Recent Results of the Guide-2 Telescope Testbed for the SIM-Lite Mission

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Abstract— The Space Interferometry Mission Planet Quest Lite (SIM-Lite) is a new mission concept to perform micro-arcsecond narrow-angle astrometry to search approximately 50 nearby stars for Earth-like planets, and also to perform a global astrometry. The SIM-Lite consists of two Michelson interferometers and one telescope. The main six-meter baseline science interferometer observes a target star and a set of reference stars. The four-meter baseline interferometer (Guide-1) monitors the attitude of the instrument in the direction of a target star. A new Guide-2 telescope (G2T) tracks a bright star to monitor the attitude of the instrument in the other two orthogonal directions. In the current mission concept, the G2T consists of a 30 cm siderostat and a 30 cm confocal telescope, similar to other four telescopes used in the science and Guide-1 interferometers. A testbed has been built to demonstrate the G2T feasibility for SIM-Lite mission. Recent results show that field-independent, star-tracking capability of the system is less than 30 μas after the SIM narrow angle analysis.

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1. INTRODUCTION

The Space Interferometry Mission Planet Quest (SIM PQ) is a space borne instrument [1] that will carry out astrometry to micro-arcsecond precision using the visible light from a large sample of stars in our galaxy and search for earth-like planets around nearby stars. SIM-Lite is a cost effective alternative concept for SIM Planet Quest (10 meter baseline), with a smaller 6 meter baseline and a 30 cm telescope instead of a third interferometer. This alternative mission concept will cover a large amount of SIM PQ's original science objectives with significant cost reduction. The basic elements of a stellar interferometer are shown in Figure 1. Light from a distant star is collected at two points separated by baseline B and combined to form interference fringes. This occurs when the internal path length difference (or delay, δ) compensates exactly for the external delay, x. The angle between the interferometer baseline and the star, α, can be obtained using the relation, $\cos(\alpha) = x/B$.

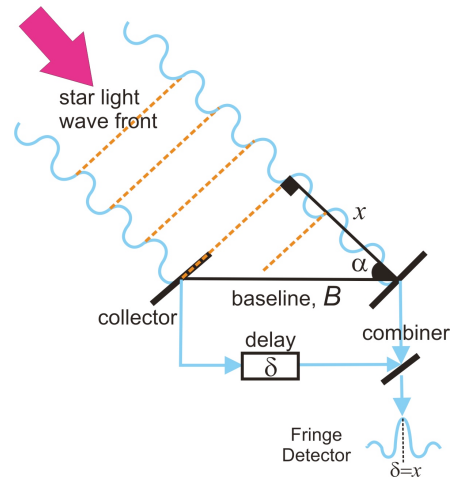

Fig. 1. Schematic diagram of the Michelson interferometer. The interference fringe is at maximum value when the delay, δ, is equal to the external delay, x. The ratio of the external delay to the baseline length is the cosine of the angle between the baseline and the star.

In SIM-Lite, two 30 cm telescopes separated by a 6-meter baseline collect light from a star. From the two collecting telescopes, the light is propagated by a set of optics to the beam combiner where the two optical wave fronts are re-combined, forming interferences. The peak interference fringe is obtained when the propagation paths through the two arms of the instrument are identical. The internal metrology sensor measures the internal propagation difference between the two arms (also known as internal delay), from the optical corner cube fiducials on the collecting optics to the re-combining optic. When the instrument is tracking the peak of the interference fringe, the external delay is the complement of the internal delay. Therefore, the measurement of the internal delay is an estimate of the external propagation delay.

SIM-Lite simultaneously employs two stellar interferometers (Science, Guide-1) and one telescope (Guide-2) to perform astrometry. Precision astrometry requires knowledge of the baseline orientation to the same order of precision as the astrometric measurement. To achieve this, a second stellar interferometer (Guide-1) is required to measure the baseline orientation in the most sensitive direction and a high-precision telescope to measure the baseline orientation in the other two directions. The

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Guide-1 interferometer and the Guide-2 telescope acquire and lock on bright "guide" stars. While these are keeping track of the rigid-body motions of the instrument, the main Science interferometer measures a target star's position projected along the baseline. The current scenario for the Narrow Angle (NA) observation requires angular position measurements to a set of multiple reference stars per a target star.

