

# Towards the Detection of Faint Companions Around Geosats

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## ABSTRACT

The detection of faint companions in the vicinity of geostationary satellites, either debris or controlled spacecraft, is an outstanding issue in the field of Space Situational Awareness. The main challenges to the detection of faint companions are related to the proximity of the satellite to the companion, as well as their brightness ratio. We discuss a novel interferometric fringe nulling technique, being developed at the Navy Precision Optical Interferometer, based on observing interferometric phases around the null crossing, where the presence of a companion shows up as large phase fluctuations. We present the results of observations of the binary star  $\eta$  Aql, a system with brightness ratio 1:100, one of the systems that are being used to develop the technique.

## 1. INTRODUCTION

The detection and characterization of faint objects around geostationary satellites (geosats) is an important issue for Space Situational Awareness (SSA). Independent of the origin of these objects, whether they are debris or controlled spacecraft, they can pose a serious threat to these highly valued assets. Furthermore, in the event of a collision, such an event can potentially contaminate the geobelt environment. The challenge of detecting faint companions around geosats is due to two issues: proximity and brightness ratio. Considering the typical dimensions of geosats (5 x 20 m), a companion with a dimension of 1 x 1 m would have 0.01 times the flux (5 magnitudes fainter), while a cubesat, which has a dimension of 0.1 x 0.1 m, would have  $10^{-4}$  times the flux (10 magnitudes fainter).

Here we describe a fringe nulling technique being developed at the Navy Precision Optical Interferometer (NPOI). This technique uses both interferometric amplitudes and phases, with particular emphasis on the phases, which are highly sensitive to source structure, and consequently more sensitive to the detection of nearby faint companions. An advantage of this technique is the ability to detect objects separated by distances less than 1 arcsec. We demonstrate this technique using observations of the multiple stellar system  $\eta$  Aql, where we detect the presence of a faint companion with a brightness ratio of 1:100.

## 2. NEW TECHNIQUE

We are developing a phase nulling interferometry technique using observations of binary stellar systems with the NPOI [1]. The basics of the method were presented in [2] and are summarized here. In Fig. 1 we present a diagram that shows a binary system composed of a bright star (red) and a faint companion (blue). The figure also shows, as a black star, the photocenter of the system. When this system is observed with a short baseline, such that the brighter, larger system is not resolved, the photocenter of the system is located close to the center of the brighter star. When the system is observed with longer baselines, the brighter target is resolved and the photocenter of the system moves towards the fainter star in the system. This photocenter shift is seen as phase oscillations in the observed fringes.

In the middle panel of Fig.1 we show the fringe amplitudes for the case of a single star (red) and a binary star (blue) with a flux ratio of 1:100 ( $\Delta m=5$  mag). When comparing the fringe amplitudes of the binary with those from a single star, we see a series of oscillations superimposed on the fringe amplitudes envelope of the brighter star. The amplitude of these oscillations carry information about the brightness ratio of the two stars in the system, while the frequency of these oscillations carry the information about the separation of the two targets along the baseline used for the observations. We can see in this figure that the amplitudes of the binary oscillations are small ( $\sim 0.2\%$ ) and hard to detect. After taking under consideration noise and calibration effects, the detection limit for binary stars, is of the order of  $\Delta m \sim 3.5$  mag.

