SIM Interferometer Testbed (SCDU) Status and Recent Results

Bijan Nemati*, Xin An, Renaud Goullioud, Michael Shao, Tsae-Pyng Shen, Udo J. Wehmeier, Mark A. Weilert, Xu Wang, Thomas A. Werne, Janet P. Wu, Chengxing Zhai

Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA, U.S.A. 91109

ABSTRACT

SIM Lite is a space-borne stellar interferometer capable of searching for Earth-size planets in the habitable zones of nearby stars. This search will require measurement of astrometric angles with sub micro-arcsecond accuracy and optical pathlength differences to 1 picometer by the end of the five-year mission. One of the most significant technical risks in achieving this level of accuracy is from systematic errors that arise from spectral differences between candidate stars and nearby reference stars. The Spectral Calibration Development Unit (SCDU), in operation since 2007, has been used to explore this effect and demonstrate performance meeting SIM goals. In this paper we present the status of this testbed and recent results.

Keywords: SIM, Interferometry, Astrometry, Spectral, Dispersion

1. INTRODUCTION

The SIM Lite astrometric mission will potentially revolutionize many branches of astrophysics. SIM Lite is an astrometric interferometer with sub micro-arcsecond accuracy.1 In a typical SIM-Lite measurement, the instrument, acquires a star and measures the optical pathlength difference (OPD) for the star at the given attitude of the interferometer baseline. Two guide instruments and an external metrology system are used along with post-processing to tie the astrometric measurement to astronomical reference points. The most demanding class of measurements for SIM Lite are the narrow-angle (NA) measurements used in the search for Earth size planets in the habitable zones of nearby stars. In this class the required accuracy in the measured OPD is 1 pm at the end of mission. In a NA measurement, the instrument switches back and forth between a target star and anywhere from 3 to 6 astrometrically nearby reference stars that have little proper motion, in order to track the position of the target star over the course of the five year SIM Lite mission. To make the 1 pm level of accuracy possible, SIM Lite averages down the random errors and uses the chopping observation scheme to filter out drift errors. With the random errors thus effectively mitigated, systematic errors become the most challenging obstacles to overcome. Over the past decade, the technology program for SIM has successfully addressed the various systematic errors that can affect the performance of SIM Lite. The last remaining class that has needed final verification has been spectral errors. Spectral errors arise from uncompensated phase dispersion in the two arms of the interferometer. Since the phase dispersion has a spectral dependence, and since the target and reference stars in general are spectroscopically different, there will be a systematic error that is spectral in nature and is not ‘chopped out’ in the measurement. The SIM Lite approach to mitigating this error is to calibrate the dispersion and remove it from the OPD measurement. Since the calibration will need to be done with high precision, it was considered necessary that the approach be verified using a testbed.

The Spectral Calibration Development Unit (SCDU) was built specifically to verify the spectral calibration scheme. Figure 1 shows the opto-mechanical layout of this testbed. The heart of the testbed is a breadboard versions of SIM Lite’s astrometric beam combiner (ABC). Functionally, the ABC combines light collected from the interferometer’s two collector assemblies. These two beams, each compressed down to approximately 40 mm in diameter, enter the ABC and are combined, polarization-separated, spectrally dispersed, and focused as dispersed fringes on the ABC’s fringe tracker camera (FTC) CCD. The FTC sees two dispersed fringes, one for s-polarized light and one for p-polarized light. The ABC contains the internal metrology beam-launcher used to send out the metrology beams that track the interferometer’s internal OPD. Finally, the ABC also contains an angle tracker assembly with its own CCD camera to track the pointing of the interferometer’s two starlight beams, as well as monitor the relative alignment of the internal metrology beam with

* bijan.nemati@jpl.nasa.gov; phone 1 818 354-0883
respect to the starlight beams. In SCDU, all the ABC-related optics reside on a ‘sub-bench’ kinematically mounted on the main bench. On the main bench reside the additional optics to form a Michelson interferometer operating in retro mode. The simulated starlight is fed in via a fiber arriving from outside the testbed vacuum chamber, is collimated and sent through the testbed, where it retro-reflects off of the two siderostats and returns to be combined at the main beam splitter. SCDU is described in detail elsewhere.2

SCDU came online in 2006 and produced its first results in 2007. While the initial results were encouraging, with the single visit error at the SIM Lite goal levels, it was observed that the error distribution had a bias. An overall bias in the delay measurement is by itself not problematic, since the post processing can solve for and remove the overall bias. However, a change in the bias from epoch to epoch can seriously compromise the instrument’s ability to achieve its NA performance goals. Such a change in the bias was in fact observed in the 2007 data, where a significant hardware change could cause as much as 20-30 picometers of bias shifts. The changes that occurred during this period were changes in the spectral band, large temperature fluctuations, and a vacuum venting-pumpdown cycle. While it may be arguable that none of these changes might occur within the science portion of the SIM Lite mission, it constituted a significant caveat on the obtained performance results.

