

External Metrology Truss Technology Demonstration (KITE)

Bijan Nemati

Jet Propulsion Laboratory, California Institute of Technology
Mail Stop 301-486, 4800 Oak Grove Drive, Pasadena, CA USA

ABSTRACT

To achieve micro-arcsecond astrometry, SIM's external metrology system must track the relative changes of three baseline vectors with a precision of tens of picometers over a one-hour time scale. The Kite testbed is designed to be the technology demonstration for a picometer-class external metrology truss. Four fiducials, two simple corner cubes and two triple corner cubes, are arranged in a planar parallelogram configuration to allow a redundant measurement of truss deformations by six metrology gauges placed between the fiducials. Each metrology gauge is capable of 20-pm relative metrology accuracy and 10- μm absolute metrology accuracy, using a beam launcher capable of self-alignment at the arcsecond level. The Kite demonstration involves the articulation of one of the corner cubes to simulate SIM instrument geometrical changes while various performance metrics are evaluated based on the readings of the individual metrology gauges. The test performance metric compares the direct measurement of length changes by one metrology gauge against the computed estimate for the same based on the other five gauges.

Keywords: metrology, corner cube, truss, interferometry, picometer, heterodyne

1. INTRODUCTION

SIM is designed to measure relative angles of stellar objects at the micro-arcsecond (μas) level.¹ It does so using three stellar interferometers simultaneously. The basic features of a stellar interferometer are shown in the figure below. At its most basic level, the interferometer measures the correlation of the stellar wavefront sampled at two fiducial points.

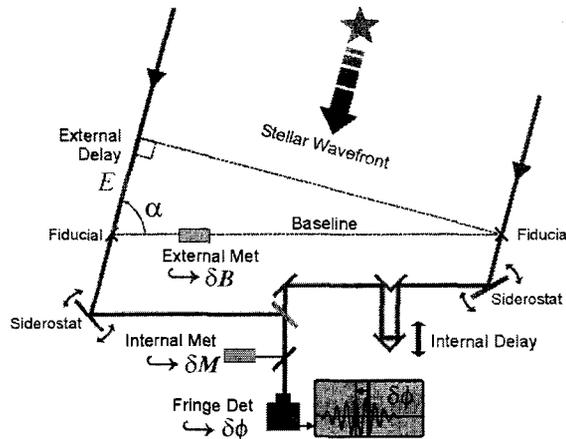


Figure 1: Basic elements of a stellar interferometer. The external delay E is the difference of the total delay as measured by the starlight fringe detector, and the internal delay, as measured by the internal metrology system. The baseline length is measured by the external metrology system.

The delay, along with a measurement of the baseline length, gives the angle between the star and the baseline in the plane formed by the baseline vector and the unit vector to the star:

* For further information contact: bnemati@huey.jpl.nasa.gov ; phone (818) 354-0883.

$$\cos \alpha = \frac{\vec{B} \cdot \hat{s}}{|\vec{B}|} \equiv \frac{E}{B} \quad (1.1)$$

In fact, it is the changes in the angle that are of greatest interest, since these can be done much more precisely. Differentiating Equation (1.1) yields

$$\sin \alpha \delta \alpha = \delta \left(\frac{\vec{B} \cdot \hat{s}}{B} \right) = \hat{b} \cdot \delta \hat{s} + \delta \hat{b} \cdot \hat{s} \quad (1.2)$$

This equation can be used and interpreted in two distinct ways. The first is that SIM measures angle differences between stars, and these are described by the first term. The second is that during the measurement of the relative angle for a given star, changes in the baseline unit vector need to be known. SIM's external metrology system measures the changes in the science interferometer baseline vector relative to the guide baseline. The system is composed of a laser metrology truss, with the fiducial points being defined by corner cube retro reflectors. Figure 2 shows the SIM reference design. There are 6 fiducials of interest. Two comprise the end points of the baseline that is common to guide interferometers 1 and 2. The other four are mounted on siderostats for the science and the spare interferometer.