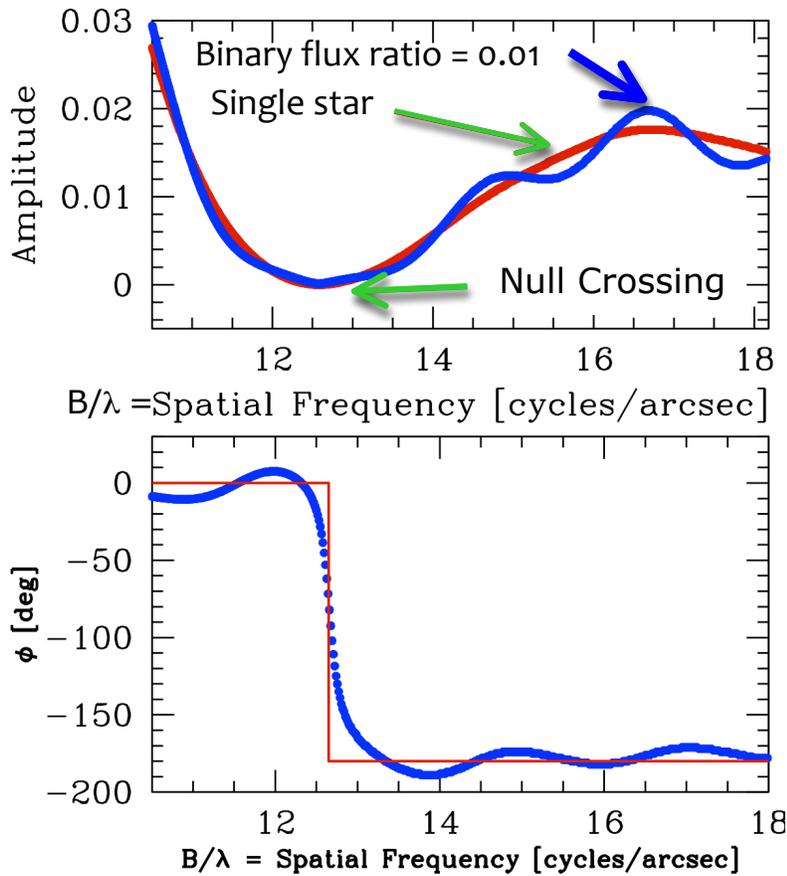
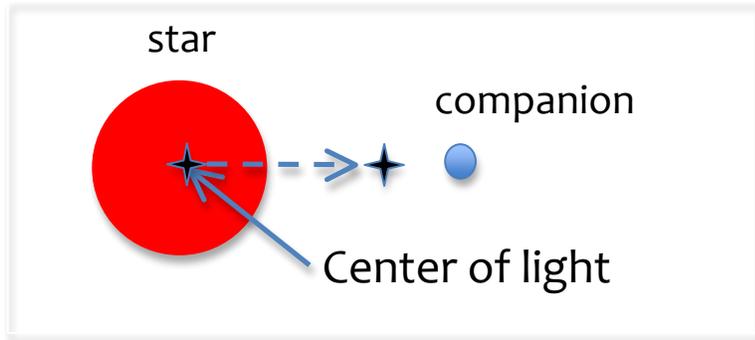


Fig. 1. The top panel shows how the position of the photocenter of the system changes when the brighter star of the system is observed with baselines of increasing length. We start with the scenario where the bright star is unresolved, observed with short baselines, so the photocenter of the system is close to the center of this star. As the system is observed with longer baselines, the brighter star is resolved and the photocenter of the system moves towards the fainter star. The middle panel shows the square of the fringe visibility amplitude as a function of spatial frequency for a single star (red) and for a binary system where the faint companion is 100 fainter than the brighter companion (blue),  $\Delta m=5$  mag. The bottom panel shows the baseline phases for the same systems presented in the middle panel.

The bottom panel of Fig. 1 shows the phases of a single star and those of a  $\Delta m=5$  mag binary observed around the null crossing. The phases were calculated using the expressions from [3]. We can see in this figure that the phases show strong oscillations around the null crossing, due to the movement of the center of light of the system from a position close to the center of the bright star to a position closer to the fainter star when observations are done near the null.

In the case of satellites, the phase signal introduced by a nearby companion can be determined using simulations. We used a set of simulation tools developed by our group [8] and show the results in Fig. 2. We can see in these figures that the presence of a companion also shows strong variations in the phases around the null crossing. In the case of satellites, which have a more complex structure than stars, we see phase fluctuations of  $2^\circ$  around the null crossing for a companion 1,000 fainter than the satellite (Fig. 2). In the case of companions with a flux ratio of 1% and 7% the phase oscillations increase to values in the range  $10^\circ$  to  $20^\circ$ . We are currently using these simulations to determine typical parameters for a future instrument dedicated to the observation of geosats.

