VI

Project Technology Readiness

> I OFTEN SAY THAT WHEN YOU CAN MEASURE WHAT YOU ARE SPEAKING ABOUT, AND EXPRESS IT IN NUMBERS, YOU KNOW SOMETHING ABOUT IT….
>
> *Lord Kelvin*

The MAM testbed showed that microarcsecond astrometric accuracy can be achieved in a stellar interferometer under realistic operational scenarios.

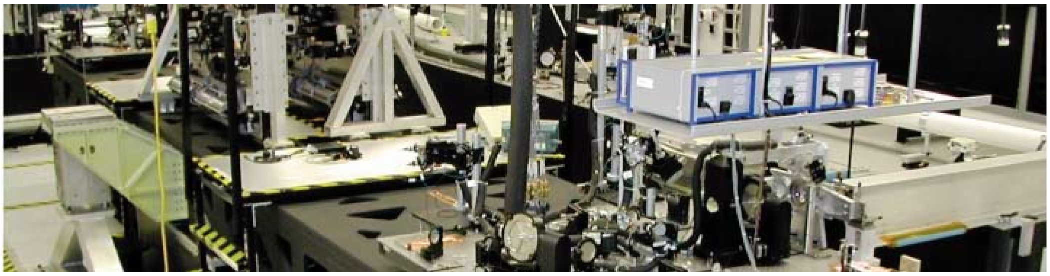
The Kite testbeds demonstrated that we can meaningfully measure the displacements of optical elements to a hundredth of an atom.

SIM Lite's beam launchers have achieved the required picometer accuracy: one to two orders of magnitude better than the best commercially available gauges.

The G2T testbed has demonstrated star tracking precision to 50 microarcseconds.

The STB-3 testbed demonstrated nanometer-level pathlength control in a flightlike environment — even for the dimmest stars, where it takes minutes to collect enough photons to estimate the fringe position.

16 Astrometric Interferometers



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ABSTRACT

Across the panoply of modern astronomical instruments, SIM Lite holds a unique position as a space-based long-baseline astrometric interferometer. As such, it represents the most capable astrometric instrument currently ever invented In this chapter, we show that interferometers are the optimal choice for wide-angle astrometric measurements, providing good performance in regimes where telescopes are not feasible. We introduce the key elements of stellar interferometry and conclude with an overview of the SIM Lite instrument architecture.

16.1 Interferometers As Optimal Astrometric Instruments

For imaging, the ideal instrument is a telescope with an unobscured circular aperture. This yields a point-spread function that is minimal in width, resulting in the highest overall definition. It is also possible, as is done in radio astronomy, to synthesize an image using an interferometer whose collectors can be moved to fill a much larger "synthesized" aperture. Doing so would afford finer definition at the expense of artifacts arising from what is usually a sparse sampling of the aperture plane. Thus, for imaging extended scenes, the telescope is the optimal instrument while the interferometer that adequately samples the aperture plane can be an approximation.

In astrometry, on the other hand, we are usually interested in the angle between unresolved objects. Here the ideal instrument is one that samples the wavefront at two spatially separated points and measures the tilt of the wavefront using the samples. The ideal instrument here is the Michelson stellar interferometer and a telescope can at best be an approximation.

We can compare the astrometric performance of the telescope to the interferometer from a signal to noise standpoint. In the absence of systematic errors, the accuracy of an astrometric instrument is approximately given by:

$$\sigma_a = \frac{w}{2\sqrt{N}} \tag{1}$$

where w is the angular width of the signal peak and N is the number of detected photons. For the telescope, w is related to the point-spread function while for the interferometer it is given by the peak fringe width:

$$w_{tel} = 2.44\frac{\lambda}{D} \qquad w_{int} = \frac{\lambda}{B} \tag{2}$$

Thus, from a photon-limited point of view, the astrometric resolution of an interferometer with a 6-m baseline and two 50 cm collectors is roughly equal to that of a 3.2 m telescope. But astrometric resolution is only the beginning of the story.

