Laser Metrology in the Micro-Arcsecond Metrology Testbed
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Abstract
The Space Interferometer Mission (SIM), scheduled for launch in 2009, is a space-born visible light stellar interferometer capable of micro-arcsecond-level astrometry. The Micro-Arcsecond Metrology testbed (MAM) is the ground-based testbed that incorporates all the functionalities of SIM minus the telescope, for mission-enabling technology development and verification. MAM employs a laser heterodyne metrology system using the Sub-Aperture Vertex-to-Vertex (SAVV) concept. In this paper, we describe the development and modification of the SAVV metrology launchers and the metrology instrument electronics, precision alignments and pointing control, locating cyclic error sources in the MAM testbed and methods to mitigate the cyclic errors, as well as the performance under the MAM performance metrics.

Keywords: interferometry, metrology, laser heterodyne interferometers, astrometry

Introduction
The Space Interferometry Mission (SIM) will be a space-born Michelson interferometer that measures the apparent position of every star in the sky, to a limiting magnitude of \( V = 20 \), with a precision of 3\( \mu \)arcsec. Astrometry to this precision requires internal measurements of the interferometer baseline change with an accuracy of tens of picometers.

A schematic of how internal metrology operates in SIM is shown in Figure 1. The starlight is collected by the two telescopes separated by the baseline \( B \) and sent down the optical train. The two starlight beams interfere at the beam combiner, and form a white light fringe once the delay-line in one arm is adjusted so that the optical path lengths of the two starlight beams match. The optical path length difference of the two interferometer arms is measured by metrology beams that traverse the exact paths as the starlight.

In its simplest form, SIM performs relative astrometry between two stars by taking a pair of internal optical path length delay measurements, one for each star. A key measured quantity is the change in the delay-line position \( \Delta d \),

\[
\Delta d = \hat{B} \cdot (\vec{s}_1 - \vec{s}_2)
\]

where \( \hat{B} \) is the baseline vector (length and orientation) and \( \vec{s}_1 \) and \( \vec{s}_2 \) are the unit vectors of pointing towards the two stars. The angular distance between the two stars \( (\vec{s}_1 \cdot \vec{s}_2) \) can then be determined once \( \Delta d \) and \( \hat{B} \) are measured by the internal and external metrology.

MAM, the Micro-Arcsec Metrology testbed, is intended to prove the feasibility of the basic operational technologies required by SIM. In particular, MAM's central goal is to show that internal metrology can track the phase of the starlight interferometer to an accuracy of tens of picometers.

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Figure 1. Stellar interferometer for astrometric measurements.

Figure 2. Simplified MAM schematics.
As shown in Figure 2, the basic interferometric measurement carried out by SIM on starlight is emulated in MAM by the white-light interferometer, contained in a major opto-mechanical subsystem called TA (“Test Article”). The white-light source that feeds this interferometer is found in IIPS (“Inversed Interferometer Pseudo-Star”), an opto-mechanical subsystem of MAM that produces a wavefront emulating that from a distant star. Linear translations of the IIPS feed mirrors create different “look” angles corresponding to different star positions. The white-light source spans 600-1000 nm with a spectrum corresponding to a 3100 K thermal source. IIPS produces coherent beams of light from two outputs at a spatial separation of 5 meters, which feed the input siderostats of TA.

**Laser heterodyne metrology**

Laser heterodyne interferometers are widely used in high precision displacement measurement and have been the choice of stellar interferometry in measuring path delays [1]. A laser heterodyne interferometer includes a laser source, frequency modulators that create a frequency difference between the reference and measurement beams, the opto-mechanical system (launcher) that launches the measurement beam into the optical path to be measured and “mix” the returned measurement with the reference beam to form the heterodyne metrology signal, and the electronics that amplify and condition the signal, as well as a digital phase meter to read out the phase information (see Figure 3).

![Figure 3. Schematics of a laser heterodyne metrology system.](image)

In designing laser heterodyne interferometers capable of accurately measuring to picometer accuracy, a number of issues that are ignored as insignificant in most interferometer designs need to be considered here.

The noise sources that limit the performance of a metrology gauge can be categorized in to the gauge errors and alignment errors. The gauge errors include:

1. Systematic errors: cyclic error, laser wavelength variation, phase-meter digitization error, diffraction errors, etc.
2. Random noise: photodiode shot noise, pre-amp thermal noise etc
3. Environmental errors: thermal drift, amplitude-to-phase error and propagation delay dispersions in the electronics.

The alignment errors mainly consist of cosine and Abbé errors, which correspond to pointing and overlap errors between the star light and the metrology beam, respectively.

