Detection of Faint Companions in the Vicinity of Geostationary Satellites

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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 related to the detection of these companion objects are their proximity to the target of interest and brightness ratio. We will discuss a novel interferometric fringe nulling technique being developed at the Navy Precision Optical Interferometer. This technique uses baseline phase observations of the target around the null crossing, where the presence of a companion shows up as large phase fluctuations. We discuss simulations of observations of satellites with companions, being used to determine the limitations of the technique and as a guide for the development of future instruments.

1. INTRODUCTION

Two areas of research that can strongly benefit from techniques capable of detecting faint companions around bright targets, with brightness ratios much larger than 1:10, are Space Situational Awareness (SSA) and astrophysics. Even though the targets of interest of these two fields have significantly different properties, SSA can take advantage of techniques developed and tested for astrophysical purposes and adapt them for its specific needs.

In the case of SSA, the detection and characterization of faint objects around geosats is an important safety issue. Whether these objects are debris or controlled spacecraft, they can pose a threat to satellites in these orbits and, in the event of a collision, they can potentially contaminate the geobelt environment. The challenge of detecting faint companions around geosats comes from the high brightness ratio, a problem similar to the detection of planets and other faint companions around stars. 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).

The development of Adaptive Optics significantly improved the ability to detect faint, close companions. However, these observations are still resolution limited by the size of the telescope used. Nulling interferometry has also seen some progress in recent years. It can detect companions 1000 times fainter than the main target, but it relies on fairly symmetric targets, which does not apply to the SSA case. One major limitation of this technique is sensitivity, which is related to the fact that these instruments use only amplitude information. Since phases carry important information about the structure and position of the companion targets, discarding the phases wastes valuable data.

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.

2. NEW TECHNIQUE

We are developing a phase nulling interferometry technique using observations of binary stellar systems with the NPOI. Observations of these systems are done with baselines that allow us to probe the brightest component of the system around the null crossing, giving special emphasis to interferometric phases. In the top panel of 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. In the situation where the system is observed with a baseline short enough so that the brighter, larger system is not resolved, the photocenter of the system is located

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close to the center of the brighter star. However, as 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.

