PHASING AN OPTICAL INTERFEROMETER USING THE RADIO EMISSION FROM THE TARGET BEING OBSERVED

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ABSTRACT

Imaging geostationary satellites from the ground, with a resolution better than a meter, is a problem that can be solved by using optical interferometry. However, the use of this technique is complicated by the fact that these targets are faint and comprise a relatively large angular size. Combining these facts with the need to detect and track interferometric fringes on short time scales (few ms), significantly impacts the number of telescopes and baseline lengths that can be phased in an optical interferometer array, thus limiting the imaging resolution that can be achieved. Here we present a novel approach we are currently investigating, where one uses the radio communications signal from the satellite to determine the optical path difference between multiple telescopes in the array. By using this approach one can integrate for longer periods of time at optical wavelengths on baselines for which there is not enough signal to track optical fringes directly, thus allowing one toachieve higher resolution images.

1. Introduction

Imaging is an important tool for diagnosing the conditions of a satellite, to detect if the spacecraft deployed properly, if structures got detached from the main body, or to detect the presence of an unwanted nearby companion. In the case of low Earth orbit satellites, most of this work can be done with a large telescope (~4m) equipped with adaptive optics. However, when we consider the case of geostationary satellites (geosats), the problem is much more complex. These satellites have dimensions ranging from a few meters to 10s of meters. At an altitude of 35,800km a structure with 10m corresponds to 0.28 mrad (~57 milli arcseconds). Compared to the best resolution of ~44 mas achievable by a 3.6m telescope at 650nm, it becomes clear that one needs to use different methods in order to achieve better resolution images.

Over the last decade, a wide range of studies investigated the viability of using optical interferometry to obtain more detailed images of geosats, with resolutions 0.5m or better [6,10-16], including the Galileo project from DARPA and currently the Amon Hen project from IARPA. The use of optical interferometry to image geosats has proven to be a challenging problem. One of the main issues for this technique is related to the faintness of geosats, they usually have V magnitudes in the range of 12.5 mag or fainter. Another important problem faced by the observation of geosats with an optical interferometer is the fact that they are stationary, so one cannot use Earth rotation to fill in the uv-plane and should rely on a larger number of telescopes instead. Furthermore, the current optical interferometers are optimized to observe stars. Given that most stars have diameters of 1 mas or less, the typical baselines employed by these interferometers, 10's of meters, resolve out the satellites and result in low fringe amplitudes, too low to detect within the typical atmospheric coherence time. Nevertheless, even with these issues, observational progress has been achieved. Our group [7,8] has used the trick of observing geosats during the glint

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season, when they become brighter than V~6 mag, and demonstrated the ability to detect interferometric fringes on these targets. This demonstration was done with the Navy Precision Optical Interferometer (NPOI), using in a first instance a single ~15 m baseline, and later using multiple baselines with lengths of ~9 m. These observations allowed us to characterize the dimensions of the glinting regions of these satellites.

Nevertheless, the idea of using glints to image geosats is not practical, due to their short durations, as well as the fact that glints are concentrated on small portions of the satellite and swamp the flux from other regions, making it difficult to detect them [17]. In order to be able to obtain high resolution images of geosats from the ground it will be necessary to develop ways to phase the different telescopes in an optical interferometer, in order to detect fringes on long baselines. In order to accurately phase an array, it is necessary to correct the optical path difference (OPD) between different telescopes on a time scale of 10's to 100's of milliseconds, the coherence time (t_o) due to atmospheric turbulence. To keep the array phased, it is necessary to detect the interferometric fringes between telescopes within t_o, and use these measurements to determine and correct OPD variations. This time limitation is complicated by the fact that geosats are relatively faint, large and have a complex structure, which results in a small number of photons (N) per t_o, low fringe amplitudes (V), and consequently low fringe signal to noise ratio (SNR~$N^{1/2}$V). Simulations presented by [6,10-16] have shown that for baselines longer than ~10 m it becomes increasingly hard, or even impossible, to detect interference fringes within a t_o, which would significantly limit the spatial resolution achievable with this technique. Bootstrapping several telescopes in a row would allow one to measure the OPD on short baselines, extrapolate it to longer baselines and integrate the signal on these baselines for longer periods of time without the need of directly detecting the interference fringe on a t_o. However, bootstrapping requires a larger number of telescopes, resulting in a more complex system, and can only be expanded to a certain level before the sensitivity drops.

Here we propose a novel technique to determine OPD based on the communications signal from the satellite in the radio frequency range. This method will allow for longer integration times at optical wavelengths on baselines for which there is not enough signal to track fringes directly. This is a passive technique with the potential to circumvent the issues imposed by the faintness and dimension of the geostationary satellites.

