Systems engineering and application of system performance modeling in SIM Lite Mission

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ABSTRACT

The SIM Lite Astrometric Observatory will be the first space-based Michelson interferometer operating in the visible wavelength, with the ability to perform ultra-high precision astrometric measurements on distant celestial objects. SIM Lite data will address in a fundamental way questions such as characterization of Earth-mass planets around nearby stars. To accomplish these goals it is necessary to rely on a model-based systems engineering approach – much more so than most other space missions. This paper will describe in further detail the components of this end-to-end performance model, called “SIM-sim”, and show how it has helped the systems engineering process.

Keywords: Systems Engineering, Modeling, SIM Lite, Astrometry, Interferometry, Exoplanet, V&V

1. INTRODUCTION

An overview of the SIM Lite mission has been given in these proceedings[1]. The SIM Lite Astrometric Observatory will enable astrometric measurements at visible wavelengths using Michelson interferometers and have the ability to perform ultra-high precision astrometric measurements on distant celestial objects. SIM Lite data will address in a fundamental way questions such as characterization of Earth-mass planets around nearby stars, the distribution of stellar and dark matter in the Galaxy, and the relationship between accreting plasma in distant quasars and the relativistic jets produced by that material. In addition, the mission will provide the most accurate fundamental reference frame available for years to come, with opportunities for addressing many other problems in astrophysics. To allocate requirements, perform system trades, verify the system and validate that the mission design addresses the science objectives of the program, it is necessary to have an end-to-end performance model. Over the past several years such a model (SIM-sim) has been developed, employing Matlab and components written in C programming language, which incorporates subsystem properties that come from several prototyping and engineering risk reduction activities. In addition, the methods of observing various types of targets, generating corresponding observing schedules, realistically processing the interferometric delay data over the mission life to estimate the astrometric parameters and reflex motions are incorporated. The subsequent comparison of these simulated parameters with their true input values allows characterization of the mission accuracy. To accomplish these goals it is necessary to rely on a model-based systems engineering approach – much more so than most other space missions. Various aspects of this undertaking will be examined in what follows.

The basic principles of the SIM Lite mission are deceptively simple. If an interferometer arm is fixed in space, it can measure the optical path delay of several targets (by moving its siderostats and delay lines) during that period, and the differences in delay can be converted into highly precise angular separations. The typical angular accuracy that is discussed here is of the order of 1 μas. In Figure 1 the schematic of the interferometer that accomplishes these capabilities is shown. To illustrate the significance of measurement and data reduction capability of SIM Lite, a comparison is made in Figure 2 of the physical scale of a few common objects and the delay change corresponding to 1 μas. Clearly this indicates that, while the concept is straightforward, its implementation in a large scale space mission is fraught with intricacies that must be resolved carefully. The systems engineering topics on this project are similar to other projects; however the precision requirements, which are beyond anything ever attempted, require judicious use of *validated* models to accomplish the objectives. *Model-based systems engineering* finds a true application in the SIM Lite project!

One of the common project systems engineering tasks is to allocate the science requirements of the mission into requirements on lower level subsystems. For example, one of the SIM Lite science objectives is to detect and determine the physical properties of Earth-like planets in the Habitable Zones (HZ) of ~60 nearby Sun-like dwarf stars. For a scale of the signals involved, if our solar system is moved 10 parsecs away, the reflex motion of the Sun due to Earth would be 0.3 μas. By observing such a hypothetical solar system many times over the course of five years (the baseline SIM Lite mission duration) the 0.3 μas signal would become detectable as noise is reduced due to multiplicity of data points.