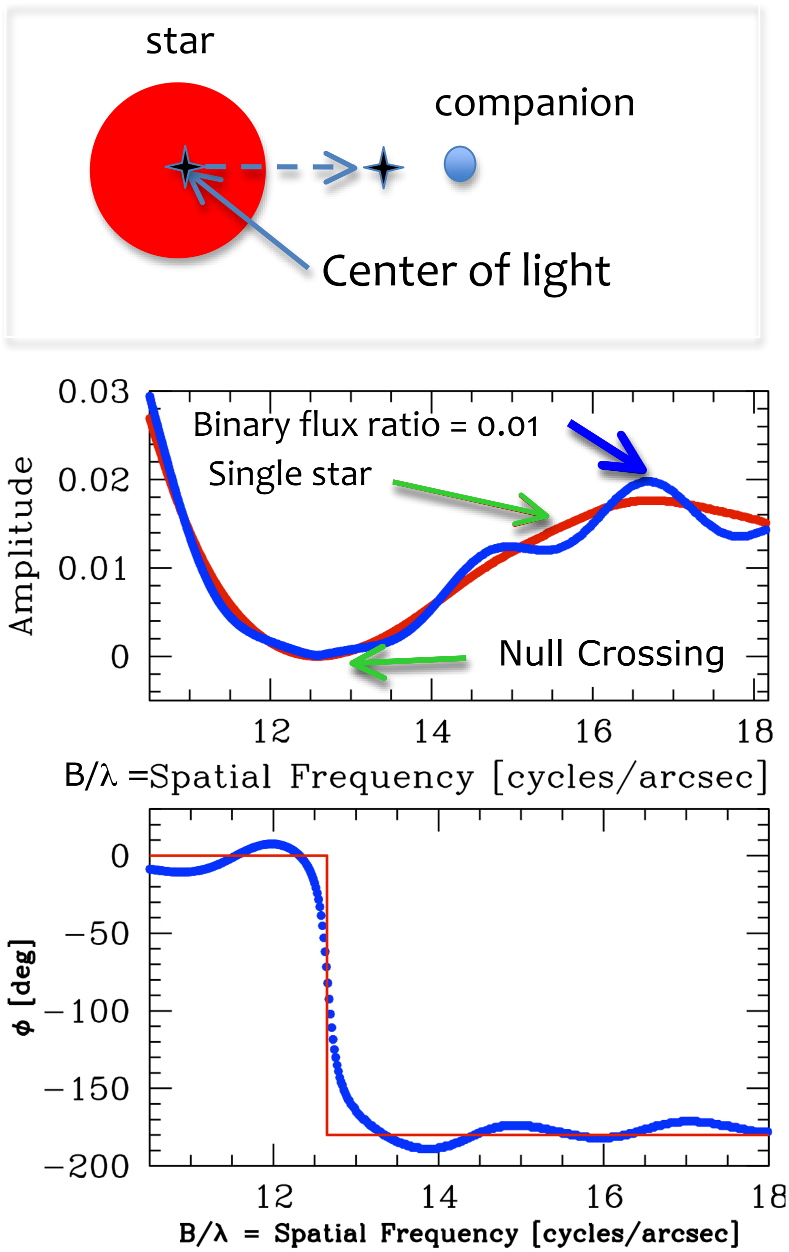

Fig. 1. The top panel shows how the position of the photocenter of the system changes when the brighter star of the system is observed with baselines of increasing length. We start with the scenario where the bright star is unresolved, observed with short baselines, so the photocenter of the system is 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.

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The advantage of using phases instead of only amplitudes to determine the presence of a nearby companion is shown in the middle and bottom panels of Fig. 1. The middle panel shows the amplitudes of a single star and a binary system with a flux ratio of 1:100 (Δm=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 and hard to detect. After taking under consideration noise and calibration effects, the detection limit for binary stars, is of the order of Δm~3.5 mag.