The reference stars observed with the science interferometer are within 1 degree radius field around the Guide 1 star for the planned NA observation. Figure 2 shows the illustration of the baseline rotation effect during the reference star observation. The science interferometer measures the angular position of the reference star projected to the baseline vector (B): $\alpha\cos(\theta)$. When the baseline is rotated $\delta\theta$ along the axis of the Guide 1 line-of-sight vector (G1), the Science and Guide-1 interferometers are insensitive to the rotation. The Guide-2 telescope then provides the measurement of the rotation along the G1 axis. A correction, $\alpha\sin(\theta)\delta\theta$, has to be made to the reference star observation performed by the science interferometer. It is important to understand how the error in Guide-2 telescope measurements affects the science NA measurement. In general, the error propagation factor ("multiplier") depends on the actual reference star positions in sky and observation sequence. However, in the case of uniform distributions of reference stars in a disk of α field of regards, the multiplier can be mathematically derived to be equal to $\sin(\alpha/2)$. In the current SIM-Lite, the NA field of radius is one half degree ($\alpha/2=0.5$) and the representing multiplier is 0.0087. This implies that one micro-arc-second error in the measurement of the position of the Guide 2 star results in approximately 0.0087 micro-arc-second error on the estimation of the position of the target star. The smallness of this number allows the use of a telescope instead of an interferometer for the Guide 2 star measurement. The Guide-2 multiplier however, increases with the angular separation from the science star to the guide 1 star, adding constraints on how SIM-Lite can use its 15 degrees field of regard to perform Wide Angle (WA) astrometry.

2. ARCHITECTURE

In SIM-Lite, the science interferometer consists of two 30 cm siderostat separated by a 6-meter baseline. The siderostat have an angular range of articulation that enables acquisition of stars in a 15-degree diameter field. An optical delay line system with a 0.8 meter travel range produce a range of internal delay that enable fringe acquisition in that 15 degree diameter field of regard. The guide 1 interferometer consists of two fixed 30 cm telescopes separated by a 4.2-meter baseline. The Guide 1 has a very narrow field of regard of only a few arc-seconds, just enough to compensate for errors in pointing the entire spacecraft. The Guide-2 telescope consists of a 30 cm siderostat and a 30 cm confocal telescope, similar to the other four telescopes in the science and guide 1 interferometer. Light collected by the telescope reflects on a holey mirror and propagates directly to the pointing system as shown in Figure 3. The aMet system in the Guide 2 telescope is designed to measure the pointing of the siderostat with respect to Guide 2 telescope bench. As the attitude of SIM-Lite changes in inertial space, the CCD camera and the fine stage of siderostat mechanism track the star. This technique allows us to keep the Guide 2 star locked on the CCD pointing sensor, at the intersection of 4