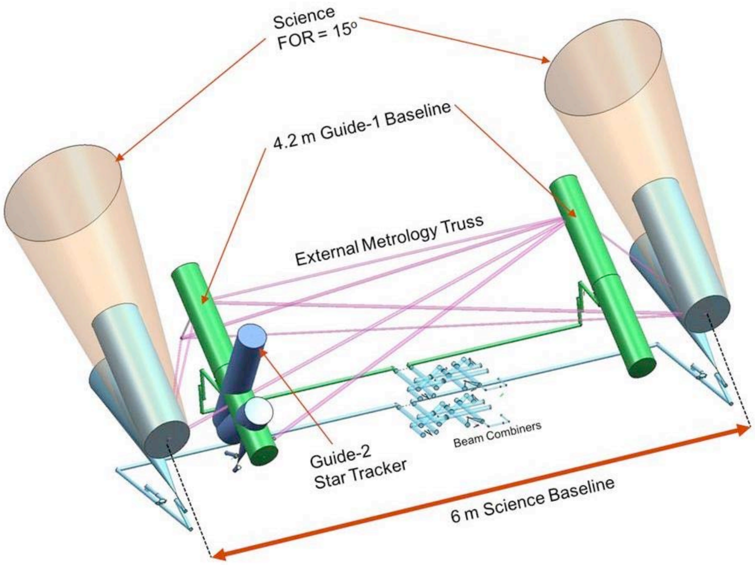

Figure 1. Schematic of SIM Lite interferometer instrumentation, a science interferometer with a guide star interferometer and a guide star telescope.

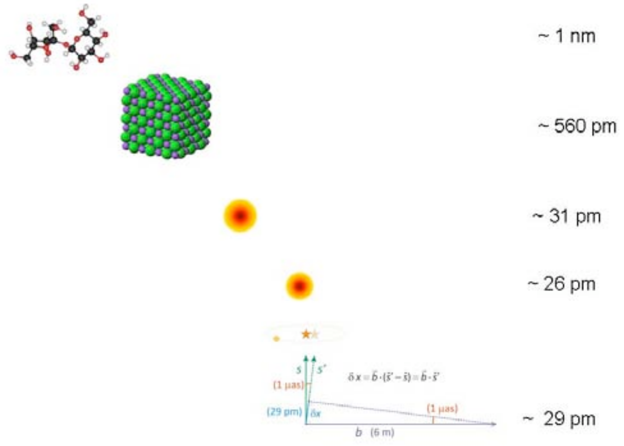

Figure 2. Physical scale of some common objects, top to bottom width of sucrose (sugar) molecule, common salt crystal *lattice* constant, Helium atom "radius", Hydrogen atom "radius" and a delay *change* corresponding to a 1 μas separation.

From a systems engineering perspective this science objective results in many system questions, such as whether a proper observation cadence can be achieved and whether the delay data obtained can be reduced to a form that enables exoplanet characterization. Furthermore, the systems engineer needs to investigate the system impact of the behavior of "reference" stars with respect to which the position of the scientific target of interest is referred. To illustrate this point, a target star and some of its reference stars are shown in Figure 3. Due to reflex motion caused by planets, the target star is expected to traverse a wobbly path in space, and the reference stars (which are chosen judiciously by astronomers to not have rapid or complex motions) also have some space motion. One question is, with such complex astrophysical signatures, can the science objective of planet characterization still be met?

