SIM Lite: Ground Alignment of the Instrument.

Frank G. Dekens, Renaud Goullioud, Fabien Nicaise, Gary Kuan, Mauricio Morales
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, Ca, U.S.A.

ABSTRACT
We present the start of the ground alignment plan for the SIM Lite Instrument. We outline the integration and alignment of the individual benches on which all the optics are mounted, and then the alignment of the benches to form the Science and Guide interferometers. The Instrument has a guide interferometer with only a 40 arc-seconds field of regard, and 200 arc-seconds of alignment adjustability. This requires each sides of the interferometer to be aligned to a fraction of that, while at the same time be orthogonal to the baseline defined by the External Metrology Truss. The baselines of the Science and Guide interferometers must also be aligned to be parallel.

The start of these alignment plans is captured in a SysML Instrument System model, in the form of activity diagrams. These activity diagrams are then related to the hardware design and requirements. We finish with future plans for the alignment and integration activities and requirements.

1. INTRODUCTION
The SIM Lite instrument consists of a Science Michelson interferometer with a 6 meter baseline and 50 cm entrance apertures. The 4.2 meter Guide-1 interferometer and high-accuracy Guide-2 Telescope (G2T), are tied to the science interferometer by an external metrology truss, which measures the changes in the science baseline vector. All the optical paths of the SIM Lite Instrument are shown in Fig. 1. For alignment purposes, the instrument consists of several “benches” or large assemblies. Each bench holds various sub-assemblies or components, such as siderostats, optical compressors, Fine Steering Mirrors (FSM), etc. These sub-assemblies need to be aligned during the bench integration and test phase. These alignment steps are described in Sec. 2. Then during the Instrument Integration and Test (I&I) phase, the benches themselves need to be properly aligned with respect to each other, which is described in Sec. 3. Details of how the SIM Lite instrument works is discussed by Goullioud et al. and a current status of the project is given by Marr et al.

There are five major benches, all of which are attached to the Precision Support Structure (PSS) so that they are kept aligned both through launch and as the thermal loads on the spacecraft change. The layout of the benches and PSS are shown in Fig. 2. The Combiner Bench at the center contains the two Astrometric Beam Combiners (ABC). The two benches on either side of the Combiner Bench are the guide collector benches. These contain the guide collecting optics, and the bench closer to the spacecraft bus also contains the Guide-2 Telescope. The Guide benches also contain all of the External Metrology Beam Launchers. The two outer benches contain the science interferometer collecting optics.

The first iteration of this alignment procedure is used to capture early requirements that affect the design of the compressor benches and the instrument. As we continue to design the hardware, the benches in particular, we will also add fidelity to the alignment and integration plans. In order to maintain a cohesive plan that is linked to hardware and to the requirements that are generated for alignment and integration, we are capturing these plans in a SysML Instrument model as Activity diagrams. A SysML model is a high level modeling language for system engineering that can contain the system design, analysis, requirements, etc. at a block diagram level. The current SIM Lite system model already contains a break-down structure of most of the SIM Lite hardware. By adding the alignment plans to the model, we further capture requirements and activities associated with specific hardware that is needed for alignment of the instrument. A few typical screen captures of the model are shown.

Further author information: (Send correspondence to F.G.D.)
F.G.D.: E-mail: fdekens@jpl.nasa.gov
The SIM Lite optical paths contain a large number of optics, whose alignment is crucial to the interferometers working properly.

The first phase is to internally align the individual benches. We will not cover the alignment procedure of the Astrometric Beam Combiners, which is described by An et al, and may assume those are already properly aligned. The two Science collector benches are nearly identical, so we will only describe one of them. The bench closer to the space-craft bus, referred to as the Inboard Science Bench, contains the Long Optical Delay Lines (LODL), whose rails need to be parallel to the light-beams, and hence we will describe the alignment plan for that bench. The Science bench on the opposite side of the instrument has static mirrors to match the reflections, but these are easier to align, so the integration is nearly identical and we can just skip some steps.
The Inboard Guide collector bench also contains the Guide-2 Telescope and six of the eleven External Beam Launchers, making that bench the most complex of the collector benches to align. We will therefore describe the alignment procedure for that bench, since the Outboard Guide bench is again a sub-set. The final step is to align all four collector benches plus the Combiner Bench to each other during Instrument Integration and Test.