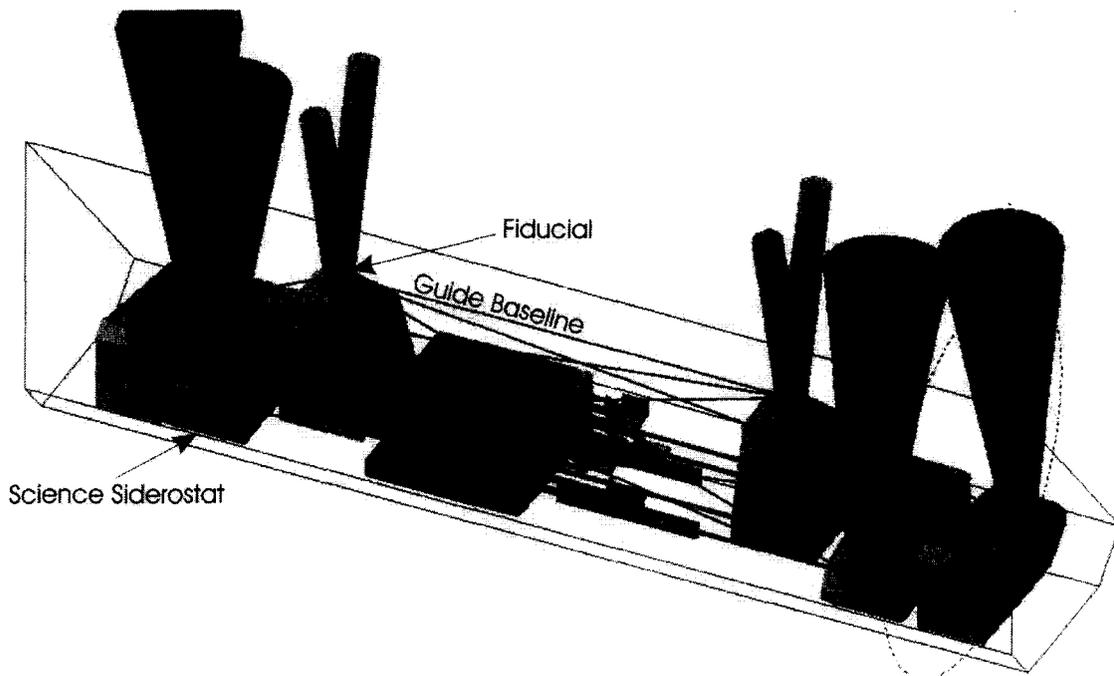


Figure 2: SIM Reference Design. The inter-fiducial lengths are measured by the external metrology system.

The performance requirements for the SIM external metrology system are derived from the SIM error budget and performance model. Currently there are three categories of external metrology errors that are accounted for in the error budget. These are:

1. relative metrology errors
2. absolute metrology errors
3. fiducial errors

Relative metrology errors include cyclic errors arising for optical or electrical cross-talk, thermal variations affecting the beam launcher optics, signal-to-noise, and electronics. Absolute metrology is the measurement of the total length of a truss leg. This is needed as a-priori information for relating the measurements of the truss leg length variations. Fiducial errors are those errors that arise from using an imperfect corner cube. An ideal cube has perfectly flat faces at exactly 90 degrees from one another, and has an ideal conductor for the coatings. A real cube, on the other hand, has faces that have

wavefront errors, have dihedral errors, and is coated with a real metal like gold. Since the conductivity of gold is finite, it has a non-zero skin-depth at the wavelength of the metrology laser, causing an error in the distance measurement as the corner cube is articulated.