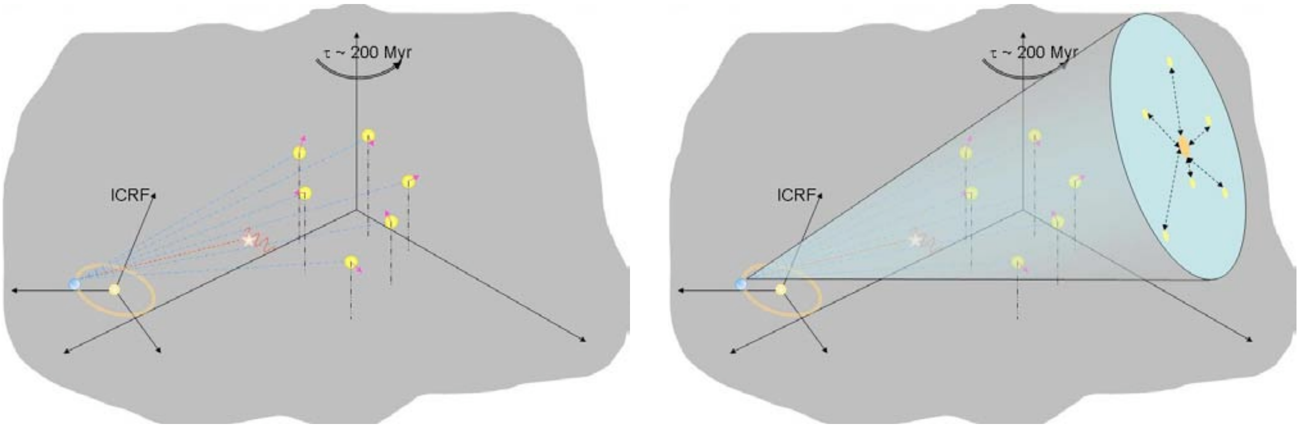

Figure 3. Observing a target of interest with several distant reference stars. In the left panel each object has its own type of space motion relative to the solar system barycenter. The right panel shows the projection of these stars onto the tangent plane as viewed by the instrument. The ICRF shown here is not strictly-speaking inertial as the solar system orbits around the galactic center with a period of ~200My.

Such a concept has been demonstrated in a “double-blind” test study commissioned by NASA HQ. In the double-blind test simulated angular offset data with a 1 μas single measurement accuracy or SMA corresponding to such scenarios were generated, and several independent teams demonstrated detectability of the target exoplanets[2].

While from the science perspective the requirement of 1 μas SMA has been shown to be sufficient for detection of nearby exoplanets, the systems engineering task is to confirm that the combination of instrument characteristics, the spacecraft performance, the observing scenarios and the data reduction algorithms in fact confirm the capability of the mission to accomplish the science objectives. This engineering task is accomplished via an end-to-end modeling and simulation approach; in addition, use of an end-to-end model permits refinement of requirements as well as identifying prudent and sometimes relaxed system level requirements.

2. END-TO-END MODELING

The unique aspect of the SIM Lite mission is that many of its science requirements are contingent on a capability that is achieved only over the entire lifetime of the mission. (The only other mission with similar constraints is the Kepler mission, where the detectability of an earth like transit relies on data from a 3 ½ year period of observation[3].) In the case of SIM Lite the abstraction of the necessary tool to enable such a capability is shown in Figure 4.

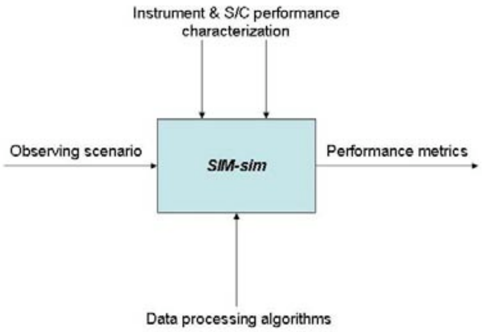

Figure 4. The end-to-end modeling capability for SIM Lite showing the constraints that drive its design and structure.

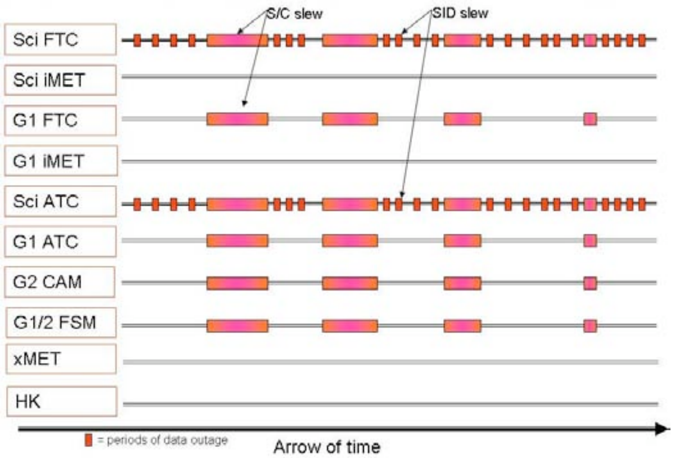

Figure 5. Various subsystems of the instrument with their data streams during a period of observation.

