

Simulated Multi-beam Observations of Be stars in the H-alpha Line using the Navy Prototype Optical Interferometer.

by

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ABSTRACT

The Navy Prototype Optical Interferometer has recently been equipped with specially-designed filters that pass H α emission in a 2.5 nm band, suppress the continuum 50 nm to either side, and pass the continuum further from the H α line. These filters allow fringe tracking on continuum light while taking data at H α . Five- and six-aperture NPOI configurations have also been implemented recently. The improvement in U-V coverage with these configurations promises greater image fidelity in multi-spectral imaging as well as in specific lines, such as the very interesting H α line. Using an array simulator operating in the AIPS++ environment, we simulate observations of H α emission, assuming approximate source structure taken from earlier work in the literature. These simulations demonstrate the increased imaging capability of multi-aperture arrays and help define optimum H α observation strategies.

Key Words: Optical Interferometry, Be Stars, H-alpha, NPOI, Simulated observations

1. Introduction

The Navy Prototype Optical Interferometer (NPOI), located near Flagstaff, Arizona, is a reconfigurable array that, when complete, will provide observations at visual wavelengths using six array elements simultaneously, with baselines up to 437 meters long. [1] A recent photo of the NPOI is shown in Figure 1. The NPOI is collaboration between the Naval Research Laboratory and the US Naval Observatory, in cooperation with the Lowell Observatory.

The current status of the instrument, including the recent advent of six-siderostat observations, is described in these proceedings by Benson, et. al. [2] At this time, six siderostats are available: the four astrometric siderostats, plus stations E02 and W07. The longest baseline is 67 m. Up to eleven baselines can be formed by the six siderostats. This will increase to fifteen baselines when the installation of the fringe-tracking electronics is complete. At this point, with five siderostats, we get eight baselines, with four, we get five baselines, and with three siderostats, we get three baselines. Sixteen spectral channels can be observed, with some flexibility in distributing them within the 850 - 500 nm range.

The study of Be stars has been of interest for many years. Two topics of particular interest are the spatial extent and temporal variability of the H α emission. In the last decade, this emission has been observed with the Mark III and GI2T interferometers [3-5] and with the NPOI in its initial three-siderostat configuration.

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With the advent of six-beam observations with the NPOI, improved U-V plane coverage and imaging fidelity are within reach. The addition of specialized narrow-band filters has made it possible to isolate the H α line from the nearby stellar continuum, improving the imaging performance.[6] Here we report on simulations of multi-beam NPOI observations of these sources using these specialized filters.

2. H α Observing at the NPOI

With the recent advent of multi-beam observations at the NPOI, we have conducted some test observations of Be stars and other H α emitting stars. The increased U-V coverage afforded by the enlarged array has yielded preliminary indications of improved imaging capability.

In order to improve the H α imaging capability, we had special filters designed and fabricated.[7] These filters were designed to pass a band as narrow as possible around both sides of the H α line (656.3 nm), reject both the nearby stellar continuum and scattered HeNe laser metrology light (632 nm), and pass stellar continuum light further out from the H α line. This arrangement allows us to isolate the H α line from the stellar continuum that would enter in the same spectral channel, but pass the continuum further from the line to enable fringe tracking.

After several design iterations, filters were made with a bandpass of 2 nm (FWHM) and transmission of 90% at H α , zero transmission beyond 2 nm but within 50 nm of H α , and roughly 80% transmission for channels further than 50 nm from the line. The center wavelength can be tuned by ± 3 nm by tilting the filter. The filters have a flatness of $\lambda/4$ and are anti-reflection coated on both sides for the 450 - 850 nm region. The transmission per NPOI backend channel is shown in Figure 3a.

The filters were placed on the beam combiner table at the NPOI in each of the three output beams of the beam combiner, after the dispersing prisms and immediately in front of the lenslet arrays. These lenslet arrays feed optical fibers that convey the light to the avalanche photodiode detectors. In order to center the H α line on its lenslet, the lenslet array in each output beam was shifted slightly from its usual position, with corresponding adjustments in the fringe detection software with some recabling. Placement in the backend optics is shown in Figure 3b. The avalanche photodiodes that are ordinarily connected to the channels blocked by the filters were recabled to receive light from other regions of the spectrum.

We have carried out a number of observations using up to six siderostats (up to eleven baselines) in 16 spectral channels, both with and without the H α filters. The array configurations used are shown in Figure 4. During the night, the observer could quickly reconfigure the array to use from three to six siderostats, depending on the declination and hour angle of the source, the quality of the seeing, and the signal-to-noise ratio. A number of Be sources with their calibrators were observed. These included the Be star κ Draconis and the close binary β Lyrae, which also shows H α emission. Initial results from these data motivated a campaign to simulate how a given NPOI configuration and observation campaign might affect recovered image quality.

