Metrology and Pointing for Astronomical Interferometers

James D. Phillips[a*], Kenneth G. Carpenter[b], Keith C. Gendreau[b], Margarita Karovska[a], Philip E. Kaaret[a], Robert D. Reasenberg[a]
[a] Smithsonian Astrophysical Observatory, Harvard-Smithsonian Center for Astrophysics
[b] Goddard Space Flight Center

ABSTRACT

Metrology and pointing will be enabling technologies for a new generation of astronomical missions having large and distributed apertures and delivering unprecedented performance. The UV interferometer Stellar Imager would study stellar dynamos by imaging magnetic activity on the disks of stars in our Galaxy. The X-ray interferometer Black Hole Imager would study strong gravity physics and the formation of jets by imaging the event horizons of supermassive black holes. These missions require pointing to microarcseconds or better, and metrology to nm accuracy of optical elements separated by km, for control of optical path difference.

This paper describes a metrology and pointing system that meets these requirements for the Stellar Imager. A reference platform uses interferometers to sense alignment with a guide star. Laser gauges determine mirror positions in the frame of the reference platform, and detector position is monitored by laser gauges or observations of an artificial star. Applications to other astronomical instruments are discussed.

Keywords: Interferometry, astronomical instruments

1. INTRODUCTION

Pointing to microarcsecond accuracy, and metrology for control of optical path difference (OPD) to commensurate accuracy, will be enabling technologies for a new generation of astronomical missions having large and distributed apertures and delivering unprecedented performance. We present a study done in the context of the Stellar Imager, and discuss applications to other missions.

2. INTRODUCTION TO STELLAR IMAGER

Stellar Imager (SI) is a far-horizon mission in the Sun-Earth Connection (SEC) Roadmap. SI's primary goal is understanding solar type stellar activity, including long-term variability, the dynamo phenomenon, and the effects of stellar magnetic fields on life in the universe.[1] In addition to solar-type stars, SI will be able to carry out ultra-high resolution studies of active galactic nuclei, quasar and black hole environments, supernovae, CVs and other binaries, young stellar objects, and many other astronomical sources.

Achieving the science goals of SI will require angular resolution at UV wavelengths of ~0.1 milliarcseconds. This resolution can be achieved with baselines of several hundreds of meters at UV wavelengths.

SI is envisioned as a sparse aperture imaging interferometer having multiple free-flying spacecraft arranged on a nearly spherical "virtual primary surface" of 65 km focal length, with baselines up to 500 m. The wavelength range is from 1550Å to optical wavelengths, giving resolution as fine as 60 microarcsec (μas). A detector array is located at the prime focus. A critical technology development required for SI is a metrology and pointing system of sufficient accuracy and resolution. Here we present a metrology and pointing approach capable of meeting the SI requirements.

* jphillips@cfa.harvard.edu, 617-495-7360

2.1. Metrology and Pointing Requirements

The metrology and pointing systems provide OPD information to the control system to allow it to keep the image sharp. Here we assume it is necessary to keep the Strehl ratio near the diffraction limit (for the dilute aperture, possibly with pupil densification), and to keep pointing stable to a small fraction of the instrument resolution.

To meet these requirements, the OPD, from a point of the source through any pair of apertures to the corresponding point on the detector, must be a small fraction of a wavelength, say $\lambda/10$ rms. For the control system to achieve this performance, the metrology and pointing system must provide information several times more accurate, say $\lambda/30$ rms. At the shortest wavelength to be used by Stellar Imager this is 5 nm.

Three time scales are important to this requirement. First, t_1 is the time it takes for disturbances to violate the requirement. The control system should have a step response time $\leq t_1/10$, which requires that it have a unity gain frequency $\gtrsim 10/(2\pi t_1)$, and the metrology system must provide updates at a rate $\gtrsim 100/(2\pi t_1)$.