In addition to providing performance metrics for the design, the end-to-end model is also a platform for designing and testing optimal algorithms for data reduction for enabling multiple science objectives of the mission. The SIM Lite instrument is comprised of several high sensitivity components described in these proceedings[4]. A cartoon of the subsystem data streams during a given time period of science observation is shown in Figure 5 where the elements whose data have a bearing on the end data products are shown.

The end-to-end modeling of the SIM mission has a long history and traces its origins back to 1999 when early design work on the space interferometry mission began[5]. The original end-to-end model has evolved significantly and been augmented over the years to characterize various SIM architectures such as SIM PlanetQuest, SIM PlanetHunter, SIM Lite. In all cases, the same fundamental components of the model have been adapted to the specific architectures; as a result it has been possible to perform comparative assessment of the current design and previous architectures. The common threads that have driven the modeling components are shown at a high level of abstraction in Figure 6. In the following sections a sample of modeling ingredients will be described.

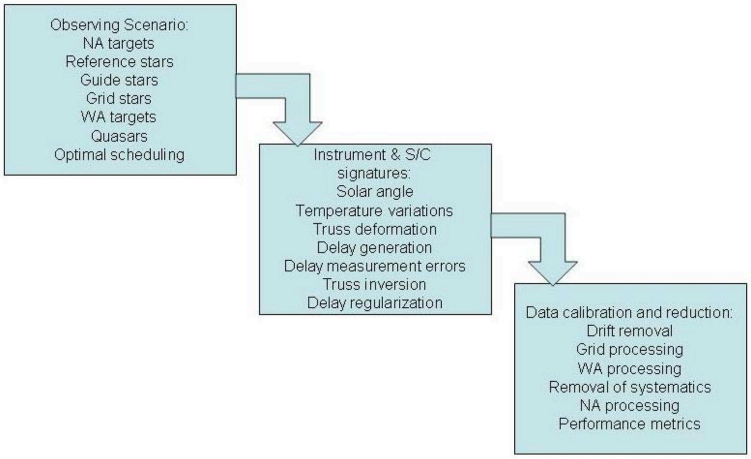

Figure 6. The common threads that have driven the end-to-end modeling for various SIM architectures.

3. MODEL DESCRIPTION

3.1 Observing Scenarios

The science objectives of the mission have led to designing observing strategies that produce an optimal signal to noise for the intended targets while maximizing the science utilization of the observatory. The Narrow Angle (NA) observations use a “chopping” method to remove a large number of systematic effects on small angular and time scales. This approach allows the observatory to obtain data with SMAs of 1 μas, thus allowing detection of Earth-like planets in nearby solar systems. There are also science objectives that do not require as stringent a SMA as exoplanet objectives and may be accomplished with measurement accuracies of several to tens of μas per visit, these types of measurement are called Wide Angle (WA) observations and utilize astrometric measurements across larger angular scales. Another scientific product from the SIM Lite mission is the observation of an all-sky stellar grid that allow a highly precise inertial reference frame to be constructed; to accomplish this objective a set of ~1300 stars almost uniformly distributed in the sky are observed many times during the life of the mission, these stars are called Grid targets. The final reference frame has a constraint that very distant quasars should appear with imperceptible parallax and proper motion, thus a set of quasars are also observed during the mission. The typical observing pattern for both NA, WA, and Grid targets is shown in Figure 7.