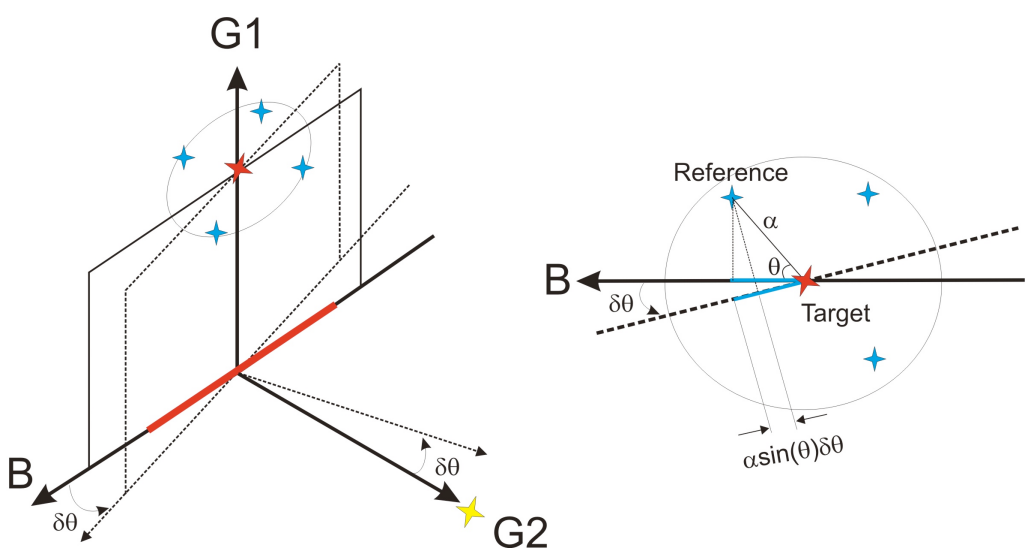

Fig. 2. Illustrations of the baseline rotation effect. The science interferometer measures the angular position of the reference star projected to the baseline vector (B): $\alpha\cos(\theta)$. When the baseline is rotate along the axis of the Guide 1 (G1) line-of-sight vector, $\delta\theta$, the science interferometer is insensitive to the rotation. A correction, $\alpha\sin(\theta)\delta\theta$ has to be made to the reference star observation.

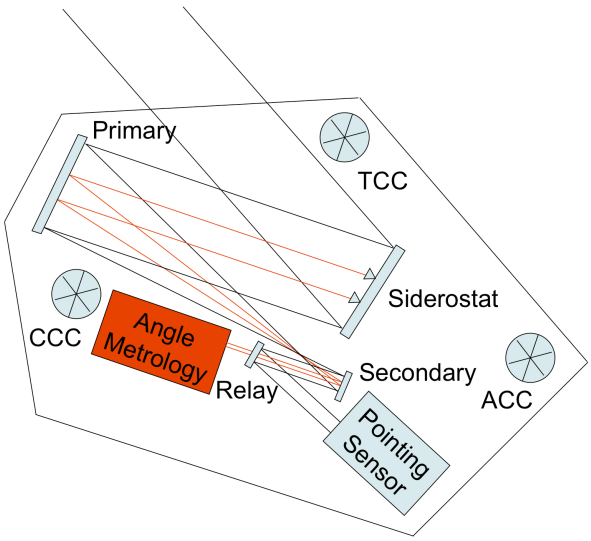

Fig. 3. Schematic drawing of current Guide-2 star-tracking telescope concept. An angle metrology beam injected through a relay mirror with a hole shown as dotted line.

pixels within a few milli-arcsecond, while measuring the larger dynamics of the Spacecraft attitude change (about 1 arcsecond) with the angle metrology sensor.

In the current SIM-Lite architecture, the Guide-2 telescope is located on the same bench structure as the one arm of Guide-1 interferometer. The line-of-sight of the Guide-2 is nearly perpendicular to the Guide-1 line-of-sight. The geometric relationship between Guide-1 line-of-sight (LOS) and the instrument truss structure are obtained by external metrology measurements using a triple corner cube (TCC), an apex corner cube (ACC), and a clocking corner cube (CCC) on the same bench. In the current architecture, it is essential to maintain the Guide-2 telescope LOS parallel and co-planar with the line between TCC and ACC. The error budget for the G2T is shown in the figure 4. More detailed description of the SIM-Lite instrument is presented by Goullioud *et. al.*[2].

3. TESTBED

The G2T testbed is designed to utilize existing prototype and brassboard optics and sensors built during the course of the SIM PQ technology development activities.[3] Figure 4 shows the phase-I configuration of the G2T testbed. The goal of the phase-I is to measure the field independent error of the G2T. White light is injected and collimated using an off-axis parabola (OAP) and propagates through the beam compressor (7:1) to the siderostat in retro-reflecting position. The beam is returned to the fine steering mirror (FSM) and focused on the pointing sensor, a commercial CCD camera. The opto-mechanical drift of the entire optical train is compensated by FSM motion, and measured by the angle metrology (aMet) gauge.