2. COLLECTOR BENCH ALIGNMENTS

2.1 Science Collector Bench Alignment Procedure

The more critical alignments of the Science collector bench are: the compressor primary to secondary mirrors (in order to have the proper wave front error), and the alignment of the delay lines, such that there is little beam walk as the Science interferometer switches between different stars. The components in the Science bench are seen in Fig. 3. They are, in order of starlight incidence: siderostat, primary mirror of the compressor, secondary mirror of the compressor, the Fine Steering Mirror (FSM), the Modulating Optical Mechanism (MOM), the two delay lines, and finally the Alignment Mirror Mechanism (AMM). The last mirror steers the beam out of the plane of the compressor towards the Astrometric Beam Combiner. In order to simplify the mounts, the large siderostat and primary mirror will not be adjustable. These will be placed to mechanical tolerances*. The following optics will have adjustment capability in their mounts: the secondary mirror of the compressor, the FSM, the delay lines (but only in tip and tilt), and the pupil mask (but only in shear).

![Figure 3. The SIM Lite Science Optical Bench Optical elements](image)

There are four phases in this alignment procedure. The first consists of only the bench with the primary and secondary mirrors of the compressor, along with a Zygo\textsuperscript{5} Interferometer and a large reference flat. The setup is shown in Fig. 4. The activity diagram shows the components that are needed for this setup as inputs on the left hand side. Note that this procedure is generic, and will be used five times, once for each of the

*Whenever we specify to mechanical tolerances, we will require that to be better than 100\(\mu\)m.
compressors. The configuration will change slightly, but not the steps. Upon completion of this setup, the bench will be taken through a low level vibration to ensure everything is seated properly and there are no shifts in the mounting interfaces. The steps for this configuration is captured in a SysML Activity diagram, whose partial screen capture is shown in Fig. 5.

Figure 4. The first alignment configuration for the SIM Lite Science Collector Bench

Next the Fine Steering Mirror (FSM) is installed, and a beacon needs to be placed at the same location where the vertex of the Double Corner Cube (DCC) is required to be located. The Double Corner Cube is embedded inside the siderostat mirror. The configuration is illustrated in Fig. 6. Since the FSM is at the conjugate plane of the siderostat, the image of the beacon through the compressor will focus at the center of the FSM. Thus, this can be used to align the FSM in shear, perpendicular to the mirror, and in piston to precisely locate the FSM at the conjugate point. The associated SysML activity diagram is shown in Fig. 7. The exact sensitivities still
need to be calculated, along with how well the beacon location needs to match the final DCC vertex location. The clocking of the FSM can be done to mechanical tolerances, and the tip and tilt alignment will be adjusted in the next setup.

Figure 6. This setup requires a beacon at the DCC vertex location in order to align the Fine Steering Mirror in shear and piston.

Figure 7. SysML Activity Diagram of FSM alignment.

After that, the final interferometric setup is configured, shown in Fig. 8. For this step, the pupil mask (not shown in diagram), Modulation Optical Mechanism (MOM), Siderostat and Long Optical Delay Lines (LODL) are installed. The reference mirror is placed such that it returns the beam when the siderostat is at the center of its field of regard. All of the optics are placed to mechanical tolerances, however, the FSM pointing needs to be adjusted in order to steer the beam parallel to the rails of the delay line, such that pistoning the delay lines does not cause beam shear. The beam shear is measured by moving the delay line from one extreme to the other of its piston range. The FSM pointing is adjusted until the shear caused by moving the delay lines is less than 80 microns over its 80 cm of travel.
2.2 Inboard Guide Collector Bench Alignment Procedure

The layout of the optical components in the Inboard Guide Bench is shown in Fig. 9. Both the Guide-1 and G2T compressors optics are installed, following the same procedure as the Science Bench, as shown in Fig. 10. The bench, with both optical compressors aligned will go through a qualification level vibration test, to ensure all mounts are seated properly, and there are no shifts.

The subsequent setup uses the Zygo as a light source to align the Guide-2 Telescope. This will be done by mounting the G2T Siderostat and Angle-Metrology Inlet fold to the bench to mechanical tolerances. The
Figure 10. The first alignment configuration for the SIM Lite Guide Collector Bench. Although two Zygo-compressor-reference flat setups are shown, they are actually done sequentially. This shows the optical configurations that are needed, and hence the holes that are needed in the bench for this alignment setup.

Angle-Metrology inlet-fold, which has a central hole to let the Angle Metrology beam through, will at first have a beam splitter mounted. This allows light from the Zygo interferometer into the Guide-2 Telescope. The Angle Tracking Assembly is then installed and adjusted to point the beam onto the CCD camera. This setup is shown in Fig. 11. The beam-splitter is then replaced with the proper Angle-Metrology inlet mirror, and the Angle-Metrology gauge is installed. The gauge has adjustments to point the 4 pencil metrology beams towards the 4 corner cubes that are embedded in the G2T Siderostat.