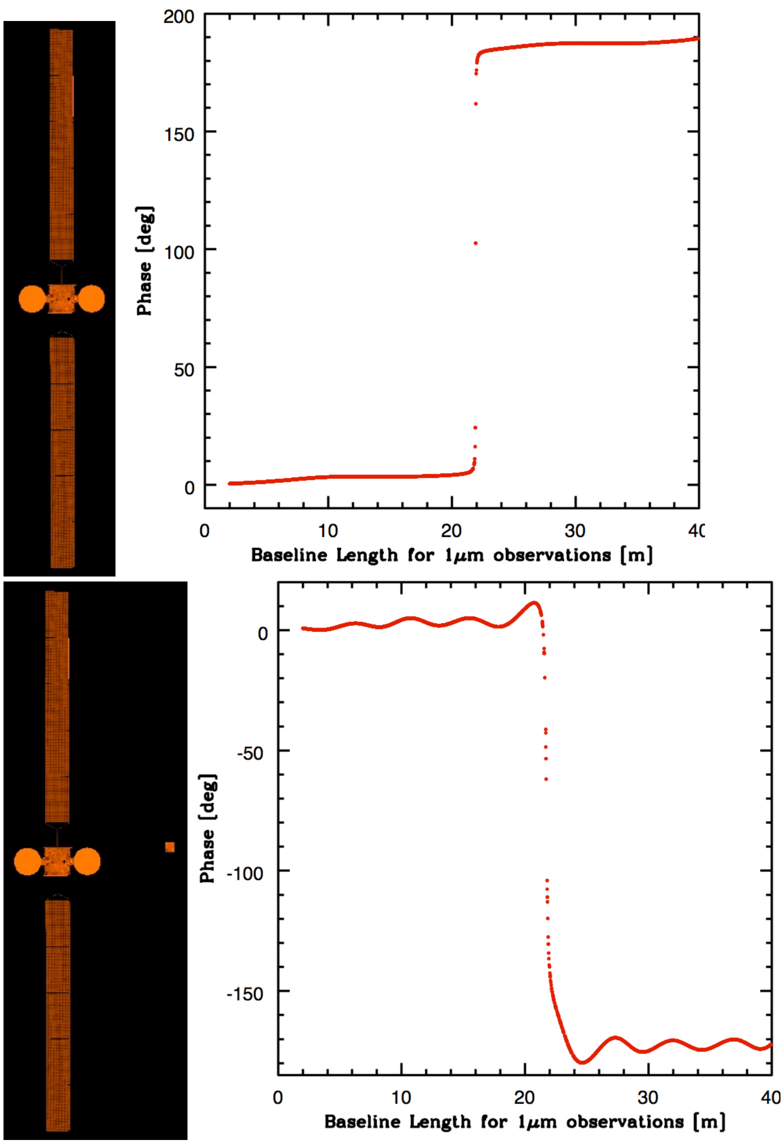

Fig. 2. The left column shows 2 satellite models, one without a companion (top) and one with a companion 100 times fainter (Δm=5 mag) than the satellite (bottom). The right column show the coresopnding baseline phases as a function of effective baseline length.

The bottom panel of Fig. 1 shows the phases of a single star and those of a Δm=5 mag binary observed around the null crossing. The phases were calculated using the expressions from [9]. The comparison of the phase and

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amplitude results shows the advantage of our phase nulling technique. While the fringe amplitude variations due to a Δm=5 mag binary are difficult to detect when comparing to a single star, their corresponding phases show a different picture. We can see that the presence of a faint companion shows as strong phase variations around the null crossing. These phase variations are due to the shift of the photocenter. When a binary system is observed around the null crossing of the brighter target, the photocenter moves from the bright companion closer to the fainter one. This shift of the center of light of the system manifests itself as strong phase oscillations.

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 [13] and show the results in Figs. 2 and 3. 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^{o} around the null crossing for a companion 1,000 fainter that the satellite (Fig. 3). In the case of companions with a flux ratio of 1% and 7% the phase oscillations increase to values in the range 10^{o} to 20^{o}. We are currently using these simulations to determine typical parameters for a future instrument dedicated to the observation of geosats.

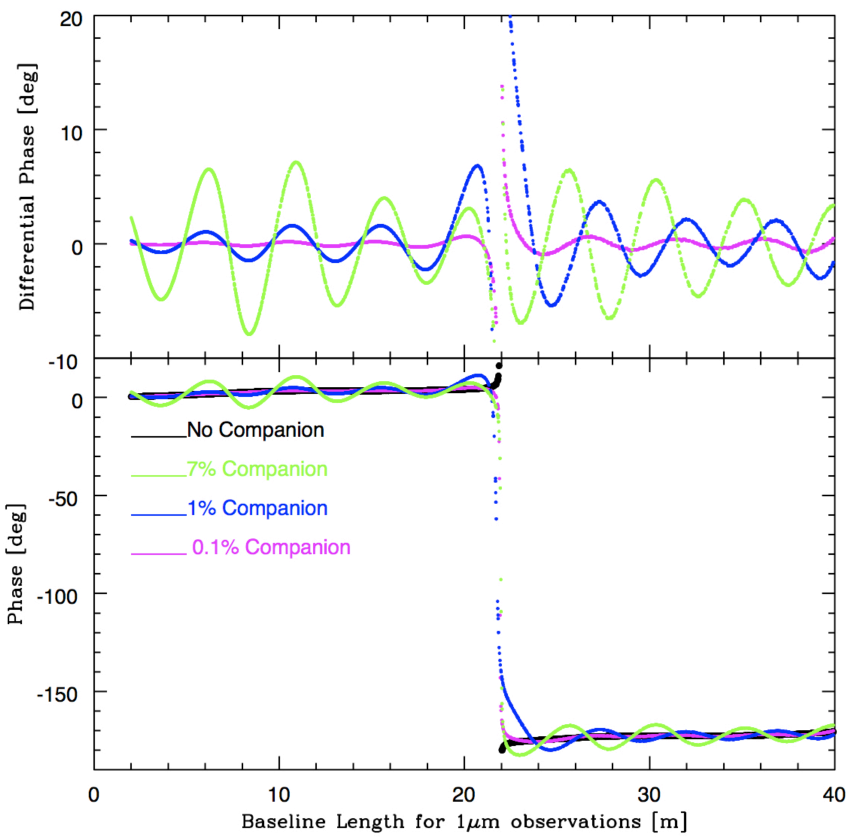

Fig. 3. The bottom panel shows the modelled fringe phase of a satellite with companions of different brightness ratios, as a function of effective baseline length. The top panel shows the phases of the models with companions after the subtraction of the phases from the model without a companion.

