# The StarLight Formation-Flying Interferometer System Architecture[1]

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*Abstract* - The StarLight project, formerly known as ST3 and scheduled for a 6 month mission in 2006, will demonstrate the new technologies of spaceborne long-baseline optical interferometry and precision formation flying necessary for the Terrestrial Planet Finder and other future astrophysics missions. A primary goal is to fully characterize the interferometer capabilities by obtaining 100-500 fringe visibility amplitude measurements for stars in the band 600-1000 nm with a variety of stellar visibilities (0.2-1.0), stellar magnitudes (Mv = 2-5), and baselines (B = 30-125 meters). Interferometry on StarLight will be performed both in a 1 meter fixed-baseline combiner-only mode and in a formation-flying mode, in which two spacecraft operate in a novel Parabolic Geometry Interferometer configuration. The Interferometer System will consist of the following subsystems, each of which will have components on both the combiner and collector spacecraft: Stellar, Metrology, Optical Bench, Electronics, and Flight Software. This paper provides an overview of the Interferometer System driving requirements, its overall architecture, and subsystems.

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## 1. INTRODUCTION

The StarLight mission is planned for a 2006 launch into an earth-trailing orbit where it will demonstrate the technologies of spaceborne long-baseline optical interferometry and precision formation flying necessary for the Terrestrial Planet Finder (TPF) and other future astrophysics missions [1]. Formation-flying control is provided by the Autonomous Formation Flying (AFF) Sensor and the two spacecraft busses to an accuracy of 2 cm range and 1 arcmin bearing angle (1 sigma). The spacecraft busses also provide power, command and telemetry services, attitude control (with 8 arcsecond knowledge), thermal control, and structural support for the interferometer [2]. The interferometer will obtain >100 fringe visibility amplitude measurements for stars in the band 600-1000 nm with a variety of stellar visibilities (0.2-1.0), stellar magnitudes (Mv = 2-5), and baselines (B = 30-125 meters), equivalent to spacecraft separations of S =40-600 meters. These measurements will provide a characterization of the formation-flying interferometer performance and demonstrate the robustness of this technique for TPF (see Figure 1). The interferometer metrology subsystem will also provide precision knowledge (25 um/sec range rate and 10 arcsecond bearing angle, 1 sigma) to directly validate the formation-flying capability.

Interferometry on StarLight will be performed both in a 1 meter fixed-baseline combiner-only mode and in a formation-flying mode, in which two spacecraft operate in a novel Parabolic Geometry Interferometer (PGI) configuration [3]. This configuration was adopted in order to save cost – instead of three spacecraft flying in a symmetric formation (with two Collectors and one Combiner), we are able to achieve multiple baselines with only two spacecraft (one Collector and one Combiner). In the PGI configuration, the Combiner spacecraft will remain at the focus of a virtual parabola (7 meters from the vertex of the parabola), while the Collector spacecraft maneuvers to various positions along the parabola such that the two arms of the interferometer maintain equal length over a variety of separations and bearing angles (see Figure 2). In this fashion, projected baselines of 30-125 meters can be achieved with spacecraft separations of 40-600 meters (implemented in 4 discrete steps). When operating in formation mode, the starlight in the right arm of the interferometer will pass through a fixed optical delay line which contains the 14 meters of round-trip vertex-focus distance. When operating in combiner-only mode, a shunt mechanism will bypass the fixed-delay line, such that the baseline is limited to the size of the optical bench (about 1 meter). This mode is useful for interferometer checkout and calibration.

[1] 0-7803-7231-X/01/$10.00/© 2002 IEEE

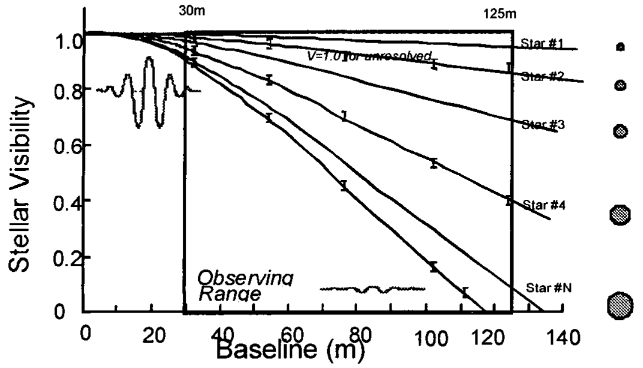



**Figure 1 – StarLight Performance Characterization**

## 2. INTERFEROMETER SYSTEM

This paper represents a snapshot of the Interferometer System design (9 months prior to Interferometer Preliminary Design Review at the time this was written). The StarLight Interferometer is essentially a conventional Michelson stellar interferometer design adapted to a space-based, formation-flying platform. The Inter-perimeter System includes the following subsystems, each of which will have components on both the combiner and collector spacecraft: Stellar, Metrology, Optical Bench, Electronics, and Flight Software. An overview of the Interferometer System driving requirements and architecture will be presented here, followed by detailed descriptions of the subsystems in Sections 3 - 7.