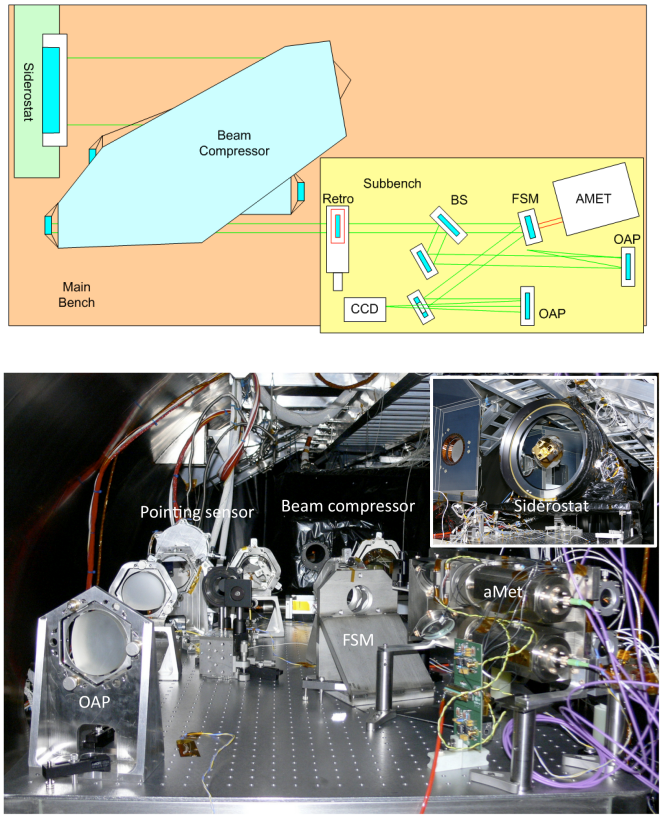

Fig. 4. G2T testbed phase-I layout and a photo.

Siderostat and Compressor

The siderostat consists of an annulus flat mirror with an embedded Zerodur cube corner at the center. The entire mirror assembly is supported off of an optical bench on three bipods with bases machined from invar and bipod legs made from stainless threaded rod. The bipods also provide thermal isolation for the siderostat. The compressor is a three-mirror anastigmatic telescope design, with a flat fold mirror to make it compact. The compression ratio is 7:1 (from 35cm entrance beam to a 5cm exit beam). The compressor has a 0.1 by 1.0 degree field of regard. The compressor consists of a large carbon composite bench, which constrains four static mirror assemblies: the primary mirror, the secondary mirror, the fold mirror, and the tertiary mirror. The composite panels form an egg-crate structure. More detailed descriptions of the siderostat and the beam compressor are in the reference [4].

Angle Metrology

The aMet system is built by modifying the existing brassboard internal metrology (iMet) beam launcher developed by the SIM. The iMet brassboard was originally built to measure the optical path difference between the two arms of the interferometer. The measurement beam (MB) was originally masked to separate beams from two different fiducials. In order to detect tip-tilt motion of the FSM using the measurement beam in G2T, a four-detector assembly

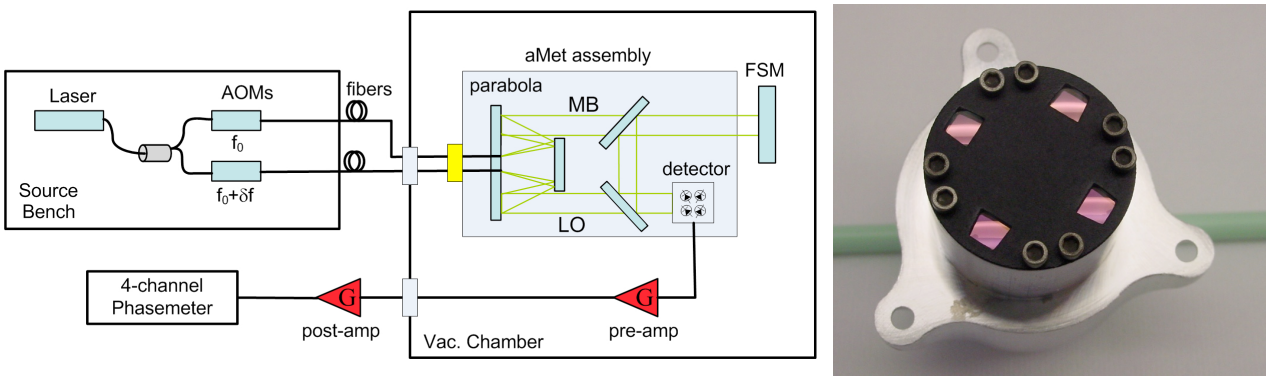

Fig. 6. Schematic of the aMet system and readout electronics. The detector assembly is shown in the photo.