The cyclic error is the most dominant error source in almost all the heterodyne metrology systems. It is caused by “stray” light contamination and/or crosstalk that follow a different path (e.g., reflecting off of an optic face and then repeating the measurement trip) and get into the measurement metrology beam.

The cyclic error also arises from crosstalk between the electronic signal trains. The major sources of crosstalk in the optical domain are:

1. Polarization leakage
2. Diffraction leakage
3. Straylight

Most traditional gauges and JPL’s early development use collocated measurement and reference beams with orthogonal polarizations, with a polarizing beam splitter to direct the measurement beam out to the fiducials and separate the return beams [2-4]. Even with the best available polarizers and careful alignment, it was not possible to achieve the degree of isolation required by SIM.

Previous studies have also shown that it is critical that both the measurement and the reference beams go through the same optics, lest the thermal differences and optical pathlength differences introduce an overly large error. The concept is to have the two beams follow the same path, but separated geometrically. This led to a novel Common-Path Heterodyne Interferometer (COPHI) design that was proposed and demonstrated at JPL in 2001, as a multi-purpose, high precision laser heterodyne metrology gauge [5-9].

In COPHI, wavefront division, instead of polarization division is used to improve the isolation between the two measurement beams, which leads to greatly reduced cyclic errors—27pm RMS in experimental demonstrations. Good thermal stability (~100pm over one hour) is also achieved because the measurement beams and the local oscillator share the same gauge optics [7].

Based on the COPHI concept, a laboratory prototype of the internal metrology launcher for MAM was developed. It inherited the same common-path design and features a wavefront division scheme that centers the measurement beams on the vertices of the retroreflectors residing on the fiducials for vertex-to-vertex measurement, thus free of any detrimental effects of the dihedral errors of the retroreflectors to the first order. This design is called Sub-Aperture Vertex-to-Vertex, SAVV.

Figure 4. SAVV schematic.

SAVV launchers

Figures 4 and 5 show the schematic layout and picture of the first SAVV interferometer [10]. Commercial off-the-shelf doublet collimating lenses are used to collimate the laser beams. To minimize thermal drift error caused by collimator de-spacing, a four-quadrant beam pattern is used, shown in Figure 6. The collimator de-spacing becomes a common-mode error, because the measurement beams reside on the same radius. The vertical and horizontal pairs are used separately in the two arms of the MAM interferometer, selected by a pair of masks shown in Figure 7. Square beam patterns are used because of the small diffraction crosstalk along the diagonals. A pair of Risley prisms on motorized rotary stages is used to align the reference beam (local oscillator) to be parallel to the measurement beams to within 1μrad.

Figure 5. Picture of a SAVV prototype interferometer.
Figure 6. Four square beams are selected from the collimated beam with a quadrant mask in SAVV.

Figure 7. A two-hole mask in Arm #1 selects a horizontal pair of the quadrant beams. In Arm #2, an identical mask rotated by 90 degrees selects the vertical beams. The central obscuration in starlight is used for laser metrology for path delay measurement.

Figure 8. Linear displacement over many laser wavelengths to detect cyclic error in SAVV. The bottom plot shows the residual after removing its DC to 4th order polynomial terms.

Figure 9. Power spectral density of Figure 7-b. The peak at 3.8Hz is attributed to SAVV cyclic error. The accumulated PSD data (bottom) indicates the cyclic error is about 67pm RMS.

Figure 10. SAVV drift vs. bulk temperature.

Figure 11. SAVV drift vs. temperature gradient.

The cyclic error of SAVV was measured with a standard linear long stroke approach, in which one of the two metrology beam paths was modulated by a piston motion by a PZT. The linear path length modulation is much longer than one wavelength; therefore, cyclic errors can be identified at the cyclic frequencies in the power spectrum of the displacement measurement. In our experiment, the laser
wavelength is 1.319 μm, and the total stroke of the PZT is ~40μm with a triangle wave modulation at 0.05Hz. Thus cyclic error with λ/2 periodicity can be found at about 3.5Hz in the spectral domain.

The top plot in Figure 8 shows the measured displacement of the PZT. We selected an arbitrary linear displacement, e.g., between 44 and 61 seconds for data analysis. The bottom plot shows its residual after removing its linear to 4th order terms. The power spectral density of the residual is calculated and plotted in Figure 9, which shows a peak at 3.8Hz indicating the existence of a λ/2 periodic nonlinear error. The total energy of this cyclic error is estimated at ~4500pm², which translates into a periodic nonlinear error of ~67pm RMS. This meets MAM’s requirements of <100pm cyclic error.