3. Simulations

In order to evaluate the effects of the current U-V coverage, and to plan future observations with a more-complete NPOI, we have carried out a program of image recovery simulations. For the latter simulations, we assumed that the full complement of 15 baselines was available. We created an image consisting of a compact (1 mas) source plus extended emission, as shown in Figure 5. We selected certain array configurations, simulated observations in the H α line with a 2 nm bandwidth, generated and CLEANed the observed image, and finally model-fit that restored image for comparison with the input source. Each simulated data set consisted of observations taken within three hours of transit, at half hour intervals, with 5% Gaussian noise added. The simulations and reduction were done in AIPS++.

We compared the results from six different array configurations: the current array; a "Y" using stations 2 and 4 on each arm ("Y1"); a "Y" using stations 4 and 6 ("Y2"); an "L" using stations 2, 4, and 5 on the north and west arms ("L1"); an "L" using stations 4, 6, and 7 on the north and west arms ("L2"); and a concatenation of the Y1

and Y2 data sets. Figure 6 is a diagram of the inner part of the array, with arrows marking the stations used in the concatenation array configuration, while Figure 7 is a schematic diagram of the current configuration.

4. Results

For each simulation, we produced a point spread function (PSF), a plot of visibility amplitude as a function of U-V distance, a diagram of the U-V coverage, and a CLEANed image. Note that these are restored images and not fits of the source structure to the visibility data. The first study was of how an H α emission might be imaged using the current array with all spectrographs and electronics active. Station coordinates and baseline lengths are shown in Figure 7. Baselines span 7.2 meters through 66.4 meters for this simulation.

The results for the current array configuration are shown in Figure 8. The CLEANed image shows that image recovery is not bad, in that the point source and the extended emission are clearly evident. By far the most successful image recovery came from the concatenation of Y1 and Y2 data (see Figure 9). The concatenation is nearly equivalent to observing with a nine-element array, although only 27 distinct baselines are present in the two data sets. (Simultaneous observations with nine array elements would produce 36 baselines.)

The images were then model-fit, using a two-component Gaussian fit. We deconvolved the width of the PSF from the widths of the model components to obtain an estimate of the source size:

$$\theta_{\text{source}}^2 = \theta_{\text{obs}}^2 - \theta_{\text{PSF}}^2$$

The results are collected in Table 1, which shows that the image from the Y1 + Y2 concatenation produced the closest match to both the extended emission and the compact component. This match is also supported by Figure 10, which compares the "truth" image to the CLEANed image from the Y1 + Y2 concatenation. In the restored image, both the point source and the extended emission are clearly evident.

This result demonstrates that, for a source that remains relatively stable between array configurations, the equivalent of a many-station array can be obtained by concatenating data from two configurations of a smaller array. There are two main requirements: (1) the array must be reconfigurable faster than variations in source structure, and (2) there must be enough fringe contrast in data from the larger configuration to allow fringe tracking

Table I. Model Fits Compared

Array	Point Source						Extended Object				
	Beam; PA mas; deg	Pk Flux Jy	Maj mas	Min mas	PA deg	Ratio maj/min	Pk Flux Jy	Maj mas	Min mas	PA deg	Ratio maj/min
"Truth"	-----	60.00	1.00	1.00	0	1.00	40.00	10.00	4.00	30	2.50
Y1	4.5 x 4.4; 95										
Image(obs)		46.30	4.70	4.30	111	1.10	20.70	7.20	4.70	29	1.53
Source			0.60	0.60		1.00		5.70	1.50	29.2	3.75
Y2	1.68 x 1.63; 111										
Image(obs)		60.00	1.67	1.63	66	1.02	<i>(Resolved Out)</i>				
Source			0.94	0.94	0	1.00					
Y1+Y2	2.09 x 2.04; 104										
Image(obs)		59.00	2.30	2.20	0	1.05	26.24	8.10	3.75	29	2.16
Source			0.94	0.94	0	1.00		7.80	3.20	29	2.44
Current	2.8 x 1.4; -35										
Image(obs)		45.70	2.90	1.70	35	1.71	2.10	6.30	3.70	24	1.70
Source											

5. Conclusions

We have presented details of the H α configuration at the NPOI, including a description of the specially-constructed filters used to isolate the line. We have also described a program of simulated observations undertaken in order to ascertain whether our results are realistic and not due to systematic errors. In addition, the simulations assist in planning future observations. Using the AIPS++ environment, we devised a two-component source and simulated H α observations with various NPOI array configurations. The simulated arrays included the current configuration as well as five more-regular arrays that will be available when the NPOI is complete. We then produced simulated images from the data and compared them to the input image.

There are two points to note about the results of these simulations. The first is that we produced true images rather than model fits to the visibility data. The second is that the concatenation of data from two configurations can produce an image that is comparable to one from a single configuration of an array with more elements.

6. Future Work:

A substantial set of H α and continuum data exists from the spring, 2002 campaign, which we will continue to reduce. We will also use the simulator to help in planning an in-depth fall campaign.