housing is designed to sample four positions on the backside of the FSM surface. The detector assembly housing consists of small lenses, a mask and high speed InGaAs photo detectors. This new four-detector assembly housing is mounted inside the original iMet box after removal of a field separator and fold mirror. Instead of using the photo-detector stage originally packaged inside the iMet, 4 separate preamps are used for the aMet. Figure 6 shows a schematic drawing of the aMet unit and the readout electronics. An infrared laser is used as a metrology beam source. The source beam is fed into two Acousto-Optic Modulator (AOM) units. Single mode optical fiber cables are used to bring the beam inside the vacuum chamber and connected to the aMet assembly. Segments of polarizing optical fibers are used between the single mode fibers and polarization maintaining fibers installed internally in the aMet assembly. The measurement beam reflects off of the FSM surface and is returned to the unit when the FSM tip-tilt is sufficiently small. The return beam then is combined with the local beam (LO). This produces a modulated signal at the detector and the photo-detector pre-amplifiers inside the chamber amplify the signal. The output of the pre-amplifier is fed into the post-amps where the sinusoidal wave is converted to square wave after zero-crossing detection. The change in phase of the square wave represents the length changes in the optical path of the beam. In this common path heterodyne interferometer metrology setup, most optical path changes are common to all detectors except the tip and tilt motion of the reflective surface of FSM. The custom-built phasemeter simply counts the time between the reference wave, generated by a separate timing board, and the four channel incoming square waves to determine the change in the phase differences ϕ_i with respect to system 100kHz clock. The FSM angle then can be converted to equivalent angle on the sky using the following equation,

$$\theta_x = \frac{2}{L \cdot CR} \frac{\lambda}{2} \left(\frac{\phi_1 - \phi_0 + \phi_2 - \phi_3}{2} \right),$$

where CR is compression ratio, L is detector mask separation and λ is the measurement beam wavelength. We use average of redundant measurements.

Fine steering mirror

The prototype is a momentum compensated design with two -side coated mirror. Three piezo-electric transducers are used to drive the mirror. The range of the motion is approximately 20 arcsecond on the sky. The quantization error is 0.4 mili-arcsecond corresponding to least significant bit in 16-bit DAC. PZT drift and hysteresis has been characterized and described elsewhere.

CCD and star tracking

The star-tracking camera is a commercial CCD package. It contains 80x80 pixel CCD (e2v CCD31-01). We use 6x6 pixel mode with 100 fps (frame per second). Dark current is approximately 50,000 photoelectron/pixel/s at ambient temperature corresponding to 45 ADC counts at 100 fps. At unity gain, one ADC count represents 11.1 photoelectron. The camera head contains thermoelectric cooler, which is not used in this application. CCD stage is mounted on a motorized translation stage for the *in-situ* focusing alignment. To focus the CCD stage, dark light subtracted image data is obtained as a function of the position. And the 2nd moment of the intensity distribution is calculated at a given CCD position. The optimal focus position is at the minimum of the 2nd moment of the intensity distribution.

The centroid calculation, performed in real time control system, is a simple "center-of-mass" formula. More sophisticated method considering a point spread function model using point-spread-function is proposed for the flight system.[5] A dark frame is taken periodically to ensure the temperature dependent effects are calibrated out. The dark frame is used in both the post-processing of the raw image data and the real time star tracking. During the tracking, the centroid calculation uses a stored dark frame values. The following equation is used to calculate the centroid.

$$C_x = \frac{\sum_i x_i \left(I_i - I_i^{dark}\right)}{\sum_i \left(I_i - I_i^{dark}\right)}$$

The sum is over 6x6 pixels and C_y is also calculated. The calibration is performed by actuating FSM PZT's with a function generator. It oscillates the spot on the CCD, while the aMet is measuring the tip-tilt of the FSM. We currently use the aMet as an absolute angle sensor after calibrating it against a commercial autocollimator system. For the flight application, real star positions can be used to calibrate the aMet sensor. The CCD centroid is highly non-linear in arcsec range, as expected. However, we are using the sensor in a narrow, linear response range. Currently, we are using a simple *I*-only control loop with single gain constant, *K*. Error signal to the control loop is the real-time calculated centroid. The output of the centroid algorithm truncates the calculated PZT values to integer and sends it to 16-bit DAC. The loop runs at 100Hz and the settling time is less than 10 seconds. The control loop dithers the DACs since the internal real PZT values are the threshold of the truncated PZT values. This side effect is clearly observable in the aMet readout. A couple of improvements are being considered to eliminate the effect, for instance, a use of dead band in the control loop.