Next the Guide-1 Fine Steering Mirror needs to be installed and aligned. This will be done following a procedure similar to that of the Science bench (back in Fig. 6), but with a beacon at the Triple-Corner-Cube location. Then the rest of the Guide-1 collector optics will be installed. This includes the two folds, the MOM, and the Guide-Optical-Delay-line (GODL). The alignment steps are similar to that of the Science bench. The GODL is actually a 1 milli-meter range pistoning mirror, that also tilts to compensate for the beam walk. This mirror is currently under design, with fairly benign tolerances, since the FSM and MOM compensate for any small deviations. The GODL is only used to compensate for any left-right arm miss-match in the Guide-1 interferometer, and possible shifts between ground alignment and on-orbit operations.

Finally, to align the External Metrology beam launchers, each Guide bench has to be placed in a support equipment truss. The truss will contain the missing fiducials, at the correct locations. This allows one to place the bench in its relative location, and have access to the beam launchers. The coarse alignment of the beam launchers needs to be done to less than 0.1 milli-radians. The beam launchers have internal fine-pointing adjustments with a range of 1 milli-radian; however, most of this range is to be used for post-launch shifts due to zero gravity and dry-out of the PSS.

3. INSTRUMENT ALIGNMENT

Once the Astrometric Beam Combiner and the four collector benches are internally aligned, we start integrating them into the instrument. In Fig. 12, we show the top view of the instrument inside the Precision Support
Figure 11. The Guide-2 Telescope is using a Zygo interferometer as the source, which is being injected by replacing a mirror by a beam splitter, and requiring the appropriate through holes.

Structure (PSS). We first describe some of the setup that is needed prior to alignment, and then describe the major steps in the instrument alignment sequence.

3.1 Setup for the Alignment sequence

Because of the gravity induced shifts between the ground alignment and on-orbit operations, special care should be taken to compensate for the mechanical distortion produced during ground alignment. Our approach to the problem is to independently support each of the five major benches as well as the PSS with “gravity offloading alignment fixtures”. Each bench will rest on top of 3 or more adjustable support points, carefully located to
minimize internal gravity sag to the bench. This will simulate the on-orbit relative locations of the benches with respect to the PSS. Each support point will be adjustable to be able to position the bench to 50µm in translation and 50µrad in the rotational degrees of freedom. Also, each of the flight alignment mechanisms need to be at the center of their range during these alignment steps. That way, the full range of the actuators will be available for correcting the ground to on-orbit shifts, and for the PSS and bench dry-out shifts. For each of the gravity off-load mechanisms, we require the stability to be better than 50µm over the time frame that we are performing the alignments.

At various times during the integration procedure, the support struts holding the benches to the PSS need to be adjusted to the correct length and attached. Each strut will be build to the approximate size, and then be adjustable to its final length. In each case, we require the shift between the optimal optical alignment, to that of the mechanically connected one, to be better than 50µm in translation and 25µrad in rotation.

For each of the following steps, we use the coordinate system shown in Fig. 13.

![Figure 13. Coordinate system for each bench, and also for the Instrument. The baseline direction is along the X-axis.](image)

### 3.2 Instrument Alignment sequence

1. **Aligning the Astrometric Beam Combiner (ABC) assemblies to the Position Support Structure:** The Science and Guide-1 Astrometric Beam Combiners are each mounted on the combiner support structure that holds the Science ABC on the bottom, and the Guide-1 ABC on top. The gravity offloading fixtures need to be adjusted to off-load the ABC structure to the Position Support Structure (PSS) to mechanical tolerances. The combiner bench will then be connected to the PSS, however, they are each still on their own support structure in order to prevent deformation.

   Both ABCs will need a ground support equipment (GSE) source attached to their stimulus fiber, in order to monitor the beams coming out of the ABC that go along the reverse star-light path, and to the Internal Metrology fiber, in order to later on monitor the return power onto the Internal Metrology detector. Also, power meter electronics will be needed to monitor the return power into the Internal Metrology beam launcher.

2. **Installing the Outboard Guide Collector Bench:** The Outboard Guide bench is the Guide bench further away from the space-craft. It is installed on its gravity offloading fixtures and placed to mechanical tolerances. It is then aligned along four degrees of freedom: shear perpendicular to the beam coming from the ABC, and tip and tilt. The distance from the ABC (along the base-line) can be left to mechanical tolerances since the Inboard Guide bench will be adjusted to make the paths equal. The clocking about the beam coming from the ABC (about the x-axis) needs to be adjusted to align the Internal Metrology
beams onto the FSM mask. This is the only degree of freedom of the setup that does not have an internal adjustment mechanism. The tip, tilt and both shear degrees of freedom can be fine tuned later on with mechanisms. Note that although the Outboard bench at this point is in place, it is not attached to the PSS just yet, in case the clocking needs to be adjusted in the next step.