As planetary wobble signatures are of a periodic nature, it is important to obtain measurements that allow temporal resolution and also obtain a large number of measurements to attain a high signal to noise for the detected signal.

In the early stages of the project design an observing strategy was developed, called the “orange peel” method, that allowed assessment of the grid astrometric performance.

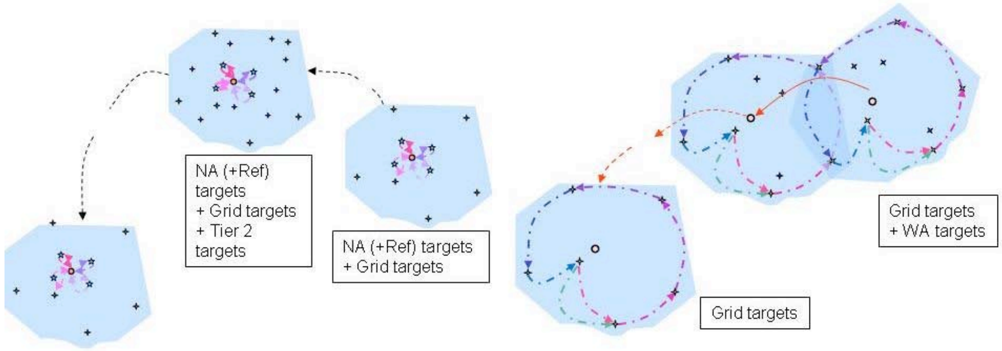

Figure 7. observation patterns for different types of targets; left panel shows observing method for NA targets, the right panel depicts observation method for Grid and WA targets.

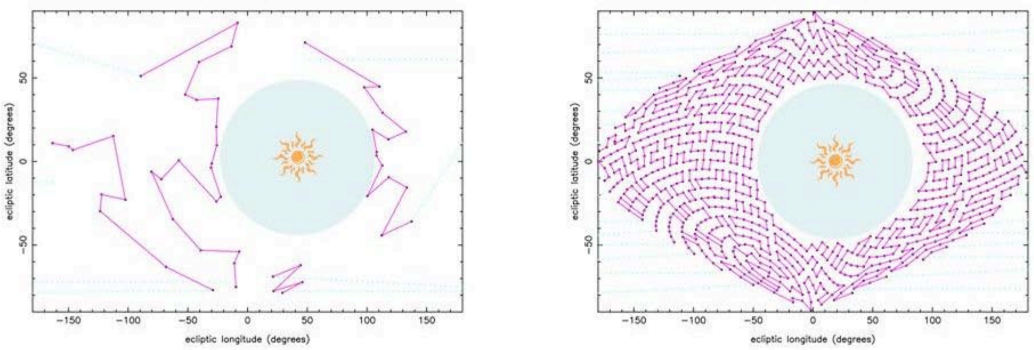

Figure 8. The left panel shows the patterns of target visits for NA exoplanet targets during a NA loop. The right hand panel depicts the pattern of visits to grid tiles during a Grid loop. The solar avoidance zone also is shown; the zone moves at the rate of 30 degrees per month.

A systems level question was whether the “orange peel” approach could satisfy the requirement of frequent observations of NA targets. Using the SIM-sim tool it was determined that only a handful of NA targets could be observed at the necessary cadences. The development team performed trades on possible observing sequences and an implementation of the traveling salesman problem was deemed to meet the cadence and efficiency constraints[6]. An example of a typical “NA loop” and a “Grid/WA loop” using the LKH algorithm is shown in Figure 8. This scheduling tool has allowed the project to assess the astrometric performance for various schemes of interleaving the NA and WA loops. The scheduling tool has enabled the systems engineering team to demonstrate that the mission architecture is capable of providing nearly contemporaneous NA observations with nearly orthogonal baselines, this feature provides astrometric measurements on two axes that facilitate identification of and characterization of planetary wobbles in the target star.