For this reason, it was decided in 2008 to continue the SCDU tests in order to identify the leading causes of the bias shifts encountered in the 2007 data. In this paper we present the findings made in the post-2008 activity on the sources of spectrally induced interferometer bias. We also present an assessment of the expected SIM Lite spectral error using the additional knowledge gained over this period from the SCDU results.

2. **SCDU OPERATION AND DATA**

SCDU emulates the aspects of a NA measurement relevant to spectral errors. The target and reference ‘stars’ in SCDU are simulated by changing the filter placed between the Tungsten white light source and the fiber that feeds the light into the testbed. No field-dependent effect are captured by this minimal ‘pseudo star,’ these having been addressed by
SCDU’s predecessor, the MAM testbed. With a cadence that mimics the nominal SIM Lite NA observing scenario, target and reference ‘looks’ are made repeatedly over an approximately 20-minute ‘visit.’ In the nominal scenario there are 12 chops per visit.

Figure 2: SIM Lite narrow angle visit typical scenario. Nominally there are 12 chops per visit.

Besides the NA visits, there are instrument calibration visits that occur on a daily basis, and a number of instrument checkout and monitoring runs that occur for brief periods at various times ranging from hourly to daily. There are also spectral characterization visits for the stars. These yield the ratio of the spectra of the target and reference stars relative to that of a calibrator star, and are supposed to be done only once per mission per star for SIM. On SCDU these are only repeated when hardware changes essentially dictate a new SIM mission instantiation. What SCDU fundamentally measures is the expected differential astrometric error a NA visit. Many such visits are created in the testing process, so that statistical data can be obtained. The overall process for the determination of the instrument error is summarized in Figure 3, and are described in detail elsewhere.

Figure 3: The data processing flow chart for SCDU’s estimation of fringe OPD, the application of spectral corrections, and estimation of the SIM Lite error.

Very briefly, the fringe phase is estimated for each spectral channel on the FTC using a monochromatic fringe model given by:
\[ y(u) = I \left[ 1 + V \cos(ku + \phi) \right] \]  \hspace{1cm} (1)

where \( I, V, k, \) and \( \phi \) are the four fringe parameters, namely fringe intensity, visibility, wave number, and phase respectively. \( u \) is the metrology-measured OPD and \( y(u) \) is the fringe intensity as a function of OPD. In the spectral and instrument calibrations, long stroke (approximately 140 \( \mu \)m) modulations are applied. By applying direct Fourier transforms to the resulting intensity versus metrology-derived OPD curves, the spectral ratios are obtained for the stars in spectral ratio calibrations and instrument parameters such as the phase dispersion function are derived in instrument calibrations. In a NA visit, a phase modulation is used to scan over different OPDs in order to produce a phase estimate. The process involves comparing the results of least squares fits to the observed and model fringes to estimate a delay difference between the two. This is iterated, in each step correcting the assumed delay in the model, until the difference between the model and observed delays falls below the required tolerance.

It is clear that the process depends on the instrument conditions remaining stable from the time of the instrument calibration to the time of a NA visit. Additionally, if there are any errors that are uncalibrated but are strictly color dependent these can directly lead to a bias in the NA error.

**3. SOURCES OF BIAS SHIFTS**

One early suspect in the search for the bias shifts was color dependent centroid shifts (CDCS) where the pointing measured using the angle tracker camera (ATC) has a color-dependent shift. Since the siderostats are controlled using the ATC data, a situation can occur where there is in fact no pointing change in going from one color star to the next, but the ATC reports a change and the angle tracker commands a tilt for a siderostat.