To investigate these errors, the Kite testbed was designed as a 2-dimensional metrology truss consisting of four fiducials. The two dimensional design allows a redundant truss with 4 fiducials. In general any 4 points can be interconnected with 6 distinct lines. In two dimensions, there are a total of $4 \times 2 = 8$ degrees of freedom (DOF) associated with these points. Since the overall location (2 DOF) and orientation (1 DOF) of the truss are not derived from the truss itself, these degrees of freedom are degenerate. Hence the number of unknowns are reduced to $8 - 2 - 1 = 5$. This means that any 5 lengths of a four-point two-dimensional truss suffice to predict the remaining length.

2. THE KITE TESTBED DESIGN

The essential elements of the Kite testbed are illustrated in Figure 3. Ideally the truss would have an aspect ratio close to unity to maximize its sensitivity to fiducial motions in every direction. In Kite, the actual shape of the truss was dictated by the need to reach the same fiducial point at largely different angles. To achieve this a pair of triple corner cubes (TCC) were designed and integrated at JPL.

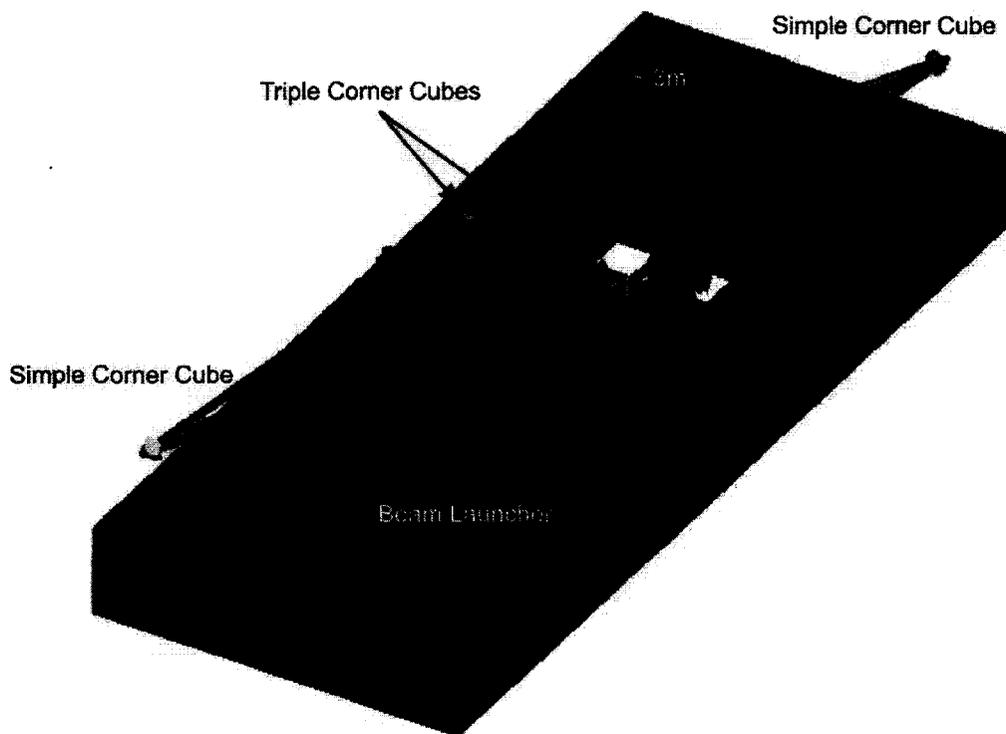


Figure 3: The Kite 2-dimensional metrology truss design. The large aspect ratio is due to the geometrical limitations of the triple corner cubes. The longest leg is approximately 3 m in length, and the shortest leg is approximately 0.52 m in length. The angle between the longest leg and adjacent legs is approximately 9 degrees.

Each TCC was constructed from 4 pieces, the most challenging being a 30-degree wedge. The vertices of the three corner cubes were measured to be about $12 \mu\text{m}$ apart.² The typical cube surface quality is $\lambda/5$ peak-to-valley, while the dihedral error in the worst case is approximately 1 arc-second.



Figure 4: Kite triple corner cube (TCC). In Kite, the TCC is oriented in such a way that the three corner cubes have their symmetry axes close to the Kite plane.