3.2 Instrument and spacecraft signatures

The early development of SIM modeling determined the expected delays for the observed targets by detailed simulation of the characteristics of the instrument system –a time consuming process. One of the necessities of an end-to-end simulator is rapid turn-around time. This way engineering questions could be addressed quickly and decisions can be made in a timely fashion. Analyses of the data from the detailed model indicated that a simpler model that used appropriate error terms could reproduce the same results as the detailed model. The present SIM-sim model utilizes instrument characterizations at the appropriate level of abstraction and is able to provide timely results. The instrument model captures the interplay of the components of the data streams shown in Figure 5 and produces delays for the periods of observation shown in that figure.

Some components of the instrument model display uncorrelated (random) noise, while other elements have a non-Gaussian nature as well as correlation because of the physical correlations within and between those elements. For example the orientation of the spacecraft with respect to the sun exposes several parts of the instrument and the spacecraft to a similar environment. The temperature profiles thus are correlated with the spacecraft orientation. Therefore, the metrology truss (shown in Figure 1) can change with respect to time. It could be due to thermal expansion/contractions as well as the metrology sensor itself being affected by temperature variations.

One significant attribute of the SIM-sim instrument model is the use of characterizations from multiple technology and prototyping testbeds. These characterizations have provided valuable performance metrics that are used within the instrument model. This attribute of the model lends significant credibility to the simulation results.

Detailed thermal simulation by the thermal engineers was performed on the spacecraft for a 100 hour period of observing science targets. The data provided valuable information for long term SIM-sim modeling. During these 100 hours the spacecraft would change its orientation and the line of sight of the interferometer would follow a set of tiles on the sky (see Figure 9). Following a careful analysis of the thermal distortion data it was determined that the thermal profiles at pivotal locations within the instrument could be derived from a simplified model.

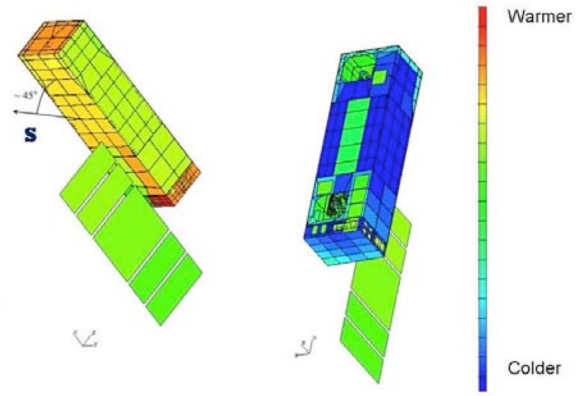

Figure 9. The temperature distribution of the spacecraft outer surface during one period of a 100 hour long thermal simulation. The left figure shows the side exposed to the sun, the right one corresponds to the opposite side (the instrument apertures). These data were used to devise a simplified thermal model to use in the SIM-sim instrument model.

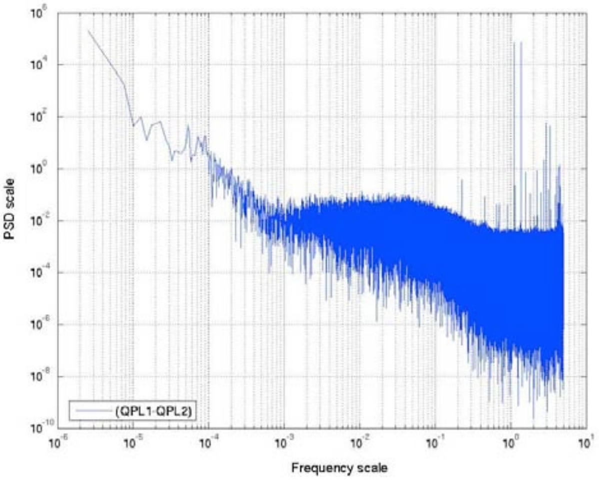

Figure 10. Representative power spectral density of metrology gauge drifts from the two-gauge experiment. These data were used to construct the conceptual model for the SIM-sim instrument model gauge drift term.