![Figure 4: Color Dependent Centroid Shifts (CDCS) in the x direction (vertical to the table) for the left and right arm beams, respectively, as measured in SCDU. The units are CCD pixels, with each pixel spanning 40 \( \mu \)rad. The two curves are for 4x4 and 6x6 pixel windows. Each curve is retraced to check repeatability.](image-url)

Such a color dependent, systematic tilt error in the siderostat can couple with a shear between the white light chief ray (as incident on the siderostat) and the metrology corner cube vertex, to result in an error of the form:

\[ d = 2S_{WM} \theta_{sid} \]  \hspace{1cm} (2)

where \( S_{WM} \) is the shear and \( \theta_{sid} \) is the siderostat error caused by the CDCS effect. The shear \( S_{WM} \) can be brought down to less than 50 \( \mu \)m. With this much shear, a \( \theta_{sid} \) of 0.2 \( \mu \)rad can cause a 10 pm error. If \( \theta_{sid} \) is random, this error would average down and not pose a risk. However, when there is a systematic source of \( \theta_{sid} \) such as CDCS, the error does not average down and can cause bias shifts. CDCS is an artifact of the standard centroid algorithm and the confluence of three factors: a) wavefront error in the measured beam, b) coarse CCD pixelation of the imaged star spot, and c) limited
active window size. Good angle tracking dynamic performance requires items b and c. Not all types of wavefront error contribute equally:coma is the leading type of wavefront error that can result in this effect. The most likely source of CDCS-causing wavefront error on SCDU appears to be multi-mode effects in the input white light source. Mitigation of this error can be accomplished by improving the effective pixelation of the spot (to at least Nyquist sampling) and using a larger window. On SCDU the CDCS can be calibrated down to 10-20 nrad. The CDCS study is described in detail elsewhere.\(^5\) The SIM astrometric beam combiner design has been adjusted to incorporate the SCDU findings on CDCS.\(^6\)

Another important source of bias in SCDU was found to be related to registration errors between the angle tracker (AT) and the fringe tracker (FT). Fundamentally, the angle tracker’s function is to ensure that the light from the left and right arms of the interferometer is a) parallel relative to each other, and b) the images from the left and right arm beams do not move on the face of the fringe tracker camera CCD. In practice, in the presence of thermal gradients, the registration between the AT and the FT can change so that the images from the left and right arm beams move on the fringe tracker.

![Figure 5: Fringe placement error categories: common-mode (left) and differential (right).](image)

Comparing the left arm to the right arm, the motion can be common-mode or differential. If there is common-mode motion from the time of an instrument calibration to the time of a NA visit, the phase dispersion function from the calibration becomes stale and there will be a calibration error. Some of this error is not observed because it will be common to the target and reference star measurements. However, a residual error remains. If there is differential-mode motion, the phase difference between the left and right arm beams will change if there are wavefront errors that make the point spread function phase profile non-flat.

![Figure 6: Measurement of the sensitivity to common mode (left) and differential mode (right) fringe placement error. Each mpix on the ATC corresponds to 40 nrad on the beam. Each FTC pixel corresponds to about 33 µrad.](image)

In SCDU, the white light source was modified to allow switching in a stabilized He-Ne source instead of the usual Tungsten halogen white light, so that instead of a spectrally dispersed streak on the FTC, one would get a single spot. With a single spot, centroid measurements are more easy to perform, and routine checks can be made to monitor the AT-FT registration. In Figure 6, the NA error is measured as the FTC placement is changed from a nominal starting point. This is done once with only common-mode motion and once with only differential-mode motion. It is found that common-mode motion is most important in the spectral direction, which matches expectations. Differential-mode motion is observed to be more damaging, with a sensitivity of about 8 pm per milli-pixel (or about 0.25 pm / nrad). Tests confirmed that the impact of mis-registration is dramatic and that improvements can be made by monitoring and
correcting the fringe placement on the FTC. Detailed tests, however, revealed a limitation to the approach of forcing a particular registration on the system. Since the sensitivity is high, any perturbing of the registration injects noise in the placement, primarily from sensing errors since sub milli-pixel sensing is required. In lieu of asserting a specific placement, a more passive approach was finally adopted, where the instrument calibration results from the preceding and succeeding instrument calibrations were interpolated to arrive at a calibration effective to the time of the NA visit. This in effect removes a temporal linear trend in the fringe placement error. This was found to be adequate for meeting SIM requirements.7

4. RESULTS

The final demonstration that the spectral effects in SIM Lite have been successfully addressed is that the bias in narrow angle testing can be shown to be constant in the presence of SIM-like disturbances. The first such demonstration came soon after CDCS was properly calibrated and corrected late in the summer of 2009. In the test shown below, a separate long stroke instrument calibration is conducted prior to each NA visit, separated by only minutes. This observing scenario is impractical since SIM Lite cannot afford such frequent instrument calibrations. However, this test does show whether the CDCS is properly corrected and what the error is after such a correction. In some sense, therefore, this test can be considered the two-color noise floor for NA visit.