The other two fiducials in Kite are simple corner cubes. Of these, one is singled out as the test corner cube, and was built to very tight specifications. The test corner cube is mounted on a six-axis rotation and translation system. Shown in Figure 5, the rotation system is comprised of a Newport goniometer stack mounted on a rotation stage, aligned to have the axes of rotation less than 50 mm at point of closest approach. The translation degrees of freedom were provided by a piezo-driven three-axis actuator from Physik Instrumente called a "Nanocube."

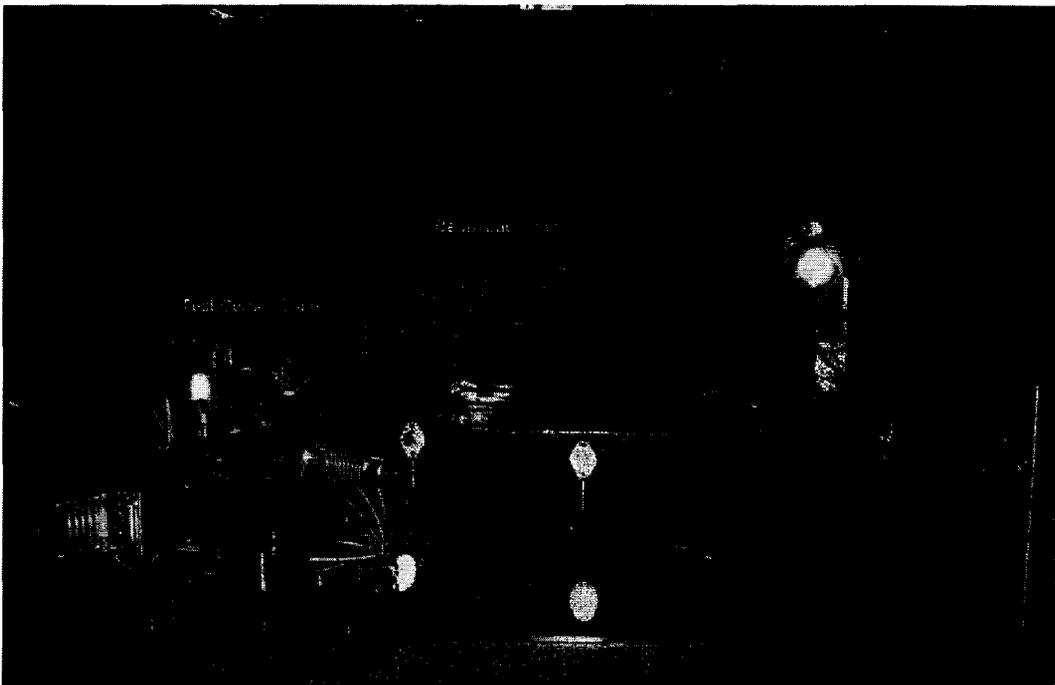


Figure 5: Kite testbed during integration and testing inside the vacuum chamber at JPL. The drawn lines indicate the location of the (infrared) truss beams. The bright spot in the picture is due to the camera flash.

In order to obtain a redundant truss, it is necessary for the four fiducials to lie in a plane. The planarity requirement for the Kite fiducials is 100 μ m. To achieve this, a theodolite, located outside the vacuum chamber scans each vertex. The nearest corner cube sits on a rotation stage and is turned so that the theodolite can measure it.

The beam launchers used in Kite were based on a JPL concept and were designed at built by Lockheed Martin. The QP beam launcher's essential improvement over traditional designs is the use of spatially separated metrology and reference

beams. It has been known for some time that polarization leakage in beam launchers that use polarizing beam splitters to separate the reference and measurement beams causes optical cross-talk and hence cyclic errors. The level of cyclic error in the QP has been measured to reach as low as about 40 pm.