REFERENCES

1. J. T. Armstrong, D. Mozurkewich, L. J. Rickard, D. J. Hutter, J. A. Benson, P. F. Bowers, N. M. Elias II, C. A. Hummel, K. J. Johnston, D. F. Buscher, J. H. Clark III, L. Ha, L.-C. Ling, N. M. White, and R. S. Simon, "The Navy Prototype Optical Interferometer," *Astroph. J.* **496**, 550-571 (1998).
2. J. A. Benson, C. A. Hummel, and D. Mozurkewich, "Simultaneous 6-station observations with the NPOI," *Proc. SPIE* **4838-94**, in press (2002).
3. A. Quirrenbach, K. S. Bjorkman, J. E. Bjorkman, C. A. Hummel, D. F. Buscher, J. T. Armstrong, D. Mozurkewich, N. M. Elias II, B. L. Babler, "Constraints on the Geometry of Circumstellar Envelopes: Optical Interferometric and Spectropolarimetric Observations of Seven Be Stars", *Astroph. J.* **479**, 477-496 (1997).
4. P. Harmanec, F. Morand, D. Bonneau, Y. Jiang, S. Yang, E. F. Guinan, D. S. Hall, D. Mourard, P. Hadrava, H. Bozic, C. Sterken, I. Tallon-Bosc, G. A. H. Walker, G. P. McCook, F. Vakili, Ph. Stee, J. M. LeContel, "Jet-like structures in beta Lyrae," *Astron. Astroph.* **312**, 879-896 (1996).
5. F. Vakili, D. Mourard, Ph. Stee, D. Bonneau, P. Berio, O. Chesneau, N. Thureau, F. Morand, A. Labeyrie, I. Tallon-Bosc, "Evidence for one-armed oscillations in the equatorial disk of zeta Tau," *Astron. Astroph.* **335**, 261-265 (1998).
6. T. A. Pauls, G. C. Gilbreath, J. T. Armstrong, D. Mozurkewich, R. B. Hindsley and J. A. Benson, "Observations of H \square in Be stars with the Navy Prototype Optical Interferometer", *Bull. Am. Astron. Soc.* **198**, 51.16 (2001).
7. Custom filters created by David E. Upton of Omega Optical, Brattleboro, VT 05301.
8. T. Cornwell, R. Braun, and D. S. Briggs, "Deconvolution," in *Synthesis Imaging in Radio Astronomy II*, G. B. Taylor, C. L. Carilli, and R. A. Perley, eds., Astron. Soc. Pac. Conf. Ser. **180**, 151-170 (1999).



Figure 1. Photograph of the Navy Prototype Optical Interferometer near Flagstaff, Arizona. Six siderostats were recently brought on line to enable up to 15 beam combinations using 16 to 32 spectral channels.

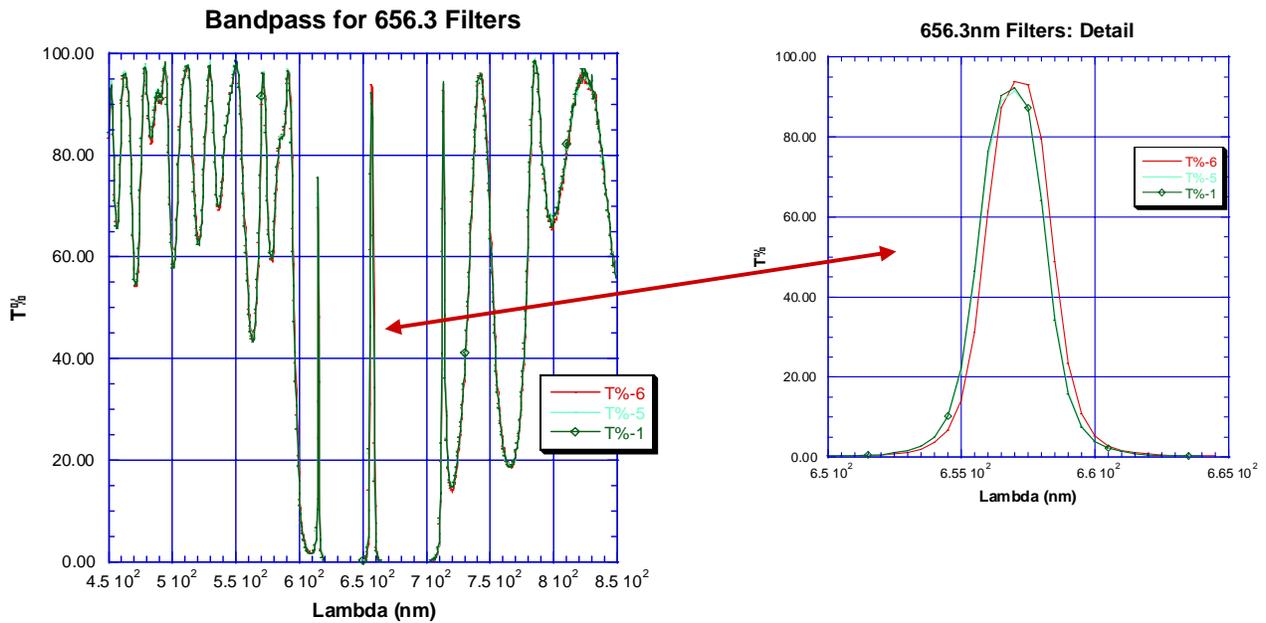


Figure 2. Spectral characteristics of custom filters designed to pass $H\alpha$ (656.3 nm), suppress the light in the adjacent channels and that from the NPOI metrology beam of 632 nm, and let pass as much light as possible in the adjacent bands to enable simultaneous fringe tracking.