The SAVV launcher's temperature sensitivity was also measured, using the lab ambient temperature fluctuation (~1°C) as the driver. In the measurement, a corner cube was placed in front of the launcher and all four measurement beams are retro-reflected from this corner cube. Sending all the measurement beams to the same corner cube ensures no differential path length drift in the fiducial. Therefore, all the errors in the measurement can be attributed to the launcher thermal drift. The thermal stability results are plotted in Figures 10 and 11, which shows good thermal stability—less than 4nm/K at room temperature. It can also be seen from Figure 10 that, SAVV drift is highly correlated with the change in the temperature gradient. Gradient fluctuations in the middle of the measurement were caused by the air conditioning cycles in the lab, which will be absent in the flight environment.

**SAVV integration and system-level test in MAM**

Figure 12. Detailed optical layout of MAM (TA+IIPS).
Demonstrating that pathlengths within an interferometer measured by metrology gauges are a reliable representation of the pathlengths traveled by the starlight, at the required level of accuracy, is the purpose of the MAM testbed. The MAM performance metric is a measure of the difference in two measured quantities (white light and metrology pathlengths). Figure 12 shows a detailed optical layout of MAM. The white light path lengths are measured with a white light fringe detector consisting of a spectrometer and a CCD camera while the laser metrology is carried out by one SAVV gauge that launches metrology beams to both arms of the interferometer.

The SIM mission design calls for a chopping observing technique, in order to reduce the effects of instrument drifts. A typical measurement involves 5 minutes of total observation. SIM can choose to chop between two stars as frequently as every 30 seconds, or as infrequently as every 5 minutes. For this reason, MAM analyses its data based on this chopping scenario using a technique similar to the Allan variance to determine the ultimate MAM accuracy [11]. Figure 13 shows a typical SAVV survey using the MAM performance metrics in terms of Allan Variances and the result after chopping to take out thermal drifts.

Figure 13. SAVV self-test in MAMTB. The plot on the left shows the Allan Variance and the one on the right shows the SAVV performance using MAM metrics with multiple chops.

The performance of the MAM testbed is limited by many factors, among which the capability to accurately measure the white light and metrology path lengths and the capability to make the metrology paths a faithful representation of the white light paths are the most critical. They can be categorized into the gauge error and alignment error, respectively.

The alignment errors include both cosine (pointing) and Abbé (overlap) error [ref]. To achieve the level of accuracy of the MAM testbed, the metrology beam has to be parallel to the white light to with 10μarcsec, with <10μm overlapping error. The parallelism is established by the alignment sensors (two ALU’s in TA, and one bore-sight sensor in IIPS (not shown)) while the overlapping accuracy is accomplished by a series of “de-center” tests that monitor and correct the metrology error by adjusting and optimizing the photo-center of the collimated white light beam in IIPS [12]. The alignment accuracy is also maintained using control loops that feed off the same sensors.

The gauge errors include systematic errors such as the cyclic error, diffraction error, and digitization error in the phase metering system, and random errors that come from the photo detector shot noise, amplifier thermal noise, etc., as well as environmental errors in thermal drifts, amplitude-to-phase error and propagation delay dispersion error in the electronic signal chain.

Among the gauge errors, the cyclic error presents the biggest challenge. Since wavefront division is employed to separate the measurement beams of the two arms of the interferometer, diffraction and stray light become the major cause for the cyclic error in MAM metrology. Cyclic errors are a direct result of crosstalk between the metrology signals, and they can be further divided by the nature of the crosstalk into intra-arm and inter-arm contributions.
The intra-arm crosstalk refers to the “self-inflicted” noise that arises within the one arm and contaminates the metrology signal of the same arm. It mainly comes from the stray light and ghost reflections as well as electrical coupling between the Local Oscillator (LO) and measurement driver electronics.

The inter-arm cyclic errors are caused by electrical crosstalk between the electronic signal trains corresponding to the metrology signals of the two arms, and in MAM, diffraction of one measurement beam into the other. The latter is minimized by the beam geometry in SAVV launchers.

A survey of cyclic errors in the MAM testbed is shown in Figure 14. The shape of the cyclic error curve indicates two commensurate components, one with period equal to the wavelength of metrology light, as plotted against path length difference in the two arms of TA, and the other with period twice this. These components correspond to the intra and inter-arm cyclic errors.

