise limit indicated by the full line. The open squares are the data for fringes on the longest, bootstrapped baseline. They lie further from the photon-noise limit because the fringe sampling frequencies used in these observations, $k = 1, 2$, and 3 fringe cycles per delay line modulation stroke, resulted in crosstalk between the fringe measurements.

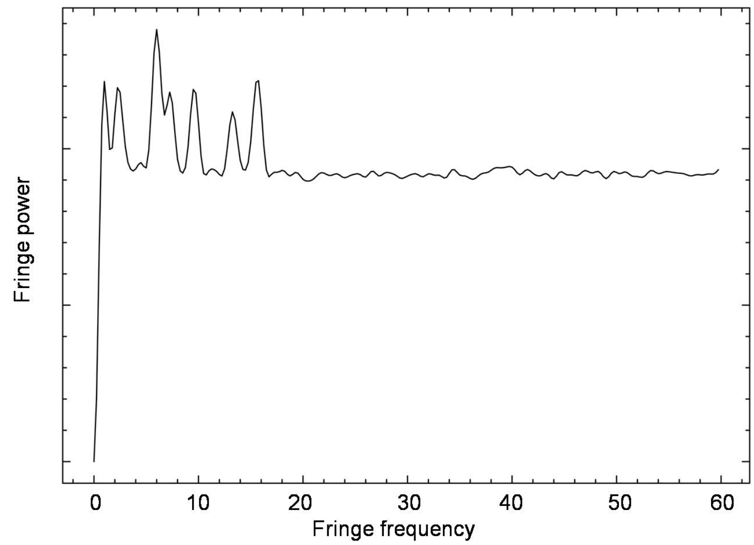

Figure 2. Fringe power spectrum in VISION data from four-element observations of an unresolved star. Units on the axes are arbitrary. The peak at fringe frequency = 1 is an artifact from the removal of the zero-frequency (total flux) signal. Six simultaneous fringe signals are seen.

Using the same observing setup, we turned on a faint light source on the beam combiner table to contribute uncorrelated light to the detectors, thereby diluting the fringes. The filled squares are the data from the bootstrapped baseline with varying amounts of fringe dilution. The dashed line shows the fit to the diluted data. The fit lies a factor of ≈ 8 above the photon-noise limit, due to crosstalk. However, the slopes of the two lines are the same, suggesting that the bootstrapping process does not introduce any additional sources of noise as the fringes become weaker.

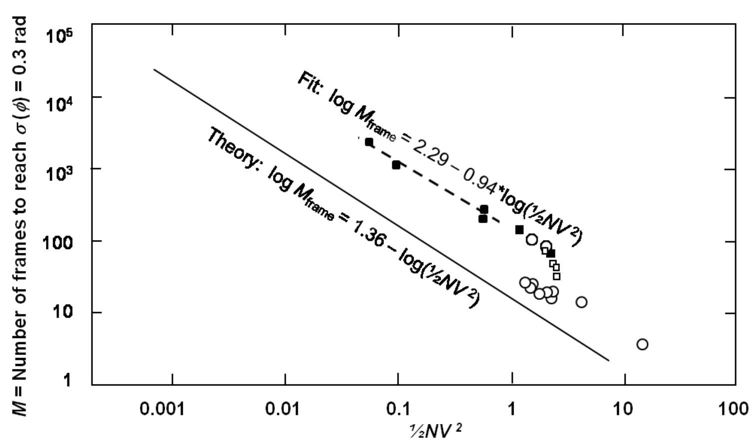

Figure 3. Phase signal-to-noise behavior vs. NV^2 in observations of Spica in the bootstrapped configuration described in the text. The ordinate is M, the number of 2 ms data frames needed to attain a phase noise $\sigma = 0.3$ radians. The open circles are data from the tracking baselines (15 m and 38 m). The open squares are data from the long (53 m) baseline without dilution by incoherent light introduced into the beam combiner. The filled squares are data from the 53 m baseline, but with varying amounts of incoherent light introduced in order to artifically reduce the fringe signal-to-noise ratio. The full line is the theoretical trend of M vs. $NV^2/2$ when only photon noise is present, and the dashed segment is a fit to the diluted-fringe data.

4. CONCLUSION

While we have not yet put multi-baseline bootstrapping into operation as of this writing, we have finished the preparation of two beam combiners to implement this technique. Both the fringe signal-to-noise ratio on the VISION combiner and the behavior of artificially diluted bootstrapped fringes on the augmented hybrid combiner suggest that bootstrapping more than two baselines together will not introduce additional sources of noise.

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