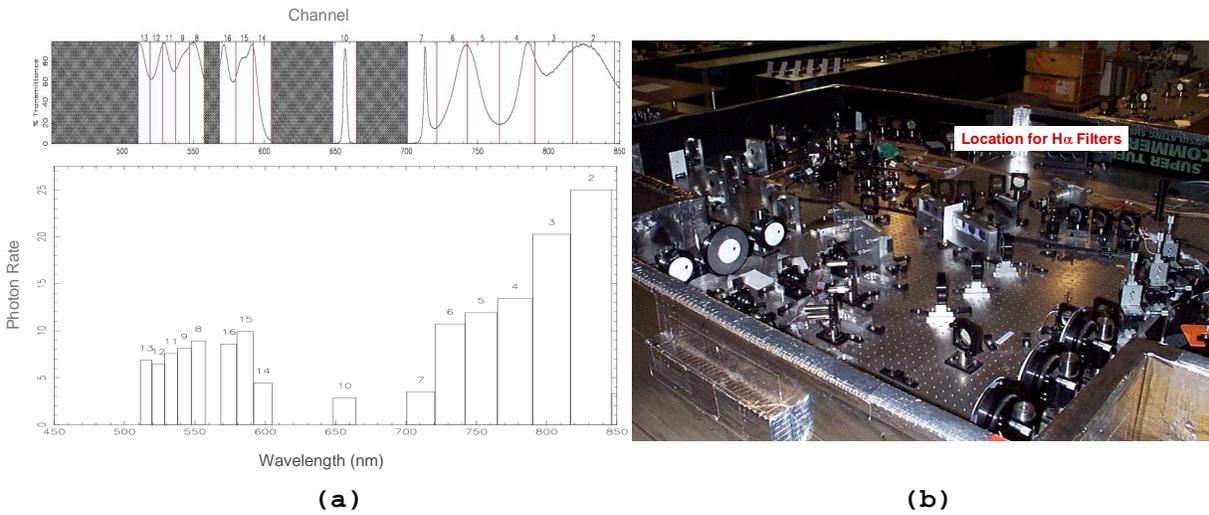


Figure 3. Custom filters and their placement: (a) Channel assignments and filter throughput with measured photon rate; (b) Location of filters on the beam combining table.

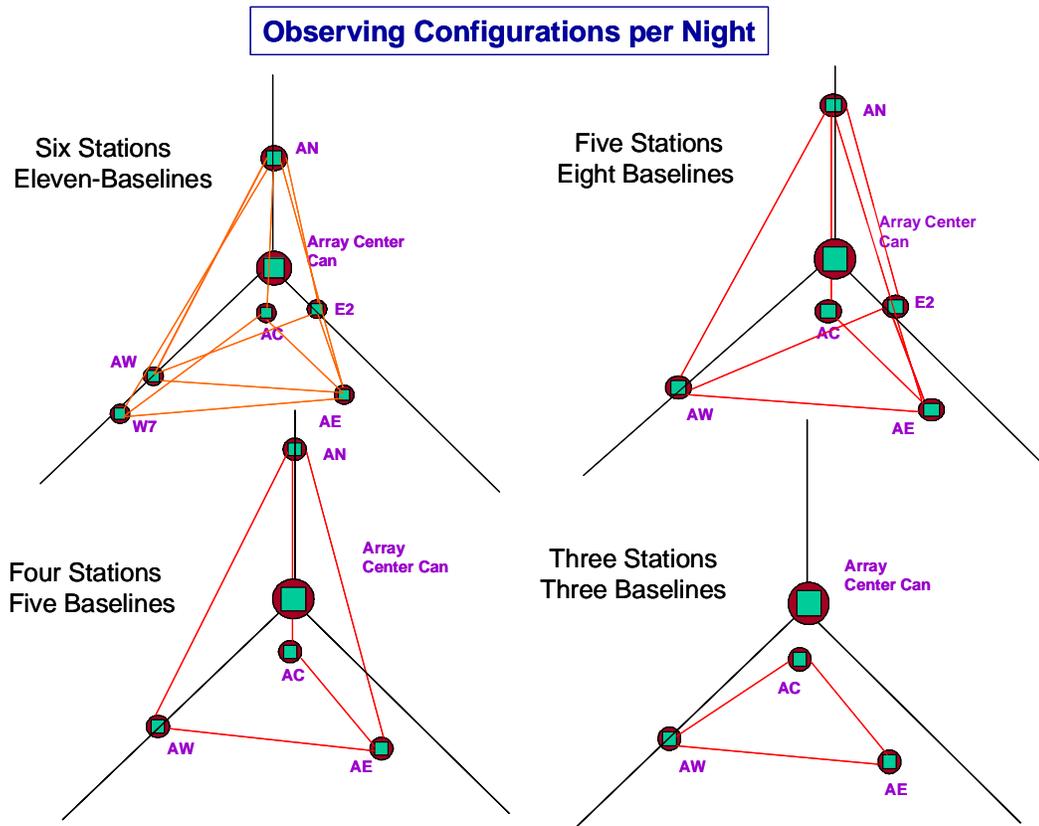


Figure 4. Observing configurations for Be H-alpha campaigns used in a given night with present capabilities at NPOI. Station positions are not to scale.