A critical advantage comes from the fact that an interferometer like SIM Lite is not limited to the field of view of its telescopes, but rather to the field of regard of its siderostats. In relative astrometry over narrow angles, one measures the position of a target star with respect to a set of reference stars. If the target star is bright and the reference stars faint, as is the case in the search for nearby Earths, one is often limited more by the photon statistics of the reference stars than the target star. In this case, the photon-limited precision is dependent on the size of the field of view. A telescope with a small camera, for example with a 3-arcmin-diameter field, would on average have fainter reference stars than a telescope with a wide-field camera, say 30 arcmin field. In general, the photon-limited accuracy is approximately proportional to the diameter of the field being observed, so that, for narrow-angle (exoplanet) astrometry, SIM Lite with a field of regard diameter of 2 degrees would be equal, in terms of photon-limited precision, to a 32 m telescope with a 12 arcmin field of view.

For precision astrometry, systematic errors and their control are at least as important as noise considerations. Here too, interferometers have advantages over telescopes. Chapter 18 will introduce the basic classes of systematic errors affecting astrometric interferometers. The SIM technology program, it will be shown, has demonstrated the mitigation of these errors down to the level of λ/60000. The technical challenges in achieving the same level of performance with telescopes are at this time formidable.

When telescopes are used for astrometry, there are two common modes of operation. One is called staring, wherein a star field is imaged on a large focal plane array. The second is called scanning, in which a CCD detector is fixed to the telescope but the telescope is scanned across the sky and the CCD is clocked out at the scan rate.

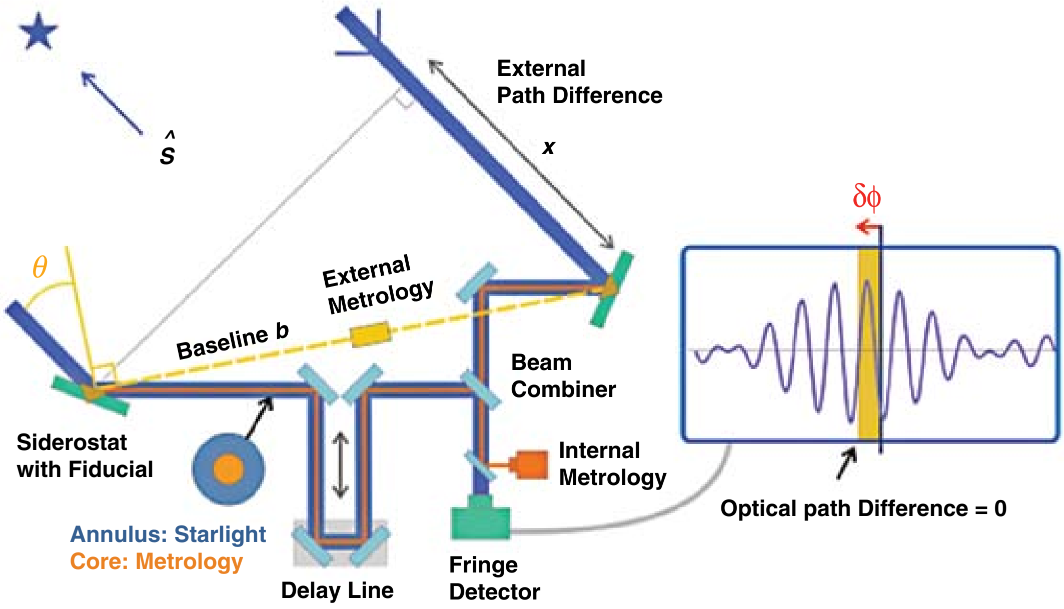
A telescope doing astrometry by staring will face systematic errors arising from sampling issues and optics errors. Astrometry at the 100 µas level has been demonstrated with the Wide-Field and Planetary Camera on the Hubble Space Telescope (HST) with 45 mas pixels and a point-spread function (PSF) size of approximately 50 mas. This is centroiding to nearly 1/500 of a pixel. Astrometry at the 10 µas level requires at least 3 to 4 pixels per PSF. For HST, with a 10 arcmin field of view, this would require a 16 gigapixel detector. If a mosaic focal plane is used to achieve this, there will be position and rotation errors among the devices. Moreover, since a variety of materials with different coefficients of thermal expansion are used to put together the CCDs in the mosaic, there will be thermal errors whose mitigation would have to be demonstrated through testing. One might argue that by placing the stellar image at the same part of the CCD (to a small fraction of a pixel) in every epoch, we can make PSF errors repeatable, and thereby avoid having to improve the sampling of the PSF. Unfortunately, at Earth's orbit, the differential stellar aberration even across the 10 arcmin HST field is approximately 60 mas, or larger than a pixel. As a result, it is impossible to repeat the positioning of the stellar image in the CCD at different epochs.