Disturbances to spacecraft positions are likely to be dominated by solar radiation pressure. A 50 kg spacecraft with a face of area 2 m^2 and 100% specular reflectivity, oriented perpendicular to sunlight, accelerates at 0.3 $\mu m/sec^2$, which would violate the requirement in 0.2 sec. However, the spacecraft reflectivity and orientation vary slowly, and the control system can maintain a model for reflectivity of each spacecraft. It can correct the mirror position either by extremely fine adjustments to spacecraft position, or by having actuators of limited range on the mirror. Only unmodeled changes in reflectivity provide a disturbance which the control system must counteract dynamically. Therefore, we take $t_1 = 20$ sec, and the metrology and pointing system must provide OPD updates once per sec.

Second, t_2 is the required integration time for a frame or binning of the data. This might be the integration time of light on a CCD for signal to overcome read noise. If a photon-counting detector is used, it might be the time required for the 1-σ error of the phase of the complex visibility on a baseline to diminish to $\pi/3$, so that a 2π error is improbable. The metrology and pointing system and the control system must be stable to at least the above accuracy for a time of at least t_2.

Third, t_3 is the time required for the entire integration. While pointing may be permitted to drift for times longer than t_2, i.e., the control system may drift, the pointing direction must be known to the required accuracy, to permit *a posteriori* image reconstruction. Thus, the metrology and pointing system must also remain stable for a time of at least t_3.

3. METROLOGY AND POINTING APPROACH

The pointing system establishes a reference platform of the required stability, using observations of guide stars or an inertial reference. The metrology system measures the positions of the apertures and detector with respect to that reference, and estimates OPD's from the target through each subaperture.

The metrology and pointing approach will be described in the context of the baseline Stellar Imager configuration described above. A schematic diagram of the optics is shown in Fig. 1. Each "mirrorsat" containing a subaperture A_i brings light from the science target to a focus at the detector, D. The path to be measured and held constant, for subaperture I, is from a reference wavefront W to D *via* A_i. W is perpendicular to the line to the center of the science target, and passes through D.

3.1. Pointing: guide star interferometer

The reference spacecraft, R, is located a distance h above the vertex of the primary, O. Let z be the science instrument's optical axis, and x and y complete an orthogonal right-handed coordinate system. The reference spacecraft has a pair of interferometers that observe a guide star, with baseline and aperture set by the required accuracy and pointing update interval (Table I). Assume that the guide star is of solar type, with V=7.5, and that the detection bandwidth is 4000Å, centered at 5500Å. The rate of detection of photons, per aperture area, is $N_o = 4\times10^6/sec/m^2$, assuming 10% overall efficiency (obscuration, reflection losses, and detector efficiency). An interferometer of baseline B detecting N photons at wavelength λ has a precision[2]

$$\sigma = \frac{1}{2\pi}\frac{1}{\sqrt{N}}\frac{\lambda}{B} \quad . \qquad \textbf{(1)}$$

With apertures of diameter

$$d = \frac{B}{\alpha} \quad , \qquad \textbf{(2)}$$

observing for a time τ, a precision σ is obtained when

$$B = \sqrt{\alpha \frac{1}{\pi\sqrt{2\pi}} \frac{\lambda_o}{\sigma} \frac{1}{\sqrt{N_o \tau}}} \quad . \qquad \textbf{(3)}$$

Setting α=6, we obtain the values in Table I (except for the first line, which is obtained by choosing the baseline required with apertures of 1 m diameter). The highest accuracy requirements imply baselines that would be achieved with free flying spacecraft. Herein, we refer to the spacecraft used for pointing as a "pointing platform," even if there are actually several spacecraft operating in concert.

A guide star of V<7.5 can almost always be found within 2° of the science target, even at the Galactic pole. The guide star interferometer's measurements are fed to the reference platform's attitude control system, which keeps it aligned with the direction to the guide star to within <1 arcsec.