The Source Model:
Point Source: 1 mas; 60 Jy
Extended Object: Elliptical:
 10 mas x 4 mas; 40 Jy
Position Angle: 30 degrees

Array Configurations:
Current: AN AC AW W7 E2 AE
Y1: E2 E4 W2 W4 N2 N4
Y2: E4 E6 W4 W6 N4 N6
L1: N2 N4 N5 W2 W4 W5
L2: N4 N6 N7 W4 W6 W7
Y1+Y2: Concatenated

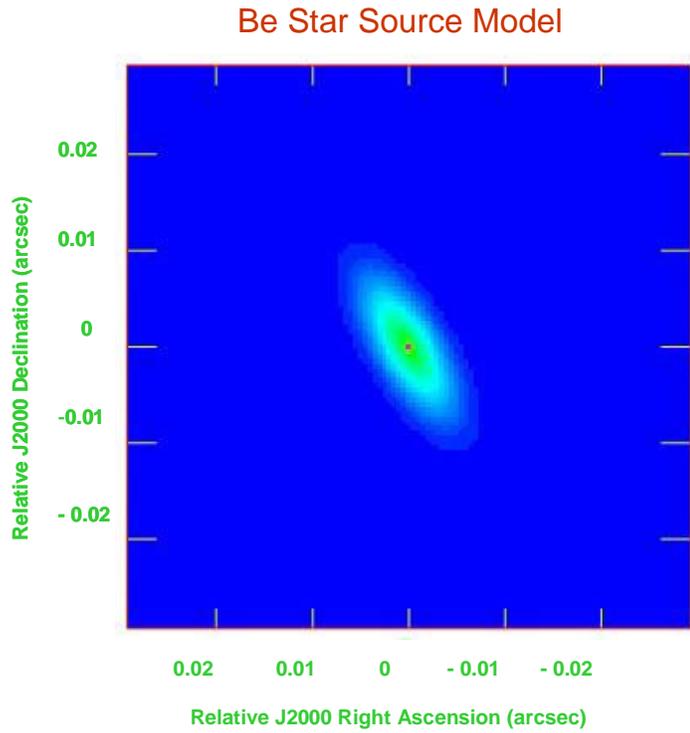


Figure 5. Source Model used for array simulations. Array configurations are also listed.

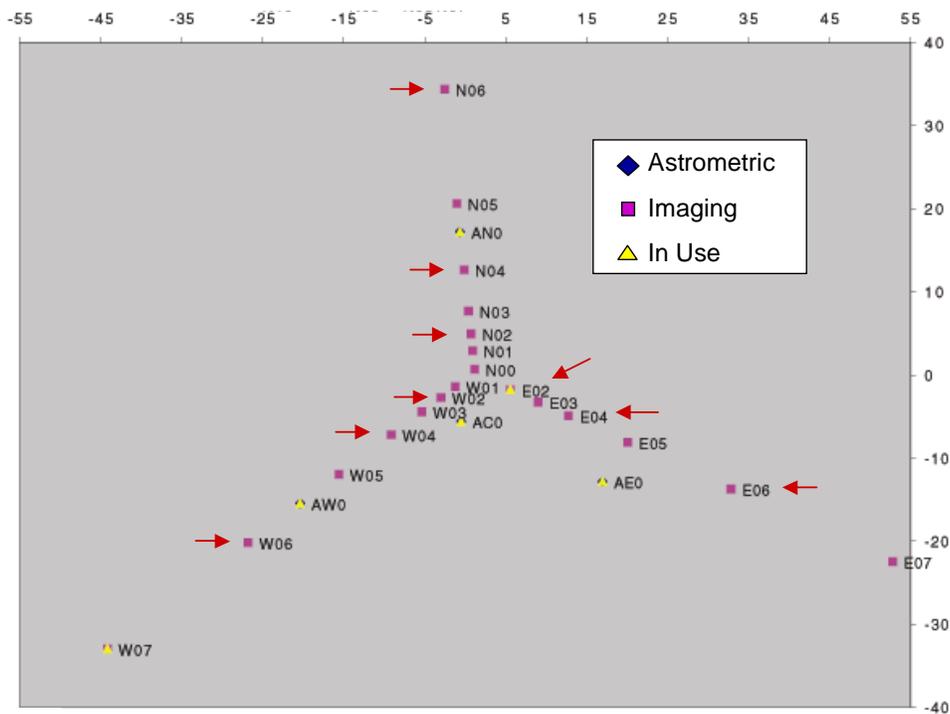


Figure 6. NPOI siderostat locations considered in the Y1 + Y2 concatenation simulation.