All existing space telescopes have at least two curved optics. If the pupil of the system is the primary mirror, the secondary is oversized, and the footprint of the starlight on the secondary depends on the position of the star in the field of view. The wavefront errors on the primary add to the wavefront errors on the secondary, but differently for each star in the field because the stellar wavefront's footprint on the secondary varies with the field position. If the wavefronts in different parts of the field of view are different by λ/100, there could be a field-dependent centroid bias of λ/100, or about 600 µas for a 2 m telescope. One could in theory do astrometry at the 60 µas level if these wavefront differences were fixed to λ/1000 between epochs, but this may not be technically feasible.

A number of astrometric telescopes perform astrometric measurements in a totally different way. Instead of staring at a part of the sky and in effect taking a picture, the telescope and focal plane array scan across the sky at a nearly constant rate. The CCD detector is read out in time delay integration (TDI) mode, matched to the rotation rate of the telescope. This approach has several advantages to the staring telescope approach. The first is that the image of a star is detected not with just a few pixels but thousands of pixels, so that small random differences in pixel quantum efficiencies are averaged. Second, many of the field-dependent optical biases are also averaged out. If star 1 scans across the middle of a CCD, and star 2 scans across the same set of pixels but a fraction of a second later, both stars will experience the same set of optical distortions. If the PSF is undersampled, (less than two pixels per λ/D), there will be a color-dependent bias in the centroid, whose value depends on how accurately the color dependent PSF is modeled. The Gaia and Hipparcos missions are the most prominent space astrometric missions that make use of the scanning telescope concept. For Gaia, each star will be scanned on average about 80 times over five years, resulting in end-of-mission accuracy of about 7 µas at magnitude 10, 20 to 25 µas at magnitude 15, and 200 to 300 µas at magnitude 20.

In conclusion, astrometry at the sub-µas level, the regime sensitive to Earth-mass planets around nearby stars, is technically feasible only for space-based stellar interferometers at this time. From both the photon noise and systematic error standpoints, telescopes are limited to tens of µas at best for the staring approach and a few µas for the scanning approach.

Figure 16-1. The minimal astrometric stellar interferometer requires the measurements of the starlight fringe, the internal path difference, and baseline length.



16.2 Astrometric Stellar Interferometry

The stellar interferometer, when used for astrometry, measures the optical pathlength difference (called relative "delay") between two light paths. These two paths originate at the source (a star) and end at the interferometer's two fiducials. The essential components of a minimal stellar interferometer are shown in Figure 16-1.

Two spatially separated samples of the starlight are collected and interfered via a beam combiner (physically, a beam splitter). Visible interference occurs and fringes are detected when the optical pathlength from the star to the beam combiner is equal for the paths through the two arms of the interferometer to within a few mean wavelengths. The fringe pattern envelope has maximum contrast when the total optical pathlength difference (OPD) is zero. Reference points (or "fiducials") for astrometry are created by introducing a pair of retroreflectors centered within the starlight beam on each of the two paths.

