The Micro-Arcsecond Measurement Testbed and Its Relationship to the Space Interferometer Mission

Gregory W. Neat
Jet Propulsion Laboratory and the California Institute of Technology, Pasadena, CA USA

ABSTRACT

This paper describes the relationship between the Space Interferometer Mission (SIM) and the Micro-Arcsecond Measurement Testbed (MAM). MAM is necessary because differences exist between the starlight and the metrology measurements through the SIM instrument optical path. The goal of MAM is to establish the methodologies required to reduce these differences. The targeted SIM instrument performance requires these differences to be at the pico-meter level. Starlight and metrology difference errors can be grouped into two categories: field dependent and field independent errors. The field independent errors are either random (i.e., vibration) or drift (i.e., thermal mirror warping). The field dependent errors introduce differences between metrology and starlight that change as a function of “look” angle. An example field dependent error is the different diffraction effects on the two beams as the delay line slews. SIM’s fundamental error mitigation approach is to reduce the field independent errors down to the prescribed error budget levels, then calibrate out the remaining field dependent portion. The paper describes the recipe to generate the MAM error budget. Since MAM is inherently a subset of SIM, the MAM testbed addresses a subset of the total SIM error budget. The paper describes the approach to determining the relevant MAM portion. In addition, it describes the derivation of the overall MAM error budget, including allocations for the pseudo star errors. The paper maps the SIM observing scenario to a MAM test measurement. A successful MAM measurement will be defined in terms of the actual measurements, the metric applied and its relationship to the MAM error budget.

Keywords: space-based interferometry, field independent error, field dependent error

1. INTRODUCTION

The space interferometer mission has a daunting list of technological challenges to address in order to show the mission is technically achievable. These challenges span from nanometer control problems to picometer sensing problems. A number of system-level testbeds have been designed, built and tested thus far in the SIM’s evolution. Each testbed is intended to address a system-level aspect of the SIM technology challenge. This approach allows for the challenges to be tackled in parallel rather than in series and therefore get to the completion date sooner. These testbeds include the Micro-Precision Interferometer\(^1\). The results from this collection of system testbeds will form the evidence that the technological challenges faced by SIM are feasible. This paper describes the portion of the SIM technologies addressed by the MAM testbed and the criteria used to assess when the problem is solved.

SIM has a number of operating modes and performance levels that are under investigation. These include nulling, narrow and wide angle astrometry, and imaging. This paper addresses some of the pico-meter technological needs of a narrow angle astrometric mission at the 3 mas/sec performance level.

The nominal SIM instrument contains three interferometer baselines (two guide, one science), a structure, a pico-meter class metrology system, and the standard spacecraft subsystems. This paper addresses the performance of the science interferometer.

\(^1\) Gregory.W.Neat@jpl.nasa.gov; phone 818-354-0584;http://www.jpl.nasa.gov
The fundamental interferometer measurement determines the difference in distance that the starlight path traveled through the two arms of the interferometer. It does this by measuring the difference between the white light fringe position and the metrology path through the instrument. The starlight is a full aperture beam (30 cm) while the metrology is only 20 mm. This measurement requires that the difference between these two beams when measuring the same path, is in the pico-meter regime. If not, the difference errors will incorrectly be attributed to a delay (the signal) and therefore be providing the incorrect star position.

The errors in the difference between the starlight and metrology on the science interferometer can be divided into two major categories: field independent and field dependent. Field independent errors are the same no matter where the instrument is "looking" in the field. For an interferometer, different field locations are achieved by articulating collecting apertures and translating delay lines. A field independent error is independent of where the collecting apertures or the delay line resides. If either of them move, the error is the same. An example of a field independent error is photon noise on a camera. Field dependent errors change as a function of location of the articulating collecting apertures and/or translating delay lines. An example is diffraction. This affects the starlight and metrology differently as the delay line translates back and forth on its rails. This difference shows up as an error in the delay determination. However, if the error is constant in time, then it is possible to calibrate out this error. The error map is measured and then later used as a "look-up" table to correct for the difference between the two. Without the calibration "look-up" table, it is impossible to tell the difference on SIM between the desired delay (signal) and field dependent error (noise). This paper describes the test, data processing and the required performance levels based on the SIM error budget, that will be used to show this problem is solvable for SIM.