2. Description of the technique

The technique described in this contribution was patented by our group [18] (US Patent #10,082,382 B2), and takes advantage of the fact that satellites generally transmit in the frequency range of a few GHz (wavelengths of millimeters to centimeters). Given that both the radio signal and optical light from the satellite (reflected sunlight) travel through similar portions of the atmosphere and are affected by turbulence in similar ways, one can use the radio emission to determine the OPD between different telescopes in an array. Although the index of refraction of air is different in the radio and optical wavelength regimes [1,2,3], the relation of this value as a function of temperature, pressure and relative humidity are well known, so measuring the OPD at radio wavelengths and converting it to optical can be done if one has a precise monitoring of the air temperature, atmospheric pressure and relative humidity. Other effects such as telescope jitter and satellite movement, which constitute a change in the geometry of the system, are the same at both wavelengths.

In Figure 1 we show a schematic description of the proposed system. This figure depicts a simple 2 telescope (semi circles) interferometer observing a geostationary satellite. Reflected solar light and radio communication signals from the satellite travel the same distance, cross similar paths through the atmosphere, and are disturbed by atmospheric turbulence effects in a similar way before they reach telescopes in the array. This radiation is collected by the telescopes and passes through beam splitters (BS circles), which separate the optical and radio parts of the signal. After passing the beam splitter, the radio signal is sent to a conventional heterodyne radio interferometer (solid line path), while the optical light is sent to an optical interferometer (dashed line). The radio interferometer correlates the signal from different telescopes and determines the OPD. The optical light is sent through optical delay lines, which are fed with OPD information from the radio interferometer, properly converted to the optical wavelengths of interest by taking into account differences in the index of refraction of air in the two wavelength regimes, and then combined in the beam combiner.

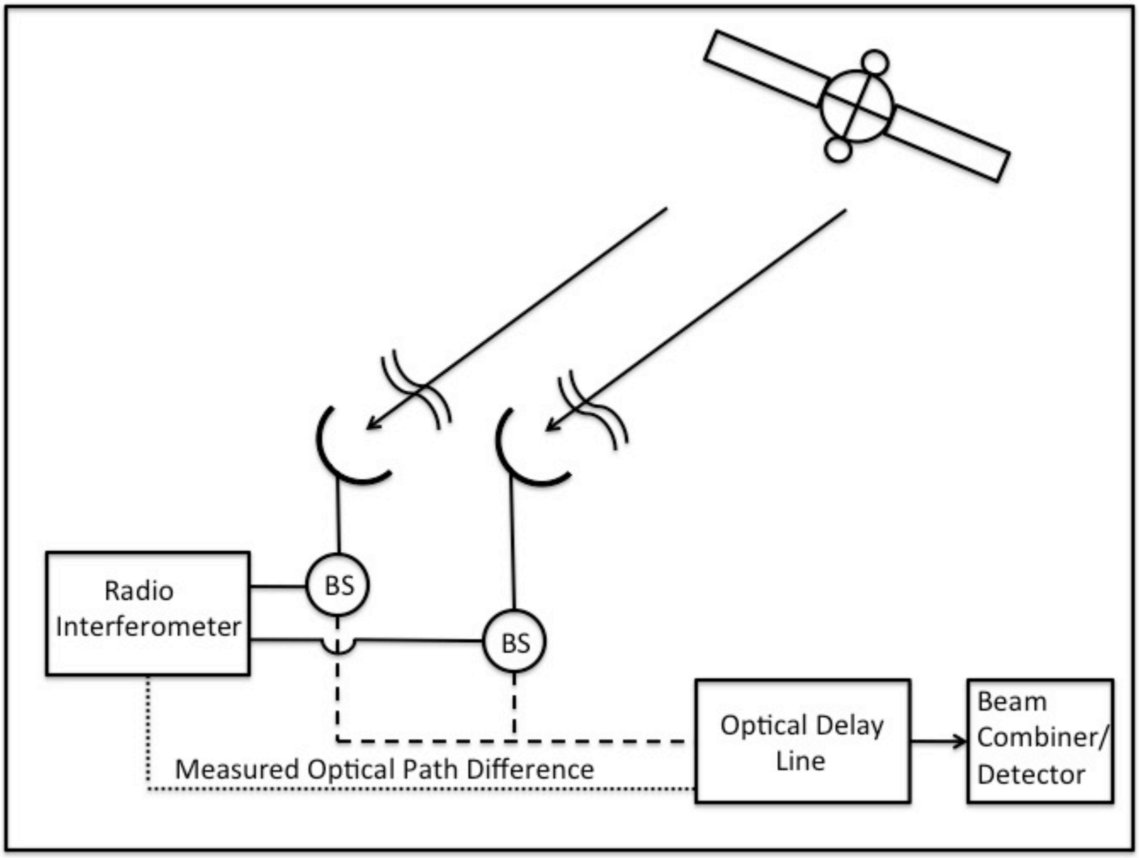

Figure 1: A schematic description of the system. Alternatively, one may envision a system using 2 sets of telescopes in very close proximity, one dedicated for the radio observations and one for the optical.