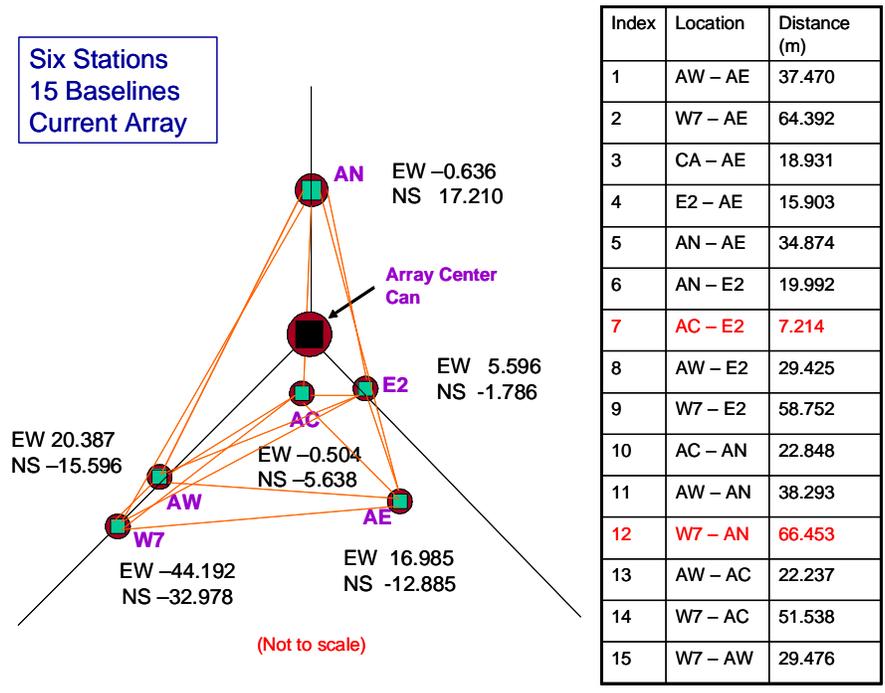
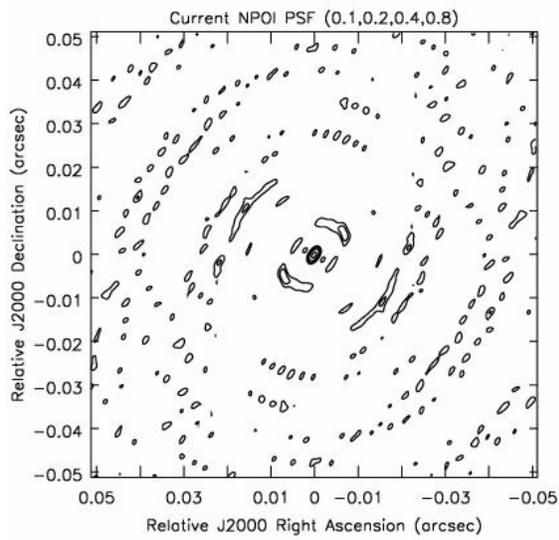
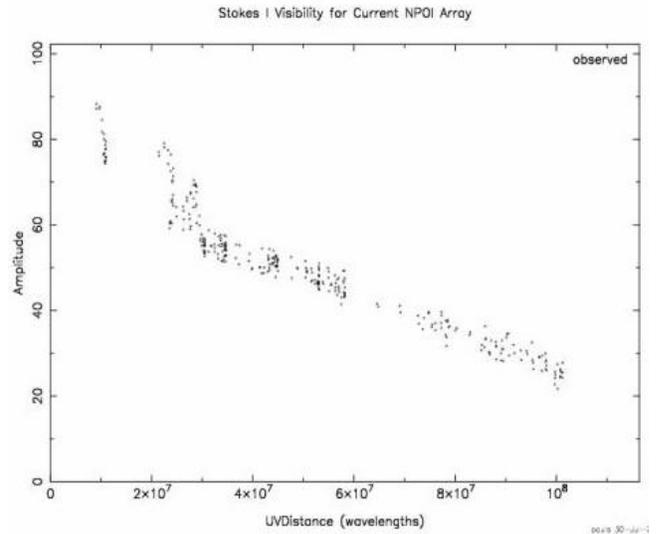


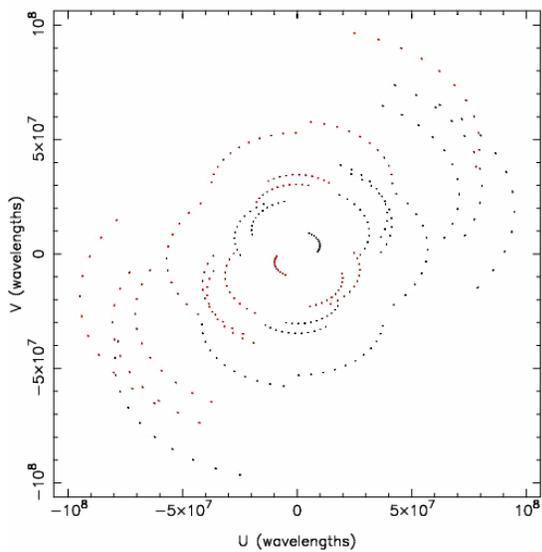
Figure 7. NPOI siderostat locations considered for the current array with all spectrographs operational. Baseline lengths are shown in adjacent table.