The SIM on-orbit observing scenario includes a field dependent calibration function measurement. This function is then used to "correct" for the field dependent errors on each of the measurements, which will be at various field points. SIM will then make a number of observations, then correct for the field dependent errors by applying the calibration function. The allocated field independent errors and the residual field dependent error post calibration, make up the error allocations validated on MAM. The field dependent calibration function is assumed to be constant over a long period (weeks?). This assumption will also be validated on MAM in the MAM environment.

2. MAM BASICS

Fig. 1 shows a fundamental difference between MAM and SIM. SIM uses metrology to measure the difference between white light and metrology in order to determine how much further the star light traveled to one aperture versus the other. In this case, the metrology goes through the instrument. In the case of MAM however, metrology goes through the entire instrument, and continues all the way to the pseudo star. SIM's white light/metrology difference signal contains the delay (the value of interest), field independent errors and field dependent errors of the instrument. In contrast, MAM's white light/metrology difference signal contains the field independent and field dependent errors of both the pseudo star and the instrument. This is fact leads to the fundamental rule of MAM:

*MAM measures directly the field dependent calibration function for the combined pseudo star/instrument system.*

The good news is that MAM directly measures the error sources of interest without the delay signal. The bad news is that the measurement includes the field dependent errors from the pseudo star.
white light - metrology = cal

white light - metrology = external_delay + cal

MAM

SIM

Fig. 1. Cartoon comparing the MAM testbed to the SIM instrument.

As with SIM, the distinction must be made between the field dependent calibration function and the measurement that is corrected by applying the calibration function. Since the MAM setup is directly measuring the field dependent calibration function, the only difference between a calibration function measurement and the measurement is the amount of time used to integrate during the measurement. The measurement has strict limits on integration time, while the calibration function measurement has no limit.

3. TESTBED PERFORMANCE NUMBER

This section describes the approach and the resulting error allocation for determining the MAM performance goal for the narrow angle, 3 μarcsec test. This allocation (in picometers) represents the value that allows us to say: "If the MAM testbed (instrument plus pseudo star) can perform at this picometer level, then it is feasible for SIM to reach its requisite picometer performance goal. The SIM number and the MAM number are different. This is because they are different instruments being tested in different environments. The goal is to understand the mapping from SIM to MAM and use it to determine the MAM performance goal derived from the SIM error budget.

Fig. 2 shows a top-level error budget for the SIM 1 μarcsec, narrow angle instrument. SIM’s error budget is defined to meet the 1 μarcsec performance goal. Therefore the mapping to MAM must include the extrapolation to a 3 μarcsec mission. MAM addresses SIM’s science interferometer errors (37 pm in Fig. 2). These errors are further broken down into brightness dependent and everything else. The brightness dependent term includes visibility, photon flux and detector noise errors. MAM does not test this entry at the SIM levels. In fact, the goal of the MAM experiment is to make this term extremely small by “looking” at a bright source and testing in ultra-quiet environment. Thus, the SIM brightness dependent error term cannot be used to extrapolate to the MAM number.
Figure 3a shows the SIM science interferometer error allocations divided in terms of brightness dependent and everything else (or the MAM portion). The next step is to extend this 1 μarcsec budget to 3 μarcsec. The simplest way to do this is multiply all entries by 3. However, this implies another design, i.e., this scaled error budget would represent a 3 μarcsec mission. What is actually desired is a 1 μarcsec mission which is not yet performing at the 1 μarcsec level. For example, if the brightness dependent error box were multiplied by 3, this implies that the siderostat area dropped by a factor of 3.