Figure 7: 2-Color noise floor data: spectral flatness (left) and NA error for each run/visit (right). The spectral band corresponds to 75% of SIM's spectral window and is only limited by photons available from the stars.

Figure 8: 2-Color noise floor data: s and p errors averaged, versus visit number (left) and sub-average deviation of N-chop averages (right). A fit of the data to white noise expectations yields 0.77 pm (26 nas).
In Figure 7, we see that, across the 6 spectral channels the error is relatively flat near zero. Channel 1 receives little light from one of the stars and hence suffers from large errors. The standard deviation of the NA visits in either of the two polarizations is seen to be just over 8 pm. Averaging over many integrations and over the two polarizations, the error is found to be nearly white, dipping down to 0.8 pm (approximately 26 nas) after 15 hours of integration. Figure 8 shows the s-p averaged data, with a sigma of 7.1 pm. Computing the running N-chop average we arrive at the plot on the right of the figure. The error goes down to 0.8 pm (approximately 26 nas) after 15 hours of integration.

In the full-scale tests, the cadence of the instrument calibrations is brought down to the SIM Lite level of once calibration every 24 hours. Narrow angle visits are done many times between each pair of instrument calibrations and the calibration results are interpolated to the time of each NA visit. These tests were conducted over the course of many months in separate batches, where a batch is defined as a group of runs following a realignment of the system. Realignments become necessary if there has been a significant hardware modification or very large thermal change in the lab environment – conditions corresponding to different mission instantiations. Many hundreds of data runs were taken over the time period. One important finding has been that each modification of the white light source, particularly if it involves rearrangement of the fibers, causes a bias shift. CDCS data taken over the same time indicate that the problem appears to be changes in the wavefront emerging from the fiber. While SCDU uses single-mode fibers, it appears that there is some multi-mode effects in the shorter wavelengths. Evidence for this is that the size of the CDCS effect is significantly less if the two stars are simulated using redder filters. Overall, there were three groups of data that could be used in this category. The final batch, 48, was sufficiently long to allow measurement of the error beyond the 200-visit point. This is approximately the number of times the targets with the most promise for Earth analogs will be visited. The SCDU narrow angle performance analysis is described in detail in a separate paper in this conference.\(^8\)

![Figure 9: NA standard deviation versus number of visits averaged. Spectral channels 2-6 are used and the noisy channel 1 is excluded. Batch 48 data was taken in early 2010. The fit to a white noise line is over the last decade of the Batch 48 data.](image)

Figure 9 shows the standard deviation of the averages of visits for increasing numbers of visits. Only spectral channels 2-6 are used since they have more light and less errors. The red line shows the astrometric error budget (AEB) allocation to instrument systematic errors for NA visits versus number of visits. We see that in batch 48 the error starts well under the AEB allocation (as it should to be compliant, since not all the SIM Lite errors are captured by SCDU). The error averages down to under 1 pm for greater than 200 NA visits. The statistics are limited in the last few points, caution is required, so we infer from this plot that the SCDU NA error appears to have reached near 1 pm with 200 visits.
5. SUMMARY AND CONCLUSION

SIM Lite’s interferometer testbed, SCDU, has identified and successfully mitigated two leading sources of color-dependent bias in astrometric measurements. Color-dependent centroid shifts (CDCS), which arise from angle tracker limitations, can produce a bias in the presence of certain wavefront errors (coma in particular) and shear error, on each siderostat, between the starlight beam and the metrology corner cube vertex. Mitigation of CDCS requires ensuring low coma, better pixelation of the image spot, and initially using as large a window around the spot as possible. Registration errors between the two cameras in the beam combiner assembly, namely the AT and the FT, lead to the walking of the left and right images on the FTC CCD. Any such motion, either together (common-mode) or oppositely (differential-mode) can also cause errors, when it occurs between the time of an instrument calibration and a NA visit. Interpolating the results of instrument calibrations to the time of a NA visit helps reduce these errors adequately for SIM Lite goals. Overall, SCDU was able to reach, in its final batch of NA visits, an error of about 1 pm, differential between target and reference observations, after 200 visits. Since SIM Lite will enjoy a more compact astrometric beam combiner design, and see better stellar wavefronts than was achieved in SCDU, the prospects for SIM Lite performance are expected to be better.

ACKNOWLEDGEMENTS

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

REFERENCES