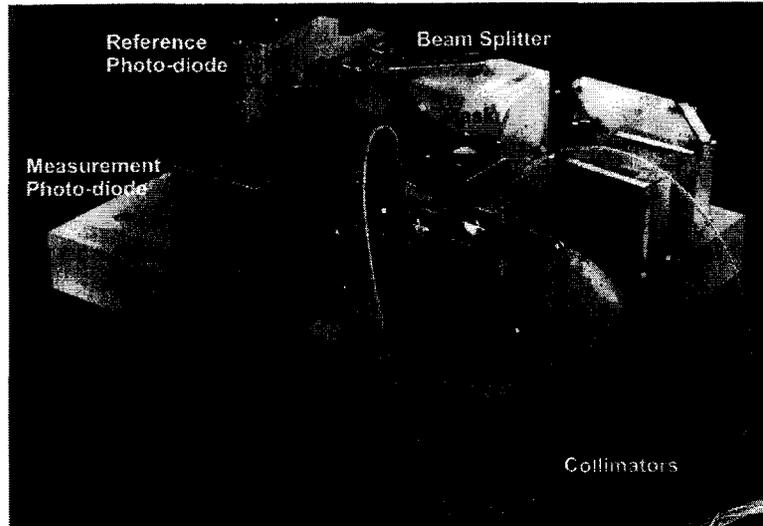


Figure 6: The QP, originally designed to be a "quick prototype" to demonstrate innovative solutions for high-performance metrology, was adopted for the Kite testbed.

The QP operates in racetrack mode, as illustrated in Figure 7.

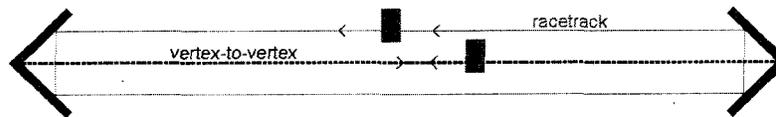


Figure 7: Metrology beam launcher configurations in racetrack mode versus vertex-to-vertex mode.

The alignment of the each beam launcher with respect to the inter-fiducial vector is necessary for precision metrology. To illustrate with a simple example, consider Figure 8 where the beam launcher is shown to be mispointed by some angle θ relative to the inter-fiducial line.

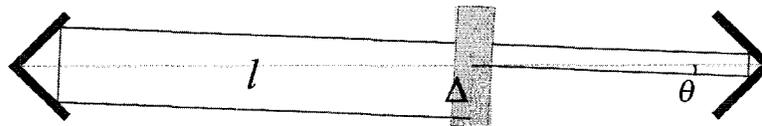


Figure 8: The effect of mispointing a launcher on the pathlength and shear of return beam. For simplicity, the launcher shown nominally works in vertex-to-vertex mode.

There are two effects that result from this. The first is an error in the metrology reading:

$$l' = l \cos \theta \tag{1.3}$$

This means that the measured length will have an error of:

$$\varepsilon = l' - l \approx -l \frac{\theta^2}{2} \tag{1.4}$$

Hence, the signature of proper pointing is that the measured pathlength is a maximum as a function of the pointing angle.

The second effect is a shear of the return beam relative to the original beam:

$$\Delta \approx 2l\theta \quad (1.5)$$

Since these two beams are combined to interfere inside the beam launcher, the shear can also be a potential source of systematic error.

Kite uses a narrowband demodulation scheme to detect and automatically minimize pointing errors.³ The essence of the technique is to dither the pointing direction by scanning conically about some axis. If this axis makes an angle θ with the inter-fiducial line, then the change in the measured pathlength is given by differentiating Equation (1.4):

$$\delta\epsilon = -l\theta\delta\theta \quad (1.6)$$

The conical scan means that $\delta\theta$ will change sinusoidally at the dither frequency, and hence so will $\delta\epsilon$. The pointing control system uses this as the error signal. The DC pointing error requirement for Kite is $\theta < 5 \mu\text{rad}$.