Each guide star interferometer will have a "pseudobaseline," formed by a pair of optical fiducial blocks, one near the entrance to each telescope. The pseudobaseline is approximately parallel to the guide star interferometer baseline, with the offset measured to high precision. The pseudobaseline's defining fiducial blocks provide optical endpoints for accurate laser gauge determinations of the direction to the science apertures and detector. The guide interferometer OPD is stabilized with respect to the pseudobaseline using laser gauge measurements, and adjustments of the primary beamsplitter position. For SI, the offset of the star from the pseudobaseline is <1 arcsec,

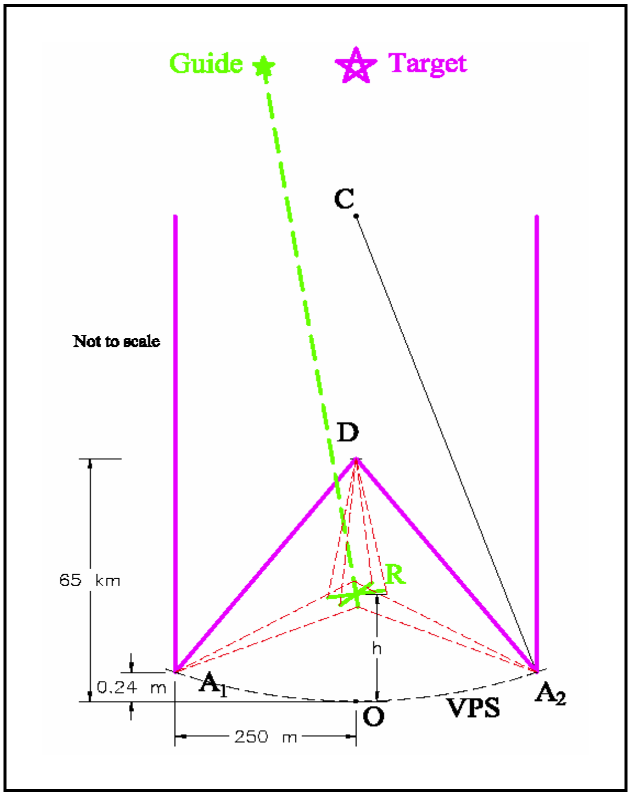

Figure 1. Schematic diagram of Stellar Imager metrology and pointing system. VPS = virtual primary surface.

σ(θ) μas	Update interval sec	Baseline m	Aperture m
0.1	1	71	1
0.1	1	21	3.4
0.1	100	6.5	1.1
1	1	6.5	1.1
1	100	2.1	0.3
10	1	2.1	0.3
10	100	0.7	0.1

Table I. Baseline and aperture combinations meeting various pointing precision and update rate requirements, for a magnitude 7.5 guide star, which can be found within 2° of the science target. Longest baselines would require five free flying spacecraft: four apertures, plus a combining hub.

and is measured to within 1 μas. The offset is used to correct the laser gauge measurements of aperture and detector positions before they are sent to the control system.

Since the fiducial block can be compact and enclosed in thermal shielding, with negligible view factors outside the instrument, it is thermally very stable. With the optical elements made of ultra-low expansion material, thermal changes of distances among them can be held to 1 pm (10^{-12} m) or below.

Since the guide star is up to 2° away from the science target, rotation of the reference platform about z must be known with an uncertainty only ~30 times as great as that about x and y. This requires a third guide star interferometer. As can be seen from Eqs. 2 and 3, if an equally bright guide star is used, the product of B and d (guide star baseline and subaperture diameter) for the interferometer that senses rotation about z need only be 1/30 that for the other two guide star interferometers, so the latter interferometer may be comparatively small.

3.2. Metrology of mirror positions

To measure the position of a mirror,† laser gauges measure the distance to it from the fiducial blocks at each end of the z-direction pseudobaseline. For the detector, the measurements are from both x- and y-direction pseudobaselines. The primary measurement in each case is an angle. It is also necessary to measure the distance to both mirrors and detector, which can be done with the same measurements used for angle.

The directions in which the laser gauges must aim their beams to follow the mirrors and detector will vary for different target star-guide star offsets, and this requires that the laser gauge beams interrogate different parts of their endpoint optics. This is termed beamwalk, and it causes measurement error due to manufacturing errors in the surfaces.