3. **Installing the Inboard Guide Collector Bench:** The Inboard guide bench is now placed on its gravity offloading fixtures. The same alignment procedure is followed as with the outboard bench; however, at this point the perpendicularity between the Guide Interferometer baseline and the Guide collector bore-sight needs to be adjusted. First, the external metrology laser beam needs to be aligned with respect to the two TCC fiducials that are inside the Guide benches, using the internal mechanism that is in the beam launcher. Once aligned, it will hold its pointing location and the metrology light is replaced by a visible light source. Second, a penta-prism is added in the path to point the external metrology light down the guide optical light path. The bench tip/tilt can now be fine tuned in order to make the collector bore-sight perpendicular to the baseline to less than 1 milli-radian.

The clocking of the bench about the baseline (x-axis) needs to be aligned to 1 milli-radian with respect to the Outboard bench. This is accomplished by turning on the internal source and aligning an external mirror with an inclination sensor in front of the Outboard bench. Once the mirror returns the beam back onto the Angle Tracking Camera (ATC), the bench roll about the x-axis will be know with respect to the inclination-sensed-mirror to about 2 arc-seconds. An illustration of this setup is shown in Fig. 14. Next, the mirror is translated in front of the Inboard bench and this time the bench itself is aligned to the mirror, until again the source light returns onto the Angle Tracking Camera. Once this is accomplished both sides of the interferometer are pointing in the same direction. Note that at this point the return power of the Internal Metrology beam launcher should be the same for both sides of the interferometer, as the light goes through its masks to each of the Triple Corner Cubes on the guide benches. If this requirement is not met on either side, both benches can be adjusted (by the same amount) about the x-axis to balance the two arms. The last adjustment is to use Absolute Metrology mode on the internal metrology beam launcher, through which we can measure the path length difference between the two arms of the Guide interferometer to better than 100 \( \mu \text{m} \). The Outboard Guide bench is then translated to minimize the difference. Once this is done, both guide benches can have their mounting struts adjusted to the correct size and attached to the bench and PSS.

4. **Installing the Outboard Science Collector Bench:** Since the Science interferometer has siderostats with 15 degrees field of regard, the pointing of the bench is much less sensitive than the guide benches; however, since we will have the guide interferometer pointing angle established with respect to gravity, we will align the pointing of the Science collector benches in the same way. Each bench is installed on their gravity offloading fixtures. The distance from the ABC, and the roll about the pointing angle will be adjusted to mechanical tolerances. As with the guide benches, the clocking about the x-axis will be verified by ensuring that enough power is returned to the Internal Metrology beam launcher. The Outboard Science bench is located in shear to the outgoing beam of the Science ABC while its internal source is on.

5. **Installing the Inboard Science Collector Bench:** The Inboard Science bench alignment is similar to that of the Outboard Science bench, however, there is one additional constraint. The Inboard Science bench need to be aligned in shear such that the Science baseline is parallel to that of the Guide. To do this, we will operate the External Metrology system to determine precisely the relative fiducial locations. Since at this point all benches are in place, the External Metrology truss is complete, and can be used to determine the Science and Guide baseline lengths, along with their parallelism. Also, as with the guide benches, the clocking about the bench to ABC light path needs to be aligned to equalize the power in the Internal Metrology return beams.

4. **CONCLUSION AND SUMMARY**

We have started the installation and alignment plans for the SIM Lite mission. These plans will be communicated with the mechanical design team, who will need to accommodate the various setups, and design the support equipment in more detail. We have started capturing these activities in a system model tool using SysML.
Figure 14. Illustration of where the penta-prism and inclination-sensed-mirror will be located on the Inboard Guide collector bench.

As the design of both the compressor benches and instrument evolves, we will add further detail to the activities and maintain a current set of associated requirements. We will further augment the alignment plans by tying it into the CAD models, such that pertinent information can be obtained from the CAD models, as well as linking the model to the DOORS requirements tool. SysML will be the foundation of this activity, and will provide traceability and capture rationale.

ACKNOWLEDGMENTS

We wish to thank John Holt, Robert Karban and especially Nicolas F Rouquette for many helpful discussions on setting up a SysML model in order to help capture the information in activity diagrams.

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

REFERENCES