3. Feasibility

In order to separate the radio and optical light we envision two possibilities. First, one can use use a thin wire grid screen as a beam splitter to separate the radio and optical radiation. This thin wire grid could be free standing or a thin film on top of an optical element along the light path. Simulations [4] have shown that a wire grid screen with cell separation of $\lambda/4$ will reflect 50% of the incident radiation (grid separation of 7.5 mm for λ=3cm), while for a cell separation of $\lambda/12$ the screen reflects 90% of the radiation (grid separation of 2.5 mm for λ=3cm). The presence of such a grid screen along the optical path will have a negligible effect to the light in the optical and near infrared spectral ranges. A second possibility would be to place a radio detector in front of the telescope, for example, behind the secondary.

Next we consider the precision that one needs to measure phase variations in the radio regime in order to stabilize the OPD to a variation smaller than 5λ at optical wavelengths. Assuming the shortest wavelengths observed in the optical are λ=600nm, the maximum OPD variation should be smaller than 3μm. For a satellite transmitting at 10 GHz (λ_R=3 cm), we have that in order to achieve ΔOPD<3mm, the radio interferometer should be able to measure phase variations better than 0.036 degrees ($\phi = 2\pi\, \Delta OPD/\lambda_R = 6.3\text{x}10^{-4}$ radians). This will require detecting the radio interference fringe with an SNR~1600 per optical t_o.

To calculate whether we can reach this SNR, we first do a conservative estimate of the radiation from a geosat that reaches the Earth. We assume a satellite at a distance of $4\text{x}10^7$m, transmitting 2W with a bandwidth of 100kHz. For a beam of 1 str, each telescope will detect $6.3\text{x}10^{-21}$ W m^{-2} Hz^{-1}. The sensitivity of a single baseline composed of two telescopes with diameters of 1.5m, observing at 10 GHz, can be estimated based on the Very Large Array (VLA) sensitivity calculation [5]. We scale the System Equivalent Flux Density (SEFD) by the area of a VLA antenna (25m diameter) relative to the area of the optical telescopes. We use single polarization observations, correlator efficiency of 93%, and integration times of t_{int}=0.1sec, which is based on the assumption that adaptive optics will be needed for the optical telescopes, which will increase the coherence time to t_o~0.1sec or longer. We find that the baseline noise is 5.3x20^{-24} W m^{-2} Hz^{-1}, which will result in SNR~2350 per frame, enough to maintain the ΔOPD< 3μm.

Next we consider differences in atmospheric refractivity (N = n-1) at optical and radio wavelengths. Based on the equations presented in [3], we find similar temperature and pressure dependencies at radio and optical wavelengths, with water vapor having a negligible effect on N in the optical, but increasing to ~6% in the radio (ν<100GHz) for T=288 K and relative humidity of 20%. Converting N between wavelengths can be done based on environmental measurements. We estimate that temperature errors of 1K will introduce an OPD uncertainty of 60nm for RH=10%, increasing to 450nm for RH=80%. In the event higher precision OPD measurements are needed, using a water vapor radiometer to obtain higher precision estimates of water vapor content along the line of sight may be needed.

Another limiting factor to be considered in this method is the effect of the ionosphere on the radio radiation. Although we do not expect the ionosphere to vary by a large amount from telescope to telescope in an array with maximum baselines of ~100m [19], we expect it to create an additional delay at radio wavelengths compared to optical. This additional delay can be calculated [9] using information about the typical total electron content of the ionosphere (TEC~$10^{17}m^{-2}$). We find that the ionosphere can add an additional delay of the order of a few nanoseconds for observations at 5GHz, much less than the typical integration time used to determine OPD. The ionosphere becomes important for frequencies lower than 1GHz.

Even though the technique presented here is not applicable to all geostationary satellites, since not all satellites transmit at frequencies greater than 1GHz, or may have weak transmitters, it has the potential to be used for a fairly large number of targets. The determination of OPD in the radio regime will allow one to correctly position the delay lines of the optical interferometer and correct their positions for the variations due to atmospheric turbulence. This in effect will allow one to integrate interferometric fringes at optical wavelengths for longer periods of time, without the need to detect them within a typical t_o (a few ms). This technique has the potential to open the possibility of observing geosats with longer baselines, to obtain higher resolution images, and potentially reduce the complexity of these optical interferometers.

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