To reduce beamwalk, it is possible to establish a separate metrology platform, with x'-, y'-, and z'-direction baselines, where (x',y',z') form an orthonormal triad and x' is approximately parallel to x, y' to y, and z' to z. This platform would allow the metrology look directions to be the same for all target star-guide star offsets. The only change required would be caused by reconfiguration of the mirrors to change (u,v) plane coverage. If each mirror moves along a one-dimensional path, the complexity of the beamwalk map is much less than if all target star positions in a two-dimensional patch must be accommodated.

Another advantage of a separate metrology platform is that if its z'-direction pseudobaseline is aligned with the science instrument's optical axis, measurements of mirror angles from the z'-direction pseudobaseline, plus the distance, would provide almost exactly the quantity required, the OPD for starlight arriving at D via M_i. Measurements from the x'- and y'-direction pseudobaselines would not be needed.

The required tolerance of the angle measurement for the mirrors is the permissible position error divided by the distance from metrology platform to mirror, $\sim 2.5\ \mathrm{nm}/250\ \mathrm{m}$. The tolerance for the detector is a fraction of the permissible pointing error. Both tolerances are of the order of 1 μas. On a 2 m baseline, the entire error corresponds to a distance of 10 pm; however because the error of several laser gauges contributes, the tolerance for an individual laser gauge needs to be about 1 pm.

3.3. Detector position

There are several ways to measure the detector position with respect to the reference spacecraft. For example, the detector could contain an artificial star that was observed by an interferometer on the guide star platform.

Intercepting all of the beam spanning a distance L between endpoints may be necessary in order to minimize systematic error. To minimize the size of the largest optic required, the beam should be diffraction-limited and have a waist in the middle of the distance. Then, to minimize the beam size at the ends, the waist radius (the distance from the optical axis at which the intensity falls to $1/e^2$ of its central value) is $\omega_o = \sqrt{\lambda z / 2\pi}$. For a wavelength λ=1550 nm

† In this paper, "mirror" refers to the subaperture reflectors (spherical, with 65 km focal length) mounted on each mirrorsat. These may be the only optical elements between the star and detector.

traversing 250 m, ω_o=8 mm. To intercept most of the beam, an aperture of at diameter at least $4\omega = 4\sqrt{2}\omega_o$ would be required, 44 mm. For a distance of 65 km, the diameter would need to be 0.72 m, which may dictate employing a shorter metrology wavelength, or accepting the error consequences of having some of the beam miss the aperture, as must be done on the paths of 5×10^9 m in the Laser Interferometer Space Antenna (LISA).[3]

3.4. Guide star acquisition

For the reference platform to acquire a guide star, the ordinary star tracker provides initial attitude information, allowing the platform to slew to within ~1 arcsec of the guide star direction. This may be close enough to allow the guide star interferometers to acquire fringes. If not, a "super star tracker" is used to refine the reference platform attitude sufficiently for interferometric acquisition. The super star tracker would be similar to the guide star telescope used in GP-B, which observes a single star, bore-sighted, with ~1 mas precision.

Once the guide star interferometer has acquired fringes, its attitude is servo-controlled so that its pseudobaselines remain within about 1 arcsec of the guide star. The offset is measured with a dispersed fringe ("channeled spectrum") approach, to an accuracy of 1 μas. The guide stars will be on the axes of the guide star interferometers' beam-compressing telescopes to within about 1 arcsec. This will reduce cost by eliminating delay lines and articulating siderostats. Also, the telescopes require only a 1 arcsec field of view, and aberrations will be negligible.

4. ALTERNATIVE APPROACHES

There are several alternative pointing schemes at an early stage of research. With all pointing schemes, metrology is needed to measure mirror and detector positions.

4.1. Science star as guide star

If it is acceptable to require the science target to be moderately bright and compact ($V \lesssim 7.5$ and $\text{diameter} \lesssim 0.1\ \text{arcsec}$), then the guide star interferometers may observe the target itself. In this case there is no need to determine the angle of the reference platform about the direction to the star, and the reasons for employing a separate metrology platform (discussed above) would not apply. There may also be an option to obtain pointing information from the science target via the main apertures instead of via separate guide star interferometers.