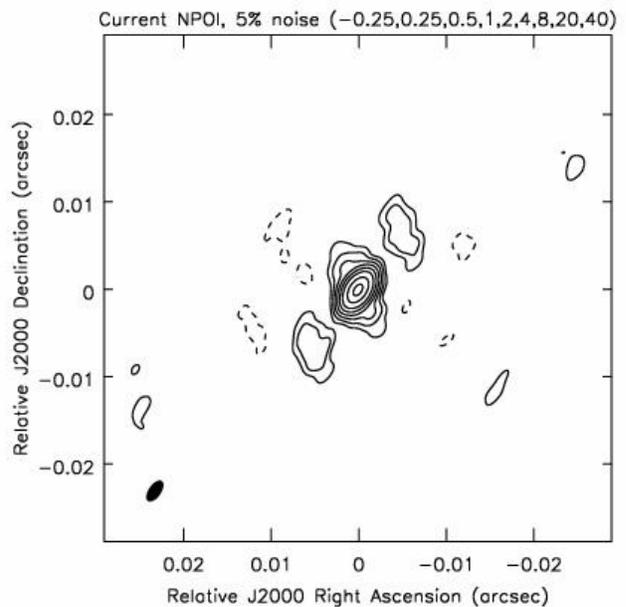
(a)



(b)

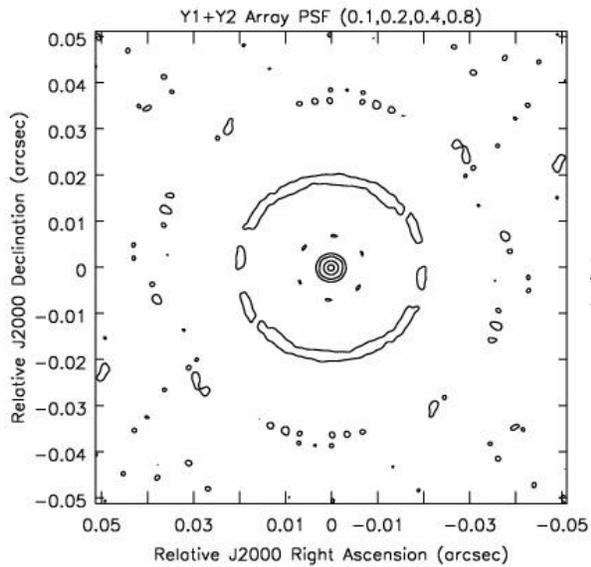


(c)

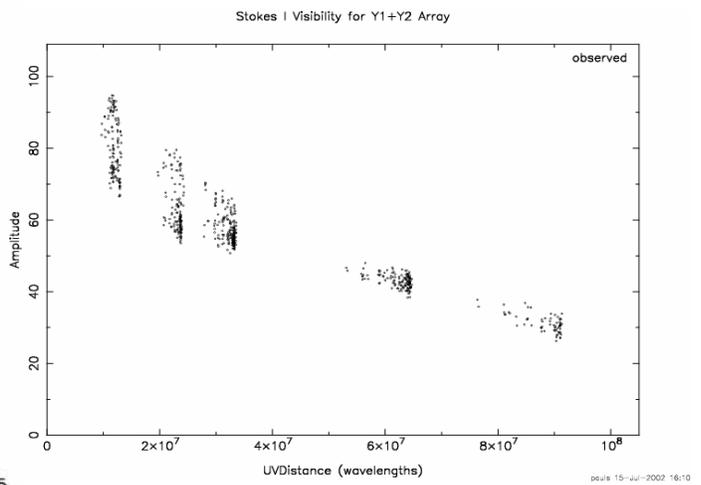


(d)

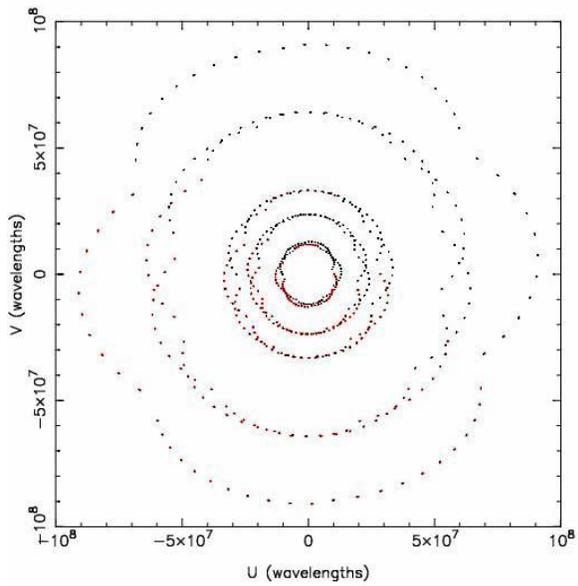
Figure 8. PSF, Visibilities, UV plot, and restored CLEANed image using the current array shown in Figure 8 for the H alpha line using the simulated source is shown above.