The interferometer baseline *b* is a vector that extends from one fiducial to the other. The total starlight path can be divided notionally into an "external" path *E*, originating from the source star to a fiducial, and an "internal" path *I*, starting from the fiducial down to the beam combiner. The difference of the total optical paths, left minus right, is given by:

$$\delta T = \delta E + \delta I \tag{3}$$

where δT, δE, and δI are the left-minus-right differences in the total, external and internal paths, respectively; δT is measured with the fringe detector and is called the white light fringe delay $\delta\phi$, as illustrated in Figure 16-1. The astrometric angle θ is related to the external OPD and the baseline length, *b*, according to:

$$\delta E = \vec{b} \cdot \hat{s} = b \sin \theta \tag{4}$$

The baseline length b is determined using both "external" metrology and post-processing of the astrometric measurements. The internal OPD is measured, modulo an overall constant offset, by the internal metrology reading δM:

$$\delta I = \delta M + C \tag{5}$$

C is sometimes called the interferometer "constant term," and is the actual internal OPD when the metrology reading is zero. Since, at the picometer level, this zero-point is initially unknown, it is determined using astrometric calibration measurements. We now define the instrument measured delay x as:

$$x \equiv \delta\phi - \delta M \tag{6}$$

Combining these, we arrive at the basic astrometric equation for the interferometer:

$$\begin{aligned} x &= \delta T - (\delta I - C) = \delta E + C \\ &= \vec{b} \cdot \hat{s} + C \end{aligned} \tag{7}$$

Hence, three measurements — the white light fringe delay, internal metrology, and external metrology — form the basic ingredients of the astrometric angle. Errors in each of these areas translate into a delay error. To indicate the level of accuracy needed, consider the planet-finding case, with a desired error level of less than 1 μas per visit. If the baseline is 6 m long and is orthogonal to the star direction, then knowledge of the astrometric angle at the 1 μas (5 picoradians) level necessitates that the delay x be measured to less than 30 pm (Figure 16-2).

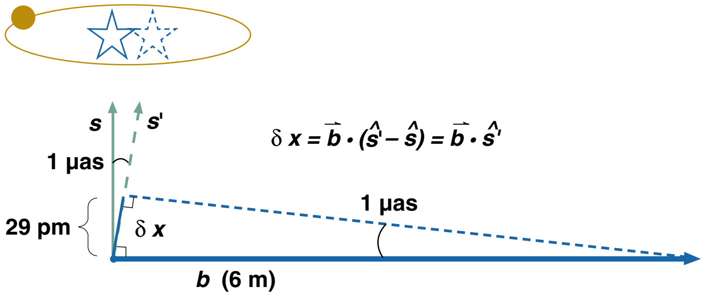


Figure 16-2. Relationship between astrometric error and delay error.

16.3 Accounting for the Motions of the Baseline

Since the astrometric measurement is relative to the baseline, variations of this vector directly affect the measurement. In a realistic space-based instrument, the baseline orientation can change by arcseconds during a measurement and its length can vary by microns. These changes must be monitored accurately to achieve a meaningful measurement.

The SIM Lite approach can be helpfully illustrated using the simplified two-dimensional situation shown in Figure 16-3. The item of interest is the astrometric position angle of the "science" star. One interferometer, designated Science Interferometer, is used to determine the angle between its baseline vector and this star. Since the measurement takes a finite amount of time, any changes in the magnitude or direction of the baseline need to be monitored while the measurement is in process.

Changes in the length of the baseline can be measured by laser metrology gauges interrogating the baseline endpoints. Changes in the direction of the baseline are measured using a combination of a second interferometer (guide interferometer) looking at a “guide” star and an external metrology system that measures the relative changes of the science and guide baselines. The external metrology system consists of a trusswork of laser metrology links interconnecting the nodes (corner cubes) at the ends of the science and guide baselines. The guide interferometer tracks the angle between its baseline and the guide star. As such, it also provides continuous baseline tracking throughout the entire set of science observations made with a common baseline attitude.

In three dimensions, the baseline can rotate in two angles, and the metrology truss can move in three directions. As a result, a second guide instrument is needed, along with a truss “roll sensor.” This is reflected in the architecture of SIM Lite.