The instrument model portion of SIM-sim generates expected metrology truss measurements; the measurements reflect both the physical deformation in the truss and any inherent drifts in the metrology gauge outputs. The test data from the two-gauge laboratory experiment, where two metrology gauges had been compared against each other, provided valuable information on the temporal and thermal dependence of metrology measurements, as shown in Figure 10. These data provided an approach for the development of a conceptual model to be used in SIM-sim to represent the thermal dependence of metrology gauge drifts.

With the addition of the thermal modeling in SIM-sim it has become possible to assess trade questions such as the choice between fabricating gauges with ultra-low thermal drift characteristics (a potentially costly approach) or identifying the acceptable thermal stability requirements that lead to an astrometric error allocation that meets the project level requirements.

To characterize the Field-dependent Delay Errors (FDEs), the instrument model furthermore uses representative Zernike coefficients that were determined from previous testbed results. This allows astrometric assessment of the science objectives under various assumptions corresponding to the temporal behavior of the FDEs.

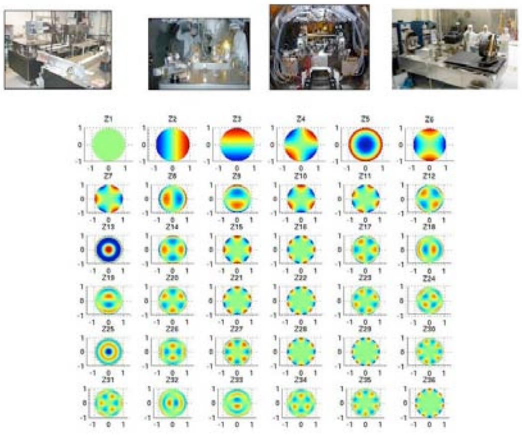

Figure 11. Some of the coefficients of Zernike terms used in the instrument model are based on the results from Kite and MAM testbeds. The coefficients are also varied in time allowing system assessment under different temporal behaviors.

3.3 Algorithms for data reduction

The regularized delay data that are generated by the instrument model portion of SIM-sim undergo a set of steps that yield estimated values for calibration parameters, such as baseline correction and ‘constant’ term for each tile and a small number of Zernike coefficients a few hundred times or so during the mission. These parameters can be used to remove systematic terms from the regularized delays generated by the instrument model. Since the estimation error improves with the number of data points it is beneficial to use a large data set for determining calibration parameters, on the other hand use of a large number of data points results in an increased time base which leads to an increase in error due to the “random walk” nature of drift terms. The flexibility of the data reduction component of SIM-sim has allowed an assessment of prudent time intervals for improved errors of the calibration terms, as shown schematically in Figure 12.

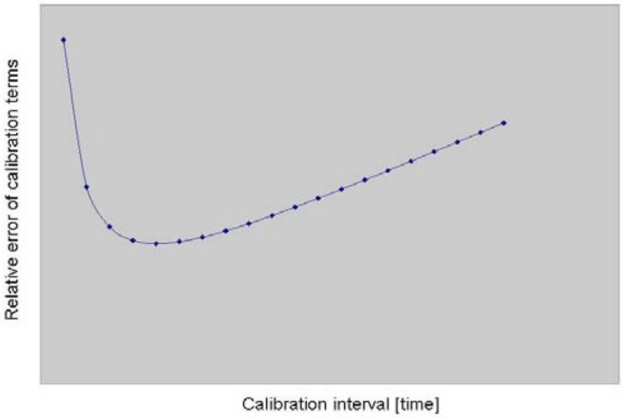

Figure 12. Interplay of improved calibration parameters with the amount of data versus degradation due to unrecoverable drift in time. SIM-sim’s data reduction flexibility allows determining the optimal time interval for calibration determination.

