ORBITING SPACE INTERFEROMETER (OSI): A FIRST GENERATION SPACE INTERFEROMETER

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Abstract

This paper discusses the technical requirements and performance of a first generation space interferometer. The performance of an interferometer, sensitivity, field of view, dynamic range, astrometric accuracy, etc, in space is set by what cannot be achieved for a ground-based instrument. For the Orbiting Space Interferometer (OSI), the nominal performance parameters are 20 mag sensitivity, field of view of approximately 500*500 pixels, a 1000:1 dynamic range in the image with one millarcsec resolution, and an astrometric accuracy of 0.1 milliarcsec for wide angle astrometry and 10 microarcsec accuracy for narrow field astrometry (few degrees). OSI is a fully phased interferometer where all critical optical paths are controlled to 0.05 wavelengths. The instrument uses two guide interferometers locked on bright stars several degrees away to provide the spacecraft attitude information needed to keep the fringes from the faint science object stable on the detector.

Introduction

A number of long-baseline stellar interferometers have been built in the recent past. One of them, the Mark III interferometer on Mt. Wilson, is a fully automated instrument that is now routinely used for astronomical observations. A number of new long-baseline interferometers are in the early stages of construction. All ground-based instruments suffer the effects of a turbulent atmosphere. For high-angular-resolution instruments, the parameters that characterize the atmosphere are the coherence diameter, r_0, linear scale over which the wavefront can be considered flat to 1/6 of a wavelength; the coherence time, t_0, the time interval over which the phase a^{s} fluctuations of the atmosphere can be considered frozen; and the isoplanatic angle, the angular extent in the sky over which the atmospheric phase fluctuations are correlated. Typical numbers for these three parameters are r_0=10cm, t_0=10 msec and a_0=4 arcsec. These three numbers limit the performance of all ground-based stellar interferometers severely.

The three atmospheric turbulence parameters all get larger at infrared wavelengths at the 6/5 power of the wavelength. In the thermal infrared, it is expected that active optics techniques will be able to operate as if there were no atmosphere as far as high angular resolution observations are concerned. The role of space-based interferometers lies in the visible and ultraviolet, where operation in space would bring dramatic improvements.

OSI

A more detailed description of the Orbiting Space Interferometer (OSI) for the space station is in the appendix. Only a brief description is given here.

The initial concept for the OSI is a set of three interferometers with 30-50 cm collecting apertures along one 10-20 m structure. Two of the interferometers (guide) are responsible for stabilizing the platform while the third performs the measurements of scientific interest. The guide interferometers will determine the orientation of the platform to 0.25 mas while the laser metrology system will ensure that the internal instrument alignment will also be stable to 0.25 mas.

The OSI will have two modes of observation: astrometric and imaging. In the astrometric mode the relative positions of objects will be determined over large (>30 degrees) and small angles (<3 degrees). For a 30-cm aperture, the photon-noise-limited astrometric precision is 0.02 mas for 1000 sec of integration on a 20th magnitude object. We expect systematic errors to always dominate the achievable accuracy. For small angle measurements the precision is expected to be approximately 0.01 mas, while large angle measurements are expected to be a factor of 10 worse. Numerous stars will be sequentially observed in this mode.

Since all three interferometers will have the same size apertures, they are interchangeable with regard to guide and science functions. This feature provides the OSI with different baselines for imaging. Additional baselines are obtained by tilting (foreshortening) and rotating the interferometer around the vector dimensional image of the object, and can be constructed with angular resolution ranging from about 2 to 50 mas. These concepts are illustrated in figure 1.

The OSI baseline concept is based on the experience gained in the design, construction, and operation of the Mark III interferometer. Several characteristics of the OSI concept result in a significant reduction of risk or increase in performance over other space-based interferometer designs. One is the use of guide interferometers.

An interferometer in space can either be rigid, structurally rigid and pointed at the target with diffraction limited precision, or floppy. With a number of large ground-based interferometers in operation or in the construction phase, it has become evident that a floppy interferometer in space would not have the gain in performance that would justify the increased cost of a space instrument. A the very least, the information on structural deformations and pointing errors must be available so that the deformations and pointing errors must be available so that the fringe data can be analyzed as if the interferometer was rigid.