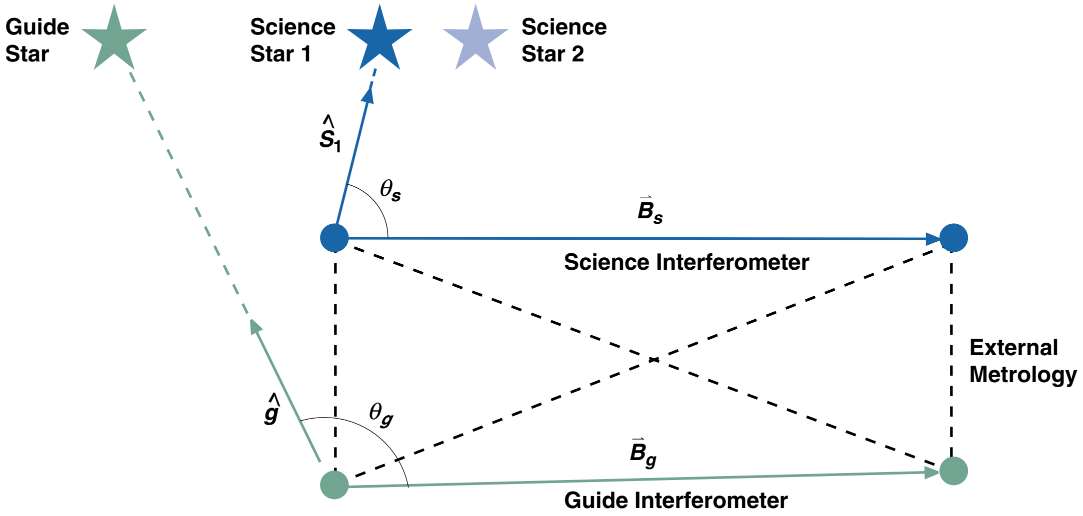


Figure 16-3. In a two-dimensional world, SIM Lite would consist of two interferometers and an external metrology system.

16.4 SIM Lite Architecture

SIM Lite consists of four fundamental sensors (together constituting the “instrument,” Figure 16-4) mounted on a precision structure and serviced by a spacecraft. The four sensors together accomplish the measurement of the three fundamental ingredients, viz., the white light fringe delay, the internal delay, and the baseline variations.

The primary sensor is the science interferometer, which provides the external delay associated with each astrometric target by measuring the white light fringe and the internal delay (two of the three fundamental ingredients). To track the variations in the science baseline (the third ingredient), SIM Lite’s other three sensors are needed. These are the Guide-1 and Guide-2 instruments and the external metrology system.

SIM Lite's external metrology system tracks the motions of six nodes (fiducials made from corner cubes) situated in a three-dimensional configuration as shown in Figure 16-5. Beam launchers situated between the fiducials send metrology laser beams that probe the distance between the nodes.

Guide-1 is an interferometer that points in the same direction as the center of the science field of regard (FOR). It is similar in performance and design to the science interferometer, except that its FOR is limited to a narrow region at the center of the science FOR, and its baseline is shorter.

Guide-2 is a telescope pointed 90 degrees away from the nominal science line of sight (LOS), and tracks the rotations of the science baseline in the plane orthogonal to the nominal LOS. The sensitivity of the science measurements to Guide-2 errors is comparatively small. SIM Lite takes advantage of this reduced sensitivity by using a simpler instrument to achieve the Guide-2 function. Guide-2 also tracks the "roll" of the external metrology truss about the science baseline (Figure 16-6).

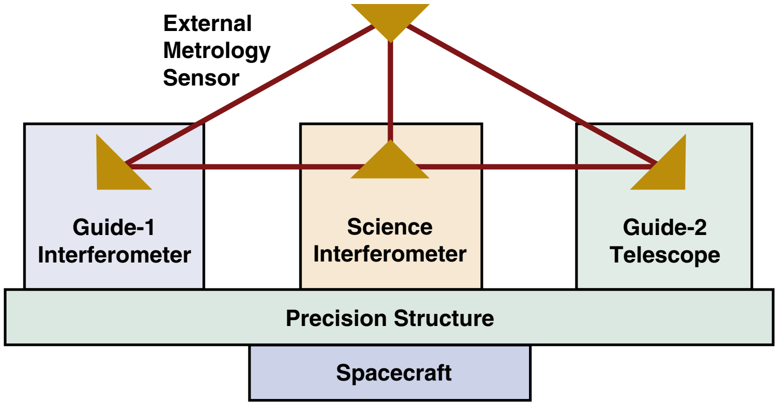


Figure 16-4. SIM Lite can be thought of as four fundamental sensors operating together to make an astrometric observation.