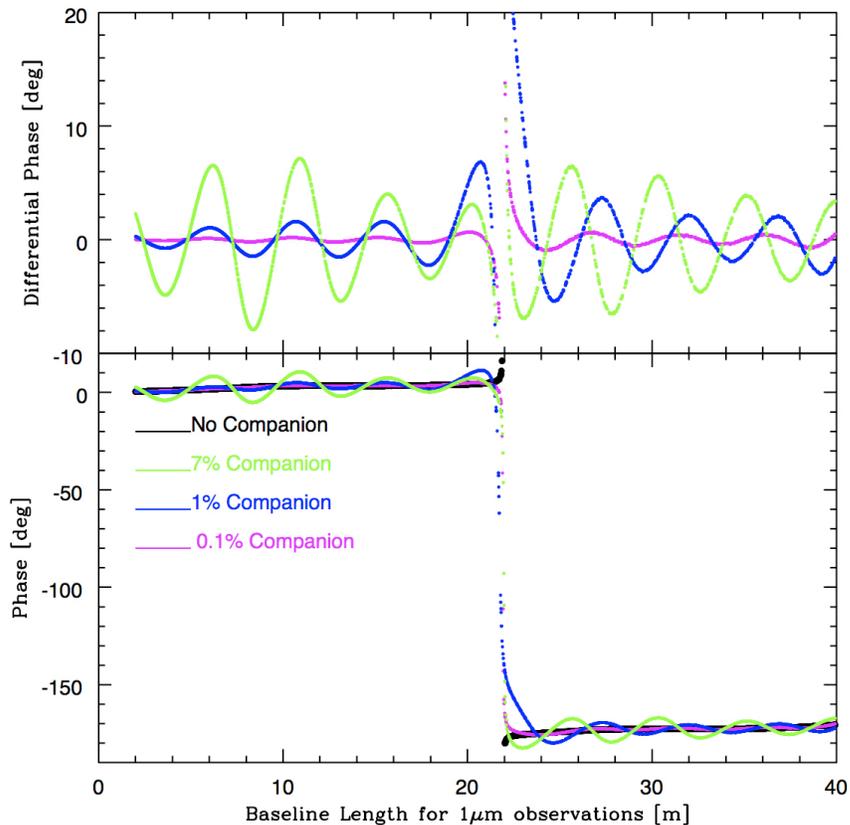


Fig. 2. The bottom panel shows the modelled fringe phase of a satellite with companions of different brightness ratios, as a function of effective baseline length. The top panel shows the phases of the models with companions after the subtraction of the phases from the model without a companion.

### 3. TECHNIQUE DEMONSTRATION

In order to demonstrate the fringe nulling technique, we are using observations of binary stars done with the NPOI. One of the systems being used to develop the fringe nulling technique is  $\eta$  Aql, a multiple stellar system. The main star in the system is a cepheid with a pulsation period of 7.17 days with a faint, relatively large separation (0.66 arcsec) secondary component[6], and a much closer tertiary component (separation of a few mas), with magnitude difference of  $\Delta m \sim 5$  mag. The tertiary component has never been observed directly, its presence was inferred based on reflex motion of the primary star, detected using the Fine Guidance Sensor at the Hubble Space Telescope [4].

Our NPOI observations were done on the night of 2005-06-29 using the stations E6, AC, AE and W7, allowing us to use baselines with a range of orientations and lengths, including E6-W7, which has a maximum length of 79 m. For

a star with a diameter of 1.8 mas, which corresponds to the diameter of  $\eta$ Aql (1.804 mas)[5], we should observe a null crossing at a wavelength of 560 nm when observing with this baseline. Observations were done with the NPOI Classic beam combiner, using the standard method of interspersing 30 s scans of the star with a nearby calibrator ( $\lambda$  Aql in our case). We used two spectrographs that simultaneously recorded fringes from three baselines each, dispersed in 16 channels in the wavelength range 560-860 nm. We used baseline bootstrapping to stabilize the fringes in the longest baseline E6-W7.

The data reductions followed the coherent integration procedures described by Schmitt et al. (2009) [7], with a few modifications. First the shorter bootstrapping baselines were used to measure the group delays for each 2 ms data frame. In order to eliminate a large number of outliers, which are due to SNR issues, we run a 9 point median filter over the group delays and use these median positions to measure the group delays again and force the new values to be within  $\sim 1.5\mu\text{m}$  of their corresponding median values. This procedure eliminates false peaks that arise due to low SNR. We use these group delays to rotate the 2 ms visibilities of the short, as well as the bootstrapped baselines, to a common central phase of the band, thus aligning them to a common reference. Following this step we can combine a large number of 2ms frames, to significantly increase the SNR of a scan and recover the baseline phase information. Given that the fringe nulling technique requires one to work in a challenging environment, where SNR is low, the coherent integrating of the scans is essential for the successful detection of faint companions. Another important step in the data processing is the subtraction of instrumental phases, due to mismatched amounts of glass along different beams. This is done using the average of all scans of all calibrator stars observed through the night. Assuming that the calibrators are unresolved and that their baseline phases are intrinsically zero, by averaging all scans one eliminates most of the differential atmospheric fluctuations and is left with the instrumental phases.