*Some Driving Requirements*

A list of some challenging requirements driving the interferometer system design is presented in Table 1 with some supporting comments below.

The ultimate validation of the StarLight Formation-Flying and Interferometry technologies will be the characterization of system performance by obtaining a set of fringe visibility amplitude measurements on a variety of stars spanning a range of baselines (the project requirements described briefly in Section 1). The resulting instrument visibility and limiting magnitude requirements are based on target star analyses in which a reasonable number of stars (~20), spanning the visibility space from unresolved (1.0) to well-resolved (0.2), were identified as suitable for observation by StarLight. In order to minimize thermal distortions, the StarLight Interferometer will be continuously shielded from the sun during the 6 month operational phase of the mission. This places some constraints on the availability of stars for repeat observations (i.e., stars within 26 degrees of the celestial poles are continuously observable, with availability dropping to about 30% of the time for stars near the ecliptic). Also, targets must meet strict criteria to be suitable in terms of visibility (i.e., binaries and stars with large apparent diameters are excluded).

The stellar pointing control requirements are driven by the visibility requirement (i.e., the precision required to control the fringe spot overlap for both arms of the interferometer). Pointing control is also obviously

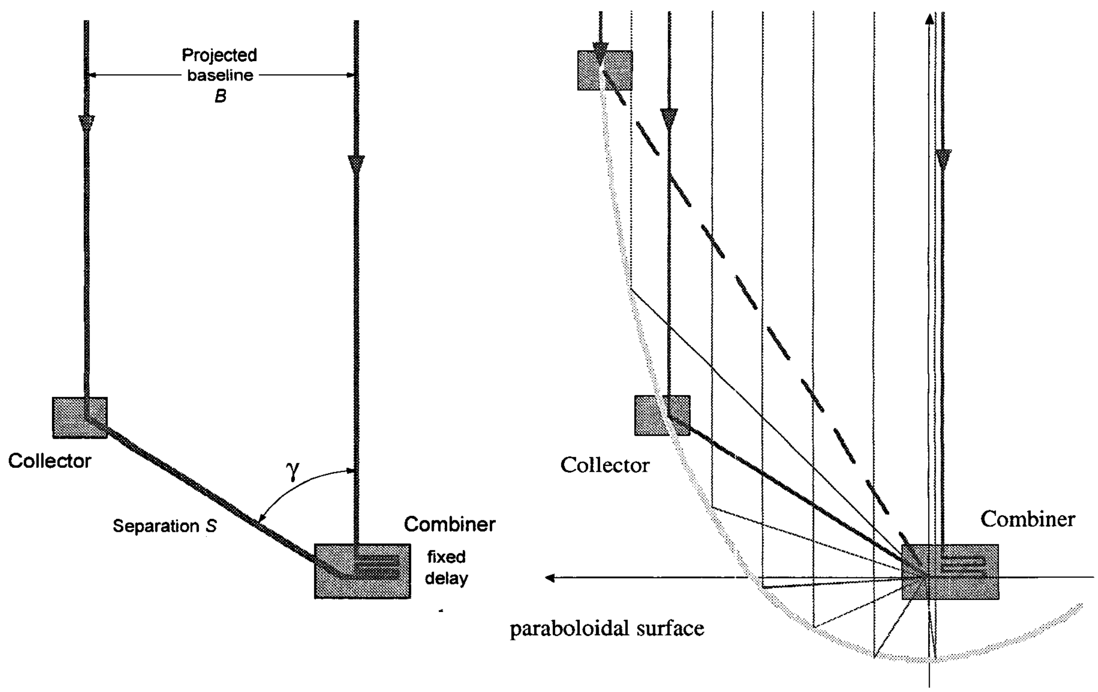



**Figure 2 - Parabolic Geometry**

| Requirement | Spec |
|---|---|
| Instrument Visibility (white-light) | 0.47 |
| Visibility Stability | 0.02 |
| Limiting Magnitude (Mv) | 5.0 |
| Stellar pointing, each arm<br>-control (per axis, 1 sigma, on-sky)<br>-knowledge (per axis, 1 sigma, on-sky)<br>-closed-loop bandwidth: | <br>0.25 asec<br>0.20 asec<br>50 Hz |
| Interspacecraft (Metrology) pointing<br>-control (per axis, 1 sigma)<br>-knowledge (per axis, 1 sigma)<br>-closed-loop bandwidth: | <br>25 mas<br>18 mas<br>50 Hz |
| Optical pathlength control, left arm<br>-control (RMS)<br>-knowledge (RMS)<br>-closed-loop bandwidth: | <br>35 nm<br>11 nm<br>300 Hz |
| Delay-rate estimation (knowledge) | 20 μm/s |
| Stellar Line of Sight knowledge | 10 asec |
| Stellar/Metrology co-alignment, on sky | 1.4 asec |
| Passband | 400-600nm (pointing), 600-1000nm (fringes) |
| On-orbit lifetime (design for) | 12 months |