![Figure 14 - Signature of cyclic error in 1319 nm metrology (north arm minus south arm): a repeatable error on measured OPD difference between the white light and metrology that is periodic in the true OPD, with period a simple multiple of the metrology wavelength.](image)

As shown earlier, stand-alone tests of the SAVV launcher yielded a cyclic error of ~67 pm. But the system-level test show in Figure 14 shows cyclic errors on the order of several hundred pm when integrated in the MAM interferometer. A lesson emerging from our experience in this area is that the full metrology system, consisting of the actual laser to be used, the frequency modulation system, the fiber distribution system, the beam launcher (SAVV), the optical train, as well as the electronics that include the preamps, post-amps, phase meter, as well as the interface and software, must be studied as a system.

The type of survey whose result is shown in the above figure requires post-processing of the metrology data. In real-time diagnostics and trouble-shooting, a spectrum analyzer is frequently used to identify sharp noise peaks at the cyclic frequencies under various testing conditions. In addition to the spectrum analyzer, we developed a peak detector circuit that captures the cyclic signature showing up as amplitude modulation. Figure 15 shows the real-time metrology telemetry that has ripple that correspond to cyclic errors when we piston the mirrors in the TA side.

These “cyclic detectors” are used in conjunction with corner cubes, beam blocks, and attenuators to confine testings to various subset of the metrology system and pinpoint the sources of noise. For
example, the back-scatter off the fiber tips inside of the launchers was long suspected to be a major
contribution to the intra-arm crosstalk. With an ND filter right in front of the launcher, this crosstalk would
have to travel two more times (back and forth) through the attenuating material. Therefore, the cyclic error
due to this crosstalk would have been greatly reduced should it be a significant factor. However, in our
experiments, we did not observe a noticeable reduction of the cyclic errors. This ruled out the back-scatter
off the fiber tip inside the launcher as a significant noise source.

Note, on this scale of accuracy, minor problems and things that appear totally innocent on the
surface can cause excessive cyclic errors. For example, we identified intra-arm cyclic noise sources in the
scattering from the beam dumps that we used within the launcher, back-reflections off the main beam
masks, electrical coupling in the grounding/shielding of the AOM’s, as well as internal crosstalk within the
RF driver. However, the majority of the cyclic noise arises from the quadcells in the alignment sensors,
especially the angle sensors that form cat’s-eye-like reflectors that create significant amount of low spatial
frequency that is more efficient in forming noise fringes with the LO.

Figure 15. A real-time metrology telemetry showing cyclic errors during in-phase pistoning of the mirrors
in TA. The mirror piston motion completes a cycle in 5 seconds, spanning over one half of the metrology
wavelength.

The periodic nature of cyclic error makes it amenable to “cyclic averaging” [13], in which path
length differences are evaluated between points on the error curve separated by a multiple of the cyclic
error period, so errors at the two points cancel. The particular implementation used with MAM is shown
schematically in Figure 16. Four mirrors, one in each arm of both TA and IIPS, are dithered with a
triangle-wave path length modulation, with a scan amplitude of half a metrology wavelength on each
mirror. Scans are synchronized, and take 5 seconds, so that 6 cyclic averaging scans are accomplished in a
single 30-second data set.

Uncorrected cyclic errors in MAM are variable, but typically amount to 600 pm. With the cyclic
averaging techniques outlined above, they are reliably reduced to ~60 pm, below the general noise floor. In
MAM, different ways of cyclic averaging can be accomplished because the pseudo-star (IIPS) can
compensate for any net path length change produced in the TA side. However, for the actual interferometer
to independently average out the cyclic errors while maintaining the total path length difference, only in-
phase piston on the two mirrors is doable, thus limiting the cyclic averaging to the intra-arm sources only,
while leaving the inter-arm crosstalk, if there is any, uncorrected.
Figure 16. Schematic of solution for cyclic averaging: four mirrors (FSMs on TA; IIPS steering mirrors) are dithered half a metrology wavelength in a synchronized pattern as indicated by the arrows.

With cyclic averaging to suppress the intra-arm crosstalk, MAM has successfully demonstrated MAM performance data of 26 pm RMS for the field independent tests and 40 pm RMS for the field dependent tests, as shown in Figure 17. The achieved performance maps to 13 pm RMS for SIM's guide interferometers and 20 pm RMS for SIM's science interferometer, below the goal level that enable single micro-arcsecond astrometry [14].

Figure 17. MAM performance metrics: (a) Chop deviation of the difference of white light OPD and SAVV metrology as a function of the number of 30-second data chops averaged together for the same field independent test. (b) Error between white light and metrology paths as a function of the number of chops averaged together for the field dependent test using the narrow angle chopping analysis.
Summary

We have developed a laser heterodyne metrology gauge (SAV) and integrated it into the MAM testbed. System-level testing in terms of MAM performance metrics yielded results that are better than the goal levels of the MAM testbed.

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