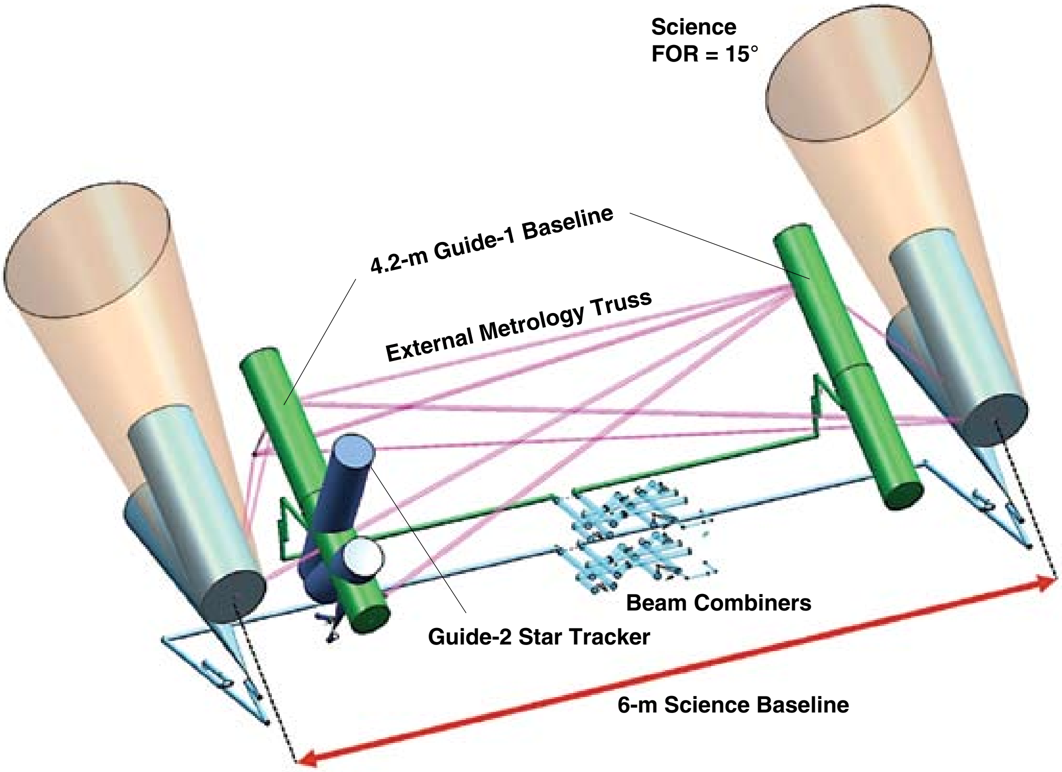


Figure 16-5. The geometry of SIM Lite's external metrology truss with respect to the science and guide sensors. The cylinders and cones represent the light paths of the interferometers and guide telescope.

Figure 16-6. The narrow-angle observing geometry in three dimensions (a), and projected onto the sky (b). The gray vector in (a) shows baseline motion $d\theta$ in the direction observed by the Guide-2 instrument.