Another system level question related to the assessment of mission performance during the in-orbit checkout (IOC) period and the instrument commissioning phase. By simulating an observing schedule for a few weeks of the IOC period and reducing the data, it was possible to demonstrate that a first-order grid determination could be performed and used for observatory performance assessment as shown in Figure 13.

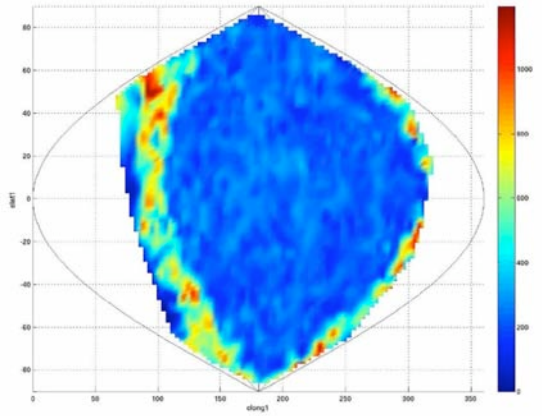

Figure 13. Example of observatory assessment scenario for determining the astrometric performance of the grid the using an observing schedule covering five weeks of in orbit checkout period.

One of the major capabilities of SIM Lite is the determination of physical properties of Earth-like planets around nearby stars. This science objective is accomplished by performing NA observations. A large amount of effort has been devoted to ascertaining the NA data reduction potential of SIM Lite. The SIM-sim platform has been used as a vehicle for demonstrating the planet-finding capability of the observatory by using representative data generated by SIM-sim corresponding to actual observing schedules that were described in Section 3.1. This undertaking has resulted in the development of new algorithms that utilize the full potential of the SIM Lite data[6].

Many science programs have been proposed that rely on the astrometric performance specifications for SIM Lite. In probing some of the potential science objectives, we have used the SIM-sim capability to demonstrate a performance even better than the requirements. As an example, through observation of a group of clustered stars it is possible to use the absolute (WA solution) parallax and proper motions of individual members to map their location and velocity and determine their relative positions and velocities. However, since the data for the members of such a program are collected within a short duration it is reasonable to expect that some of the systematics in their data are common mode and could be removed at the same time. Using this line of reasoning the SIM-sim data reduction algorithm was augmented to take such common mode behavior into account. As a result of this investigation, it was possible to show that science programs using *differential* parallax and proper motion can expect a nearly 10-fold improvement in accuracy compared to using the absolute parallax and proper motions.

Like many other projects, the SIM Lite project uses a high level error budget to track the performance of the system in an easy to use excel spreadsheet called the Astrometric Error Budget (AEB). The AEB accounts for all known sources of error and is used as a tracking device to allocate requirements and roll up lower level errors and provides the current best estimate (CBE) of the astrometric performance. On a periodic basis the SIM-sim tool is used to perform astrometric performance assessment using the same parameter set as the CBE settings, the estimates from the two methods are compared to ensure consistency in performance assessment.

4. CONCLUSIONS

The development of a SIM-sim end-to-end model has enabled the project to address multiple systems engineering questions and to provide avenues for assessing requirements, fine-tuning observing strategies, improving the data reduction algorithms and examining the post launch astrometric expectations. In the course of technology development and testbed activities a large body of data has been generated. These test data have been utilized to help in the development of conceptual models for the instrument behavior. The use of characterization test data in SIM-sim has thus provided a large degree of credibility in the obtained results. Due to the infeasibility of testing the observatory in full during ATLO, the “test as you fly” (TAYF) paradigm is not possible. The verification and validation of the SIM Lite mission will rely heavily on analysis (using models such as SIM-sim) as the method of verification and validation. The work to date has set the stage for further investigations of other science capabilities and readiness for support of the V&V program.

5. ACKNOWLEDGEMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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