In order to relate the readings of the gauges to each other and have the system work as a truss, knowledge of the absolute lengths, i.e. absolute metrology, is needed. The essence of the absolute metrology technique is to measure a change in the phase detected by the metrology gauge as the laser frequency is changed. Various techniques have been used to achieve this. Kite uses the switched heterodyne method for absolute metrology,⁴ where two different lasers separated in frequency by a definite amount are alternately fed to the metrology gauge. The phasemeter reads the phase in each case.

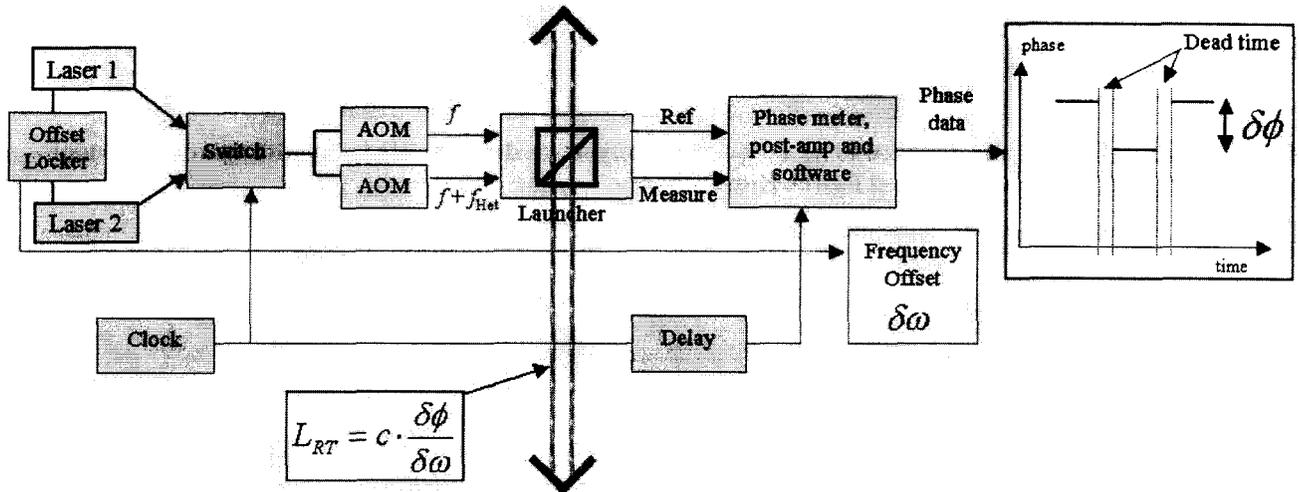


Figure 9: Switched heterodyne absolute metrology system architecture.

The ratio of the phase difference over the (angular) frequency difference is proportional to the absolute round trip path, according to the relation:

$$l = c \frac{\delta\phi}{\delta\omega} \quad (7)$$

One can rewrite Equation (7) in terms of the wavelengths of the two lasers:

$$\delta\phi = \phi_2 - \phi_1 = 2\pi \left(\frac{l}{\lambda_2} - \frac{l}{\lambda_1} \right) = \frac{2\pi}{\lambda_s} \quad (8)$$

where λ_s is called the synthetic wavelength and represents the ambiguity distance of the absolute metrology. It can be shown that the synthetic wavelength is given also by:

$$\lambda_s = \frac{c}{\delta f} \quad (9)$$

where δf is the frequency difference between the lasers. For Kite, $\delta f = 5$ GHz, so that $\lambda_s = 6$ cm. This means that the round trip path must be known to the nearest 6-cm interval with negligible error. A tape measure survey of the Kite truss has been done with an error of less than 10 mm. In terms of inter-fiducial distance, the ambiguity is half the synthetic wavelength, that is, 30 mm. The absolute metrology system needs to provide distance measurements for the Kite at the 10 μ m level.