We present in Fig.3 the baseline phases of  $\eta$  Aql as a function of spatial frequency for the final coherently integrated scans, observed with the E6-W7 (79m) baseline. We note that we fitted and subtracted a quadratic phase component, as a function of wavelength, from these 3 scans, to eliminate a residual atmospheric contribution. These scans were obtained within  $\sim 2$  hours of each other, and, considering the orientation of the baseline and declination of the target, we mostly see a variation of the baseline projected length as a function of hour angle and very little change in the baseline angle ( $< 2^\circ$ ). The phase oscillations, as a function of UV distance, can be clearly seen in Fig.3. These oscillations are consistent with the presence of a binary component. The strongest evidence of a binary component comes from the phase structure around UV distances from 130 to 140  $M\lambda$ . In the case of a single star, one would expect to see a simple  $180^\circ$  jump between two channels, but not a gradual, small decrease in the phase from UV distances of 120 to 135  $M\lambda$ , followed by a fast phase increase from UV distances of 135 to 142  $M\lambda$ . We also show in Fig.3 a model corresponding to a binary system with  $\Delta m = 5$  mag and a separation of 18 mas. The primary component in this case has a diameter of 1.804 mas. This model is in good agreement with the observations, indicating that our technique can detect the presence of binaries with  $\Delta m = 5$  mag with the current NPOI system, and potentially even system with larger brightness ratios. We plan to repeat these observations with the Vision beam combiner [9], which has higher spectral resolution and will allow us to detect the phase oscillations due to the binary companion with a higher precision.

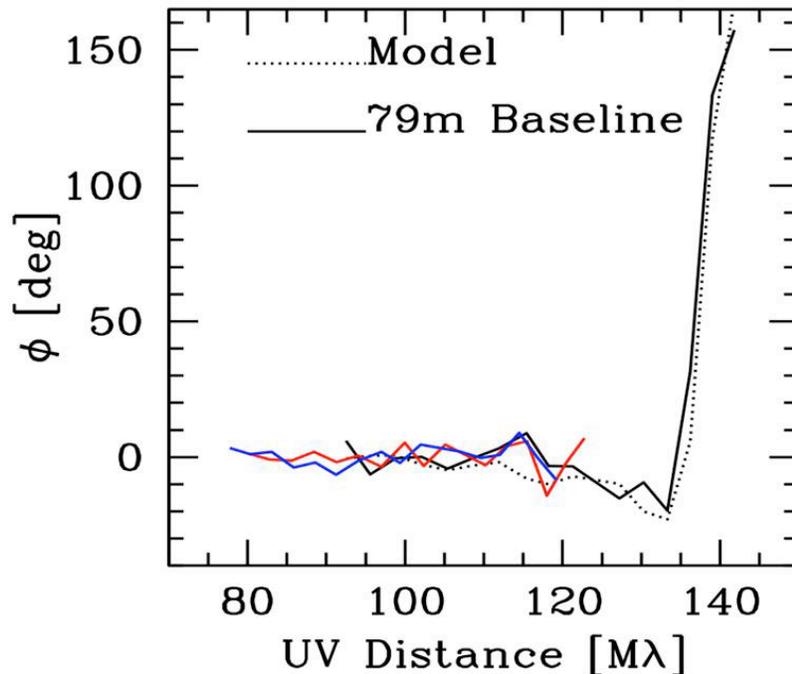


Fig. 3: Baseline phases as a function of UV distance (spatial frequency), after the subtraction of a residual atmospheric component (quadratic phase component as a function of wavelength). The red, blue and black solid lines correspond to 3 different scans, separated by  $\sim 2$  hour. The dotted line correspond to a model of a binary star with  $\Delta m \sim 5$  mag, separated by 18 mas, with a primary star diameter of 1.804 mas.

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