In contrast, the intent here is to keep the instrument the same, just allocate errors to the challenging sources. Thus, Figure 3b shows the re-apportioned MAM allocation. This was determined by keeping the overall SIM science number at the 3 times level as compared to the 1 μarcsec, but keep the brightness dependent error at the original 1 μarcsec level. The MAM allocation is then increased until its root sum square with the 1 μarcsec brightness dependent number equals SIM science 3 μarcsec allocation.

This number (105 pm) represents the allocation of picometers that MAM is responsible for testing. Note however that the error terms in the SIM error budget assume “truth” is known. Each entry in the error budget represents the difference between the actual SIM value and “truth”. This works fine for allocation, however, when verifying these allocations, allowances must be made for measuring the actual value and defining truth. For example, suppose an oscilloscope is needed to measure the performance of a device. In this case, if the oscilloscope is noisy relative to the signal levels from the device, the overall measurement will be dominated by the oscilloscope as opposed to the device of interest. This measurement noise needs to be accounted for in the allocation/verification process. In the ideal case, the measurement noise can be removed. Alternatively, the device and the oscilloscopes noise are combined and therefore result in a single value.
In the case of the interferometer, the function of the oscilloscope is served in part by the pseudo star. It is necessary in order to measure the performance of the test article (interferometer). To date, we do not have a test which directly measures the performance of the pseudo star on its own. The next best thing is to measure the interferometer individually, then measure the combined performance of the interferometer plus the pseudo star. From this combined measurement, the performance of the pseudo star can be inferred. Since the MAM pseudo star is an inverse interferometer, the estimated allocation for its errors are equal to that of the interferometer. Thus, the “measurement noise” of the setup results in a square root of two scale factor to the MAM number extracted from the SIM error budget.

The final mapping from MAM-to-SIM involves the data processing. The original SIM error budget represents a single SIM measurement. When SIM actually performs the measurement however, the desired quantity is the difference between two single measurements (as defined in the SIM error budget). MAM will perform a measurement in the same manner as SIM. Thus, the errors represented in a single MAM differential measurement are a result of two SIM measurements as defined by the error budget. This introduces a second square root of two factor in the definition of the MAM performance number.

Fig: 3c shows the MAM error budget in terms of the mapping from SIM. The scale factor between SIM 1 μarcsec and MAM 3 μarcsec is 10. A factor of 3 for the mapping from 1 to 3 μarcsec, a factor of 2 for the re-apportioning between brightness dependent and the MAM allocation, a square root of 2 for the pseudo star, and a square root of 2 for the differential measurement.

In summary, if MAM can achieve the performance levels associated with the three boxes in Fig. 3c, then MAM has demonstrated that it is feasible for SIM to achieve its 3 μarcsec science interferometer performance goals.

4. PERFORMANCE TEST TIME

The top-level MAM performance number (210pm) described in Section 3 is the combination of two error terms: a field independent and a field dependent. In relation to SIM, these entries map directly into SIM measurements and data processing of the measurements. Three elements are needed to map SIM measurements/calibrations to MAM’s: 1) the measurement, 2) the field dependent calibration function, and 3) the corrected measurement. The following subsections describe each of these elements, their relation to the three error budget entries, and their relationship to each other.

4.1 Measurement

The measurement represents a single SIM narrow angle observation. The definition of a SIM measurement is explicitly defined in the SIM error budget. It involves observing a target star (one suspected to have orbiting planets) for 300 seconds, slewing to one or more reference stars, and observing them for 300 seconds total. The desired quantity is the difference in delays between the target star and the reference star(s).

The integration time per observation for both the reference and the target is limited in order to support the science demands for the entire mission. This however limits the reduction in random noise on the measurement. For example, if there were no limit on integration time, then the random error in the measurement could theoretically approach zero. It is also possible to interleave the reference and target observations in order to remove drift errors. This observing sequence is called “chopping” and its period is dictated by the time constant of the drift errors.

In the mapping from SIM to MAM, the measurement is associated with the field independent entry (180pm). The approach for MAM is to initially reduce the field independent errors to the 180pm level. During this test, by definition, the test article and pseudo star remain at a single field point location. The follow-on test to record a measurement, involves moving to multiple field points to emulate the target-reference SIM observing scenario.