3. CURRENT AND FUTURE NPOI CAPABLITIES

The Navy Precision Optical Interferometry (NPOI), located in Anderson Mesa, in Flagstaff, AZ [1,2] is a premier Navy facility. The main goals of this optical interferometer are astrometry, high-resolution imaging of celestial objects, and the development and testing of new challenging interferometric techniques. Thanks to recent

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infrastructure investments, we have been able to commission new stations, a new beam combiner, and a new fringe tracker. Combining this new infrastructure with maturing observational and data analysis techniques, allows us to explore and develop new techniques, with a potential for cutting-edge scientific results.

The NPOI array is composed of an astrometric sub-array, four fixed stations, and an imaging sub-array, six movable telescopes that can be positioned in 30 stations located along the Y shaped arms of the array. The system allows one to combine the light from up to six stations, from both arrays. Some of the areas where the NPOI has played an instrumental role are, the observation of glinting geosats [7,14], binary stars [3,17], stellar diameters [5], stellar structure [10,11], and circumstellar disks [16]. The NPOI has also been used as a testbed for the development of new observational techniques, such as coherent integration [4] and differential phases [12].

The NPOI uses 50 cm siderostats, limited to an effective aperture diameter of 12 cm, due to feed mirrors. This aperture is a good match to the atmospheric coherence length of the site. Considering the stations that are currently available we are able to use baselines with lengths ranging from 8.8 m to 98 m. These baselines allow us to observe null crossings in stars with diameters in the range 1.2 to 18 mas. We are currently commissioning stations E10 and W10, which will give us access to a 435 m long baseline, and access null crossings in targets with a diameter of ~0.25 mas. A major limitation of the NPOI is sensitivity, being currently limited to the observation of targets brighter than V~6 mag. The low throughput is due to the combined effect of short integration times (2 ms), needed to freeze atmospheric turbulence, small apertures, and the larger number of mirrors and windows present in the system. This detection limit constrains the work on geostationary satellites to the observations of glinting targets around the equinoxes.

Two visual beam combiners are available at the NPOI. The original beam combiner (NPOI Classic) observes with 16 channels in the wavelength range 550-850 nm [2], which results in a spectral resolution R~30. This beam combiner can be operated with the original fringe engine and a new fringe engine, called New Classic [8,15], which increases the data rate by a factor of 10, as well as the number of available baselines. The second beam combiner, VISION [6], is a CCD-based six-beam focal plane combiner using polarization-maintaining single-mode fibers to spatially filter the light. The spectral resolutions achievable with VISION are in the range R~200 to 1000.

During the next year the NPOI system will see a series of upgrades that will significantly improve our scientific capabilities in the SSA and astrophysics areas. The first major improvement will be the installation of three 1 m telescopes equipped with adaptive optics. These telescopes will be delivered in 2017 and commissioned in 2018. These telescopes will be put in an initial compact configuration, with baseline lengths in the range 7.8 to 15.5 m. However, these telescopes will be located on movable platforms, which will allow us to move them to different positions along the array, giving access to longer baselines. The second major improvement will be the commissioning of a near-infrared beam combiner, which, combined with the larger apertures, will result in increased sensitivity and wavelength coverage, where satellites are brighter due to higher reflectivity. The increased sensitivity will allow us to observe geosats through a longer period of time through the year, thus allowing us to develop new observational and data reduction techniques tailored towards geosats and other targets in similar orbits.

Other important upgrades, currently underway, include the integration of the New Classic fringe tracker that will allow us to use it for regular operations, thus giving us simultaneous access to all channels and baselines, as well as more agile baseline bootstrapping capabilities. These developments, in turn, will allow us to operate longer baselines and achieve better resolution. We are also designing and building a CCD-based angle tracker and new electronic controllers for the Fast delay lines. These improvements will increase our fringe tracking stability, which will also represent a gain in sensitivity.

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