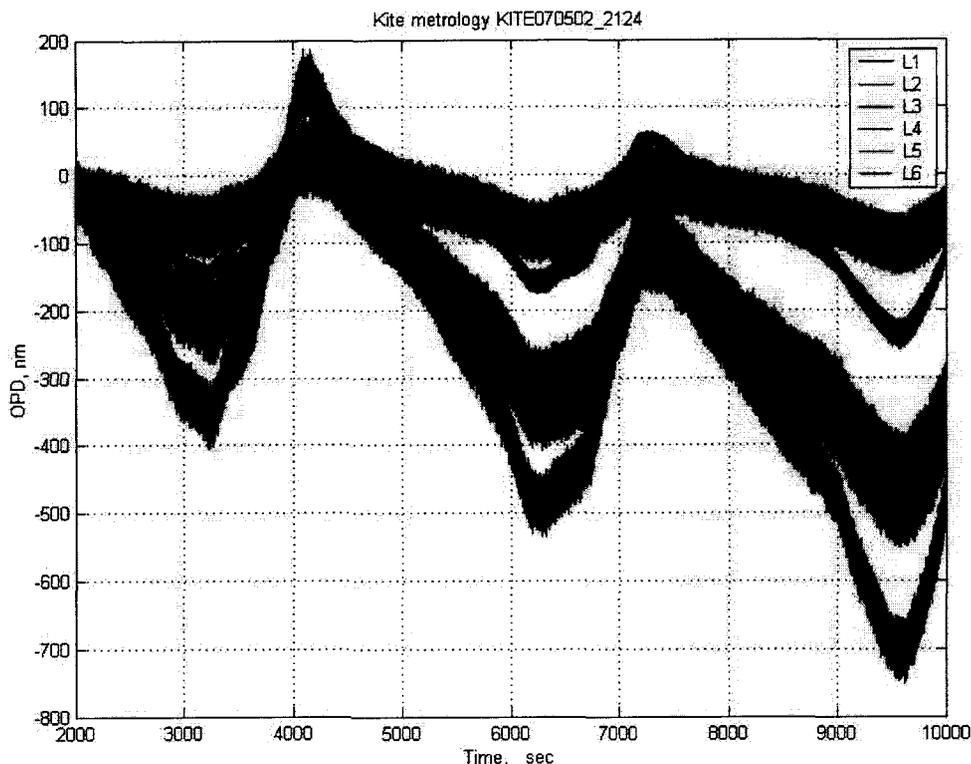


Figure 10: Kite truss metrology telemetry from all the legs under quasi-static conditions. The periodic variation in the measured pathlengths is thermally driven.

3. DATA

The Kite data acquisition system allows readout of metrology data from all truss legs at 1 kHz. The basic data set used for the analysis of the data are the survey results from absolute metrology (6 numbers indicating the length of each leg) plus the relative metrology data. The longest leg of the Kite is used as the test leg, so that the other 5 legs are used in predicting the readings of the metrology gauge for this leg. The test corner cube, shown in Figure 5, is moved or articulated according to the category of testing required. In all testing modes, the basic quantity of interest is the Kite error metric:

$$\Delta_i \equiv L_i^{2,meas} - L_i^{2,pred} \quad (1.10)$$

where $L_i^{2,meas}$ is the direct measurement of the test leg of the Kite (“Leg 2”) and $L_i^{2,pred}$ is the prediction using the other legs. The index i indicates the telemetry item, so that one such Δ_i is computed for each millisecond of data. As mentioned earlier, the measurements are in fact relative. The procedure used is to add the absolute metrology length for each leg to the relative metrology measurements.

$$L_i^{k,meas} = L_0^{k,abs} + L_i^{k,rel} \quad (1.11)$$

where the index k ranges from 1 to 6 for the legs of the Kite. The sum is obviously dominated by the many-micron class error in the absolute measurement. However, the relative variations are properly handled in this method. A simple analytic formula gives the predicted length at each data point.

Beyond the basic error metric Δ_i , the next quantity of interest is the so-called per-look average. The term “look” originates from SIM observing scenarios and represents a 30-second average:

$$\bar{\Delta}_{30} \equiv \sum_i^{30\text{sec}} \Delta_i \quad (1.12)$$

In Kite’s case this translates into averaging the error metric over 30 seconds.