4. Narrow Angle Analysis

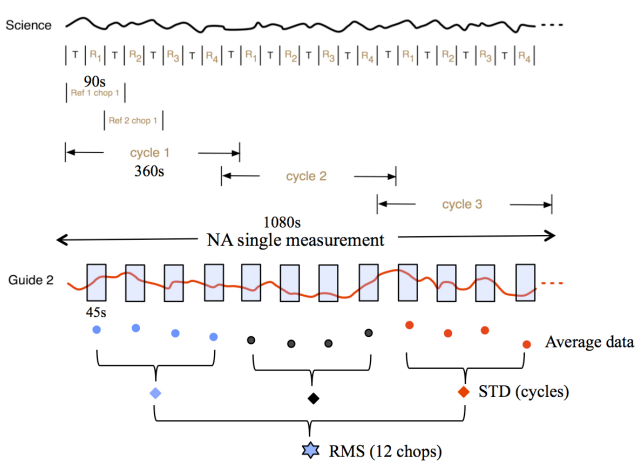

Fig. 7. G2T narrow angle data analysis

Figure 7 demonstrates the concept of an NA observation scenario. The science interferometer measures the target star position by chopping between multiple reference stars nearby. The sequence starts with 15 seconds of observation time on the target star T, during which time the interference fringes are collected. The observation is followed by about 15 seconds to slew and reposition the two siderostats and the optical delay line to acquire fringes on the first reference star R1. After 45 seconds of observation on R1, the siderostat is slewed again back to the same target star T to be re-observed for 15 seconds. This concludes the "Chop." Then, the siderostat is slewed to the second reference star R2, we observe for 45 seconds, and slew back to the target star. The siderostat continues slewing and observing between the target star and the other reference stars R3 and R4. This concludes "Cycle 1." Finally, the sequence repeats from the beginning and builds "Cycle 2." During the entire sequence, the Guide 1 interferometer and the Guide 2 telescope are locked on their respective stars, monitoring changes of the instrument attitude in inertia space. More details on how NA observations is performed in space is discussed by Milman.[6]

To evaluate the G2T stability in the testbed the following algorithm is used to process the raw data representing overall system error: (1) form 45 second averages of input data, (2) skip the period of slewing and target observation (~45s total), (3) compute standard deviation for every cycle, (4) calculate root-mean-square (RMS) of all standard deviations as many cycles as are necessary to achieve 12 chops (~1100 sec), (5) calculate the RMS of the resulting series (3 hr run) to produce the NA metric. In this analysis, a linear drift of instrument during the time scale of one cycle (360 s) contributes to an error. This time scale is longer than the legacy SIM NA chop time scale (90 s). This implies more stringent stability requirements on Guide-2 telescope.

It is feasible to observe reference stars in a reversed order per every cycle (e.g., R1 to R4 then R4 to R1) in the SIM-Lite mission. This will improve the performance when the G2T instrument drift is pure linear or odd time polynomial. When the error is in a quadratic form or even time polynomial, the non-reversed order observation is expected to produce a better result.

5. Recent Results

In the current SIM-Lite architecture, the most stringent stability requirement of the G2T stems from the lack of a capability to monitor the change in the line-of-sight of telescope independently with respect to the rest of system. Therefore, it is very important to maintain opto-mechanical stability of the G2T during the NA observation time. The G2T stability was tested in vacuum using the phase-I configuration described in the Figure 4. The objective of the test is to demonstrate that the entire G2T system is capable of tracking a simulated star (white light injected from an optical fiber tip) to the level below 50 µas over many hours. The white-light source is a commercial heat lamp residing the outside the vacuum chamber. The light is injected through the optical fiber. In the current setup, we use intensity corresponding to star magnitude of 3.75. Noise characterizations show that CCD readout system is photon noise limited and scaled by square root of number of photons, $N^{1/2}$.