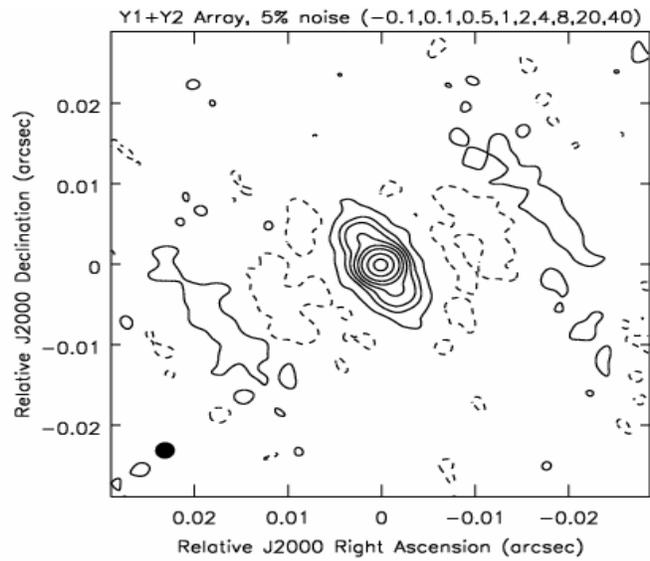
(a)



(b)

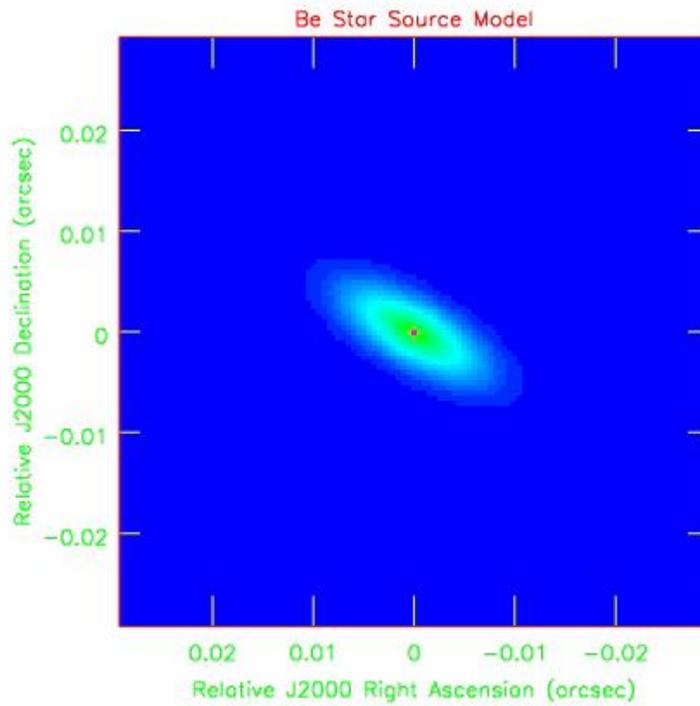


(c)

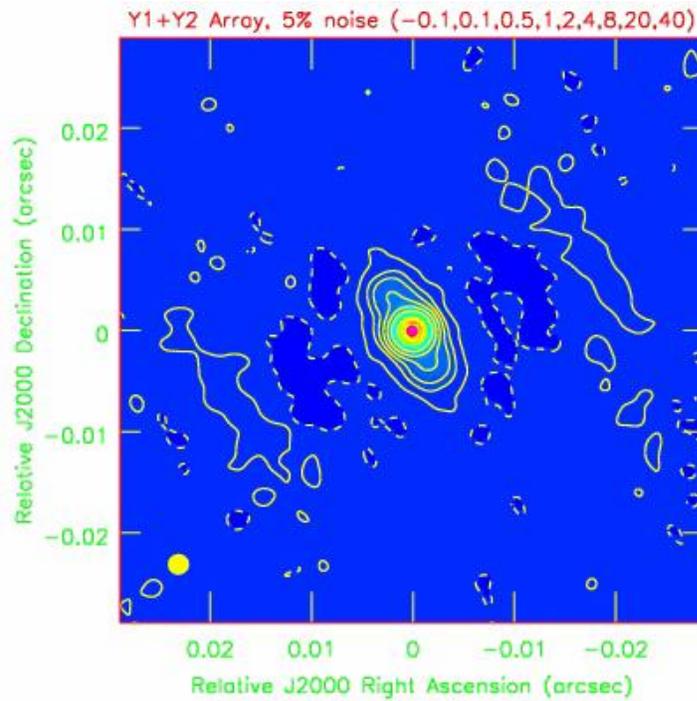


(d)

Figure 9. Simulation results for concatenation of Y1 and Y2. (a) PSF of combined beams; (b) Visibilities; (c) UV coverage, including conjugate points; (d) Restored CLEANed image with restoring beam in lower left corner.



(a)



(b)

Figure 10. Images compared. (a) Simulated "truth" image vs. (b) image of source using concatenated Y1 and Y2 arrays. This is best match of the compared candidates.