Technology Requirements

To take advantage of space-based operation, the interferometer must make use of the lack of a turbulent atmosphere. Although r_0, the coherence length, is infinite in space, the use of arbitrarily large collecting optics is limited by cost. Although there is no atmosphere, if the structure vibrates or cannot be pointed with sufficient precision, the coherence time of the spacecraft will limit sensitivity in the same way a turbulent atmosphere will. High sensitivity at low cost requires the use of moderate sized optics and a very stable structure that can be pointed with extreme precision.

As part of a larger effort to understand large controlled space structures, the JPL Control Structures Interaction (CSI) effort has chosen as a mission focus a long baseline stellar interferometer based on OSI. A part of this effort includes a detailed instrument definition, and a mission operations definition. With an instrument and operational scenario defined, the CSI effort will develop the technology to build and control a large space structure with the 10 nanometer stability needed for interferometry.

A preliminary analysis of the types of structural noise in a spacecraft was performed by putting the Hubble Space Telescope momentum wheels on the truss for OSI, a 20-m graphite epoxy truss with the lowest resonance at around 10Hz. It was found that vibrations due to the momentum wheel produced displacements of a few microns at a few hertz at the end of the truss. The net result is that the coherence time of a totally uncontrolled and passive structure is a few milliseconds, compared to 10 msec for the turbulent atmosphere.

CSI technology has at its disposal a large bag of tricks such as passive isolation of the noise source (momentum wheel), passive isolation of the optics critical for interferometry, use of balanced actuators that do not change the momentum or angular momentum of the structure when they move, as well as active structural members etc. Very large reductions of structural noise is possible with active systems.

Key to active systems is a laser metrology system that can measure the nanometer level displacements that will affect the optical path of the starlight. As part of our ground-based astrometric interferometry, we have developed a number of optical trusses based on laser interferometers that can be adapted for space. One such laser metrology system is now being analyzed by the JPL CSI effort for their focus Michelson interferometer (FMI), their version of OSI. It is the opinion of the JPL CSI group that the requirements needed for interferometry are not that hard.

Limitations of Orbiting Interferometers

In addition to internal stability, a technological question that is being addressed by CSI, external stability (attitude control) is also required. OSI is using two guide interferometers to look at nearby bright 11-15 mag guide stars to determine spacecraft attitude to a fraction of the resolution of the interferometer (to 0.1 milliarcsec (mas)). As interferometer baselines increase, the attitude control requirements will increase. The problem of accurate attitude control comes from the relativistic effect called stellar aberration.

The use of bright guide stars for attitude control assumes that the positions of the stars are constant with time. Because of spacecraft orbital motion, the apparent position of a star could be as much as 5 arcsec away from its true position. The magnitude of the effect is v/c radians where v is the velocity of the spacecraft and c the speed of light. There is an effect for the Earth's motion around the sun but the Earth's orbital motion is known with very high precision, including the effect of the Moon and the planet Jupiter. Spacecraft orbital motion must be known to 1 m/sec for a 20-m interferometer using guide stars within 0.1 radian of the science object. By using a GPS receiver on the spacecraft, the velocity can be determined to 10 cm/sec. Hence, without too much trouble, orbiting interferometers with 200 ms baselines are feasible. For interferometers much longer than 200-ms, another method for determining spacecraft orbital velocity is needed. One possibility is to add several interferometers to the instrument to measure the stellar aberration in real time. Other schemes are possible but all of them will significantly increase the complexity of the interferometer.

Science as a Driver

Whenever technology provides an increased measurement capability such as a new wavelength of observation, higher sensitivity or, in the case of stellar interferometers, higher angular resolution, new phenomena are observed. In our observations with the Mark III interferometer on Mt. Wilson, we have resolved double stars that were not resolved by speckle interferometry on 4- and 5-m telescopes. But even our current 32-m baseline is insufficient for some science objectives. In one case, we have easily resolved a spectroscopic binary with a maximum separation of 66 mas and a minimum separation of 4-5 mas (the other side of a very eccentric orbit). The stars themselves are expected to have diameters of the order of 1 mas. With another factor of 2 increase in baseline, the stellar disks would be clearly resolved. In this case, the orbits of the two stars are close enough that we would be able to observe the tidal distortion of the stellar photospheres. Hence, we are in the process of building a six-element 200-m array.

Stellar interferometers are a class of instruments with which (without new technology, hence, modest cost increases), one can obtain orders of magnitude increase in angular resolution that will give us a much clearer picture of a large number of astronomical objects.