The most basic mode of testing is quasi-static, where no intentional motion is applied. Figure 10 is an example of data from a quasi-static run, spanning a few hours. The most prominent feature observable is the large periodic variation with approximately a one-hour period. This is a thermally driven variation, and can be seen to cause approximately half 600 nm of variation in the longest leg over an hour.

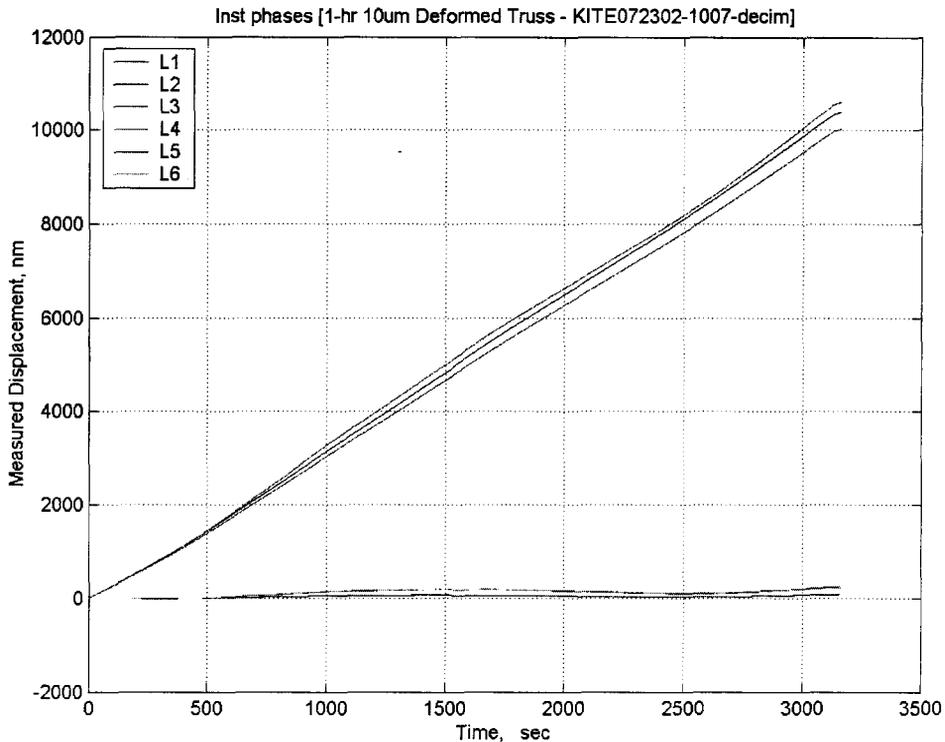


Figure 11: Long duration run with intentional truss deformation along the long direction of the Kite.

Another example is the data run shown in Figure 11. The truss in this case is intentionally deformed and the metric error is computed. The result appears in Figure 12, which shows that original measured change in the long leg of the Kite, along with the estimated, which in the figure appears nearly indistinguishable. In picometer units, the difference is also plotted. The figure shows clear sign of a cyclic error, a few hundred picometers peak to peak. This error, which arises from cross-talk is being reduced. Additionally the remaining cyclic error can be reduced via averaging.

In Figure 13 the metric data is shown after being binned into 30-second looks. The de-trended plot has a standard deviation of 178 pm.

4. CONCLUSION

This paper has presented a brief overview of the Kite testbed at JPL. In a two-dimensional test, the Kite testbed has shown that the readings of the six planar gauges can achieve a self-consistency of less than 200 pm over an hour. Many other tests are being currently conducted and have been planned to provide a complete picture of the metrology truss performance expectations for SIM. Overall, the results so far have demonstrated that a high performance metrology truss that can meet the SIM requirements is technically achievable.

5. ACKNOWLEDGEMENT

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

6. REFERENCES

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