The data recorded during the field independent test is simply a long time series of the difference between the white light and metrology through the entire path. The data is then processed as though it was an actual observing sequence. However, that sequence can be parameterized since the target and reference slews are not actually happening. For
example, consider the different ways to process a ~10 minute data set. One way is to integrate the first 300 seconds and call that the target star field independent error. Then skip over the next 15 seconds to represent a SIM slew (this is the nominal time assumed for a slew and settle between stars). Next, integrate the next 300 seconds to represent the reference star field independent error. Finally, subtract the target star average from the reference star average to give the overall field independent error.

Another way to process the same data set is to integrate for 30 seconds and call that the target star field independent error. Then skip over the next 15 seconds of data and call that the slew and settle time. Next, integrate the following 30 seconds of data and call that the reference star field independent error. Then repeat this sequence 10 times. Note that the total integration time on the target star remained at 300 seconds as did the reference star. Note also, that more time needs to be allocated to slewing for this scenario.

Field independent errors are of two varieties; random and drift. Averaging reduces the random errors. It does not matter whether the integration time is contiguous or broken up into discrete time periods. Chopping enables the reduction of drift errors. This approach assumes each field point sees the same time dependent error. The drift in the reference star measurement on either side (in time) of a target star measurement is then used to estimate the drift in the target star. This estimate is then removed from the target star value. The chop time is defined by the time constants of the drift errors.

In this example, these two scenarios could be applied to the same data set. Note that nothing actually moved in this processing. The data was all from a lab measurement, with the test setup at one field position. The reference star and target star integration times were artificially defined by the processing. The significance of this approach is that it directly measures the quantity of interest: the field independent error of a MAM measurement. The resulting value is not polluted with the field dependent error term since the entire test occurs at a single field point.

Since processing is inexpensive, the data can be reprocessed to cover the entire integration/chop time space. Fig. 4 shows this space defined in terms of integration time, number of chops and field dependent error. As a point of interest, the indicated plane in this surface corresponds to an Allan variance plot with the assumption that the slew time is zero. The contour line on the plot indicates 300 second integration time. MAM (and SIM) can be anywhere on that line. The surface that results by reprocessing the data with the different # chops and integration times, will be used to select the actual observing scenario for the field dependent tests. This would be the points on the surface that reach the 180pm level at or before the 300 second integration time is reached.

Once the observing scenario has been selected from the points that satisfy the field independent error requirement, then the actual measurement can occur with the prescribed parameters (#chops, integration time). In the lab test for the measurement, the test article and pseudo star actually slew to target and reference star locations. The difference between white light and metrology at each field location corresponds to the respective target and reference star field independent and dependent errors. The field independent error is by definition 180 pm, and the field dependent error is assumed to be zero for the measurement.

4.2 Field Dependent Calibration Function

The field dependent calibration function is a “look-up” table that contains an error map of the differences between starlight and metrology as a function of field position. SIM will generate this function by combining component level models and measurements in an “a la carte” fashion. The measurements performed on the components have no restriction on integration time. In the case of MAM, this function for the test article and the pseudo star, can be directly measured by sweeping over field angles and recording the white light and metrology difference. This is considered cheating however with regard to mapping to SIM since SIM is unable to perform a similar measurement on-orbit. The MAM activity will measure this function directly in order to quantify the white light/metrology difference across the narrow angle field. In this measurement, there is no limit to integration time.
4.3 Calibrated Measurement

The field independent error in the calibration function is defined as the deviation of the measurement from the true value. The result is the linear term in the calculation of the measurement. The measurement is defined by the deviation from the true value and the field dependent correction to the true value. The measurement is defined by the deviation from the true value and the field dependent correction to the true value.
function). The calibration function is assumed to have all of the field dependent error, with no field independent error. The result of the combination of these two to form the calibrated measurement, is the root sum square of these two independent error sources (210pm).

ACKNOWLEDGEMENTS

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

REFERENCES