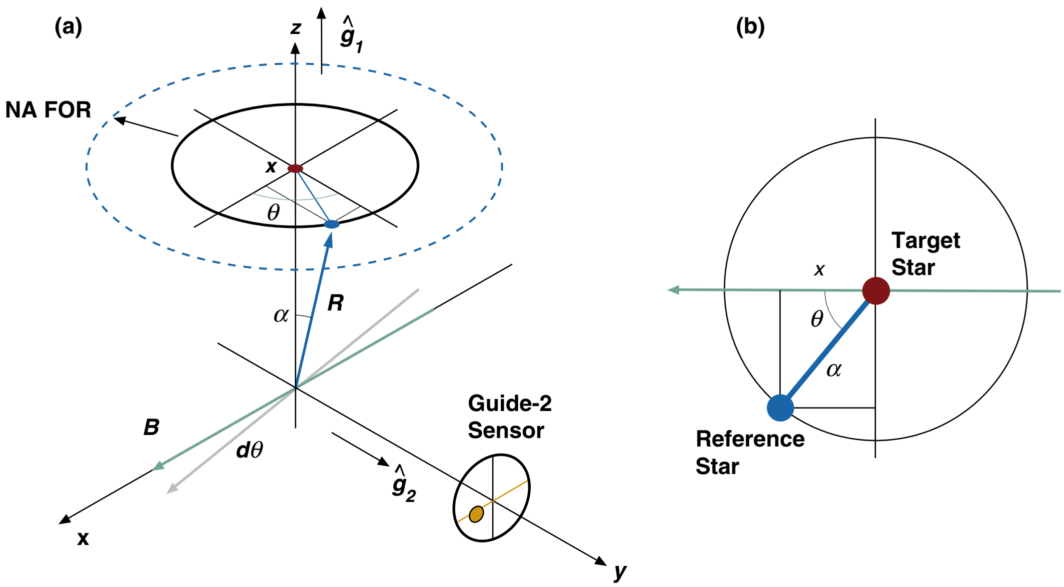
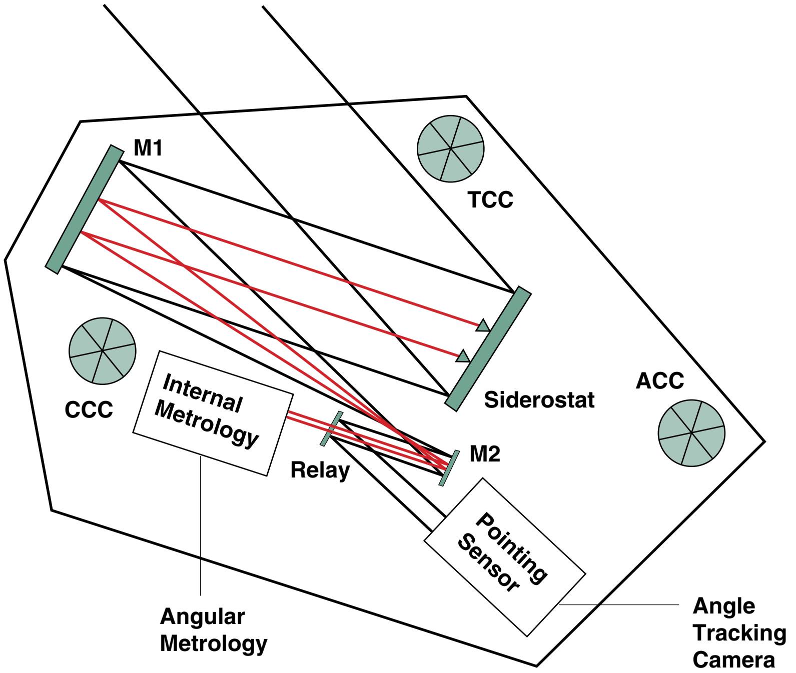


Figure 16-7. Guide-2 telescope schematic. The pointing sensor is an angle tracking camera. These corner cubes (ACC, TCC, and CCC) act as fiducial reference points.



Shown schematically in Figure 16-7, the Guide-2 telescope uses an angle tracker camera and an angular metrology system to tie its measurements to the rest of SIM Lite. To achieve the tie, fiducials are mounted on the Guide-2 bench so that its motion can be monitored by external metrology. The telescope images the guide star on its angle tracking camera. Using its siderostat fine stage, it maintains its line of sight on the desired spot on the camera focal plane. The measurement of rotation is then made using an angular metrology system that measures the tip/tilt of the siderostat relative to the bench.