4.2. Superfluid gyro

Gyros based on superfluid ^{4}He (at temperatures below the lambda point, 2.2°K) have been constructed, with angular sensitivity of $3\ \text{arcsec/sec/}\sqrt{\text{Hz}}$.[4] Work is going on at GSFC and the University of Maryland on a version employing microfabrication on a Si wafer and a Single Electron Transistor (SET) intended to improve this to $4\ \mu\text{as/sec/}\sqrt{\text{Hz}}$.

4.3. Kilometric Optical Gyro

In the presence of rotation, the Sagnac effect introduces a phase shift between beams traveling in opposite directions around a closed path. This is the basis for various rotation sensors. A ring laser gyroscope of area 1 m^2 has been operated at the shot noise limit.[5]

For Stellar Imager, a km scale gyro is expected to be required. This instrument will be complicated by several factors. The work cited above was performed in a cavity bored out of a solid block of Zerodur. Mirrors with reflectivity 0.999999 were used, resulting in a finesse approaching 10^6. The Stellar Imager gyro would be based on mirrors mounted on free-flying spacecraft whose orientation would be under servo control. Residual vibrations will tend to couple power into higher order cavity modes, limiting the finesse. Also, keeping mirrors in space sufficiently clean to maintain this reflectivity would be difficult.

4.4. Telescope

A telescope could in principle observe guide stars and a beacon transmitted by the detector spacecraft. However, the sensitivity of a telescope is inferior to that of an interferometer. The ratio of the uncertainty of an astrometric telescope to that of an interferometer of comparable overall size is[2]

$$\frac{\sigma_T}{\sigma_I} = \frac{3\pi^2 F}{8\sqrt{2}} \quad \textbf{(4)}$$

where F is the focal ratio of the telescope's primary, and here we have omitted the factor of 2 pertaining to a Ronchi ruling, since this telescope may be bore-sighted and employ a roof prism. We have also increased the uncertainty for an interferometer by a factor $\sqrt{2}$ because with the telescope and an appropriate arrangement of roof prisms, all photons can contribute information in both orthogonal directions, but this is not so for the interferometer. For an f/15 astrometric telescope, the ratio is 40. Since the cost of a spacecraft is closely related to its size and weight, this predicts that an interferometer has a significant cost advantage over a telescope.

Note also that, by comparison with the interferometer example above, the telescope would need to observe guide stars *at least* as bright as V=7.5, and therefore must look as far as 2° from the science star to find a guide star. Since the detector is near the science star, as seen from the reference platform, the telescope must have a field of view of 2° in order to observe both detector and guide star.

Another advantage of an interferometer over a telescope is in the metering of the instrument in the presence of thermal changes. For the same astrometric precision, the interferometer's apertures will be smaller than the telescope aperture. Thus, baffling will be more effective, and monitoring the position of one or a limited number of points on the mirror yields a more faithful indication of the position of the whole surface. The GP-B telescope achieves stability of ~0.1 mas/yr, but it does so by rolling about the line of sight every 1-3 min., and by operating at liquid helium temperature, which reduces thermal expansion.

4.5. Mechanical Gyroscope

A mechanical gyroscope, even one as refined as that developed for GP-B, is not a viable option, because its readout noise is too high. The GP-B gyro uses an electrostatic suspension, and drag-free control of the satellite to reduce spurious torques due to the suspension. Operation at liquid helium temperature conveys several advantages: reduced thermal expansion and a readout based on the London moment and Superconducting Quantum Interference Devices (SQUID's). This readout minimizes spurious torques. However, the short-term noise of these instruments makes them inadequate for the Stellar Imager task. The limit to gyro sensitivity imposed by SQUID noise is 0.1 arcsec $Hz^{-1/2}$, presumably for signals at the spacecraft roll rate. This is consistent with the statement that the gyro sensitivity is limited by readout noise to 0.1 mas/yr after 14 months of integration.[6] To point Stellar Imager to 1 µas in 1 sec requires 5 orders less noise for a signal frequency of 1 Hz. The GP-B gyro falls far short of meeting the Stellar Imager requirement.