All G2T optics is in fixed positions during the test except the FSM, which is in the closed loop operation with the CCD pointing sensor. In this configuration, the sum of CCD

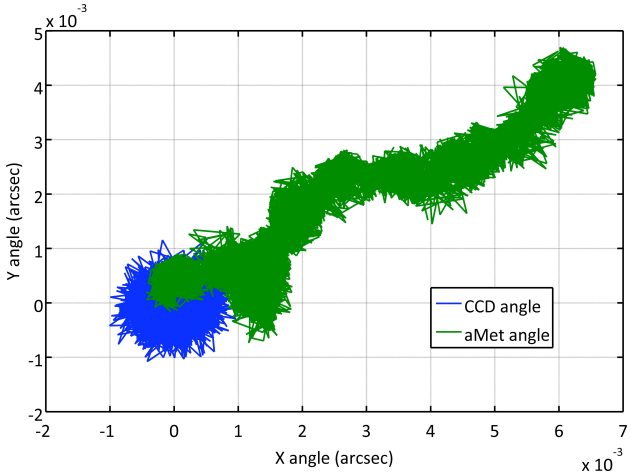

Fig. 8. Performance of the CCD star-tracking and angle metrology. The angle metrology system measures the tip-tilt angle of the FSM while it is in the closed-loop with the CCD pointing sensor.

pointing sensor and the aMet readout represents the angular position of the FSM. Any non-zero value of the sum represents the overall error of G2T, including the thermal distortion of optics and readout system drift, etc. A typical data run (3hrs long) is shown in the Fig. 8. We took the data continuously over many days. Raw angle data of x-tilt and y-tilt are narrow angle processed, separately. Figure 9 shows the summary of data analysis. Each points in the Fig. 9 represents the RMS of the NA processed data over 3 hrs. The dashed lines are results from the NA analysis without removing the linear drift term. The solid lines are the NA analysis after removing linear drift term over 3 hrs. The slow linear drift (over 3 hrs) is a significant contribution to

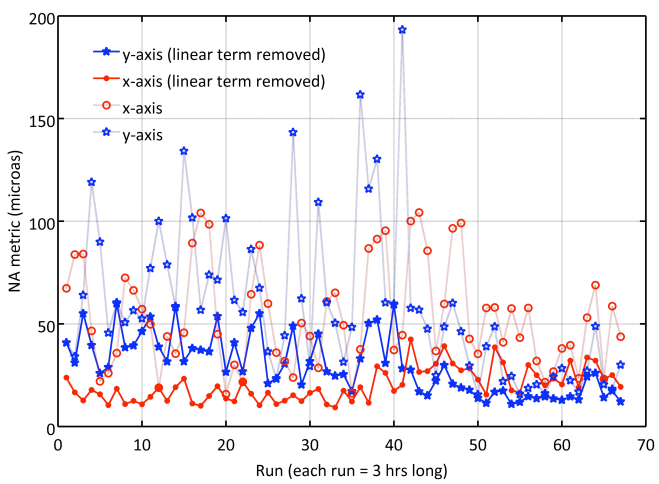

Fig. 9. The results of narrow angle analysis of G2T data taken over 200 hrs. Each point represents result of 3 hrs run.

the G2T error. The current results show that the goal level of stability (~50 μas) has been achieved in the testbed. It is also found that the major portion of the error is sourced from ambient thermal environment change.

In the phase-II of the testbed, we will test the field-dependent, star-tracking capability of the G2T by articulating the siderostat. The siderostat is in the close-loop with the CCD pointing sensor. The angle metrology gauge and the corner cubes on the siderostat measures angular positions of the siderostat. The FSM is used to inject the white light in different angles and its angular position is monitored by another angle metrology gauge. In this configuration, it is possible to simulate and test the effects of SIM-Lite attitude control system disturbances on the G2T star tracking performance.

ACKNOWLEDGEMENT

We thank R. Smythe, F. Nicaise, E. Hovalnd, X. Wang, J. Shaw, G. Sun, and R. Zimmer for technical support. This work was supported from the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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