4.6. Mirror position: metrology from the center of curvature

Another concept for measuring the positions of A_i is to transmit a spherical wavefront from an additional spacecraft placed at C.[7] The portion of the beam falling on each aperture returns to a focus at C, and it interferes with a reference beam. An image of the primary is formed on a detector array. Each aperture corresponds to a distinct area of the image. The several fringe patterns are analyzed separately to obtain the tilt and piston of each aperture. (Higher order distortions could be monitored as well.) Absolute distance can be measured in a manner similar to that in which the TFG does (see below), by shifting the wavelength.

This scheme measures very nearly the set of quantities desired, and measures directly to the surfaces of the primary mirrors. The resulting simplicity may compensate for the expense of a separate spacecraft. With this scheme for internal metrology, a pointing reference is still needed, and the best approach is likely to be the guide star interferometer outlined above. The position of the satellite at C would be monitored, similarly to the monitoring of the detector craft, D.

5. BLACK HOLE IMAGER

A black hole imager, part of NASA's Structure and Evolution of the Universe (SEU) roadmap, will employ X-ray interferometry to reach sub-micro-arcsecond angular resolution, almost six orders of magnitude higher than that of the HST. It will allow imaging the event horizon that borders the black hole. This mission, and even the precursor "pathfinder" mission, would image X-ray structures with unprecedented detail in many astronomical sources and address key science questions in astronomy and general relativity.

The black hole imager will use X-ray interferometry to capture a picture of a black hole with sub-microarcsecond angular resolution – a key goal of the Beyond Einstein Program of the Structure and Evolution of the Universe science theme. Concepts involve subapertures on free-flying spacecraft separated by baselines of ~1 km, combining beams at a detector spacecraft at a distance much larger than the baseline. While grazing incidence optics will likely be used to relax tolerances, nm positioning of mirrors with respect to each other within aperture spacecraft, and micron lateral positioning of each mirror set, is likely to be needed, and a pointing reference accurate to better than 0.1 μas. Advances in metrology are needed.

The metrology and pointing problem may be amenable to the same approach as in Stellar Imager: a reference platform stabilized to the required accuracy with observations of a guide star. Mirror positions would be monitored with laser gauge measurements, and the detector position with laser gauges or by observing an artificial star. The angular tolerance is substantially tighter, which would require a guide star interferometer, if used, to be substantially larger. The guide star interferometer requirement may be relaxed for short times with an inertial reference, allowing the guide interferometer to be made smaller.

6. TRACKING FREQUENCY GAUGE

The Tracking Frequency laser distance Gauge (TFG) differs from the traditional high-precision (heterodyne) laser gauge.[8,9] The TFG employs a single beam, not two distinct beams as with the heterodyne gauge. This frees the TFG of the nm-scale cyclic bias of heterodyne gauges and simplifies alignment.

The classic version of the TFG has demonstrated 2 picometer (pm) incremental distance accuracy in 1 min on a stabilized optical path, and 10 pm in 0.1 sec on a path with only passive stabilization. While the requirement for Stellar Imager is ~1 pm, other work[10] has a goal of 0.1 pm. (Incremental distance is the change of distance from an initial offset. Absolute distance includes the estimation of the offset.) Absolute distance determination has been subjected to a preliminary test, to an accuracy of 0.1 mm. A new version of the TFG, now in the planning stages, will achieve similar or improved incremental distance precision, improved absolute distance, and will employ a space-qualifiable laser, likely a distributed feedback (DFB) semiconductor laser operating at 1550 nm. The components will be in fiber-connected packages, reducing sensitivity to air turbulence and thermal expansion, and simplifying setup, testing, reconfiguration, and repair. The TFG's precision for both incremental and absolute distance measurements can be independent of the distance measured.[9]

It is possible to build a simplified version of the new TFG, comprising only a tunable DFB laser, with no separate phase modulator. As with all laser gauges, the simplified version would require beam-launching optics, the interferometer whose length is to be measured, and a photodetector, plus electronics. The precision would be of the order of 1 nm.

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