**Table 1 - Some Driving System Requirements**

important for star acquisition although the precision is somewhat looser than that driven by visibility. A note about control bandwidths: the baseline design assumes we need a 50 Hz closed-loop bandwidth for the stellar pointing control loops. Recent analysis suggests that we may only need 10-20 Hz bandwidth. In any event, sensor latencies associated with the stellar pointing servo drives a challenging 500 Hz sample rate requirement for the camera. This is consistent with a need to provide 500 Hz camera sampling for actual fringe tracking.

The interspacecraft pointing control accuracy is likewise driven by the instrument visibility requirement. Whereas the stellar pointing control requirement refers to inertial pointing on each spacecraft, the interspacecraft pointing requirement refers to the need to compensate for relative motion between the two spacecraft.

The optical pathlength control requirement refers to the need to adjust the left arm of the interferometer in order to compensate both for local pathlength changes (combiner-only) as well as delay residuals between spacecraft. Again, this is driven by the visibility requirement. This control requirement drives the Metrology Subsystem to provide optical pathlength knowledge for both arms of the interferometer to an accuracy of 11 nm, 1 sigma at a sample rate of 3 KHz.

Interferometric fringe detection on StarLight is challenging due to delay and delay rate uncertainties. Delay uncertainty means the exact optical path delay for each observation varies due to the fact that formation-flying isn't perfect (i.e., interspacecraft range uncertainties exist). It follows that the optical path delay

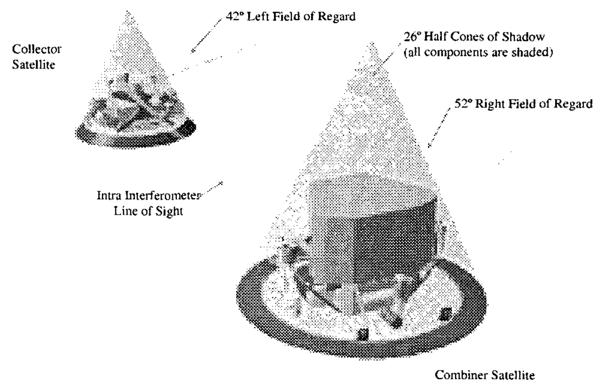



**Figure 3 - Formation Configuration**

is also likely to be time-varying due to spacecraft formation (range) control residuals so even if one knows where to look for the fringe, it's easy to lose unless one knows which way it's moving. Therefore, on StarLight, fringe acquisition is preceded by an iterative process known as delay and delay-rate estimation and formation trimming. This process has been described elsewhere [4] but it's worth mentioning that the delay rate estimation in particular poses challenges for the interferometer system (e.g., left stellar angle rate knowledge of 14 mas/s).

*A Tour of the Interferometer*

As shown in Figure 3, there are two "arms" of the interferometer, defined from the point of view of the interferometer camera located at the beam-combiner focal plane on the combiner spacecraft (more on this to follow). The right arm extends towards to the star. The left arm extends towards the star via the collector spacecraft, whose primary purpose is to host a relay mirror. The large Fields of Regard in azimuth are to accommodate the wide range of formation geometries required for multiple baselines.

*Combiner Hardware*

Figure 4 depicts the combiner spacecraft. The disk shaped sunshade/solar array and square structure are referred to as the spacecraft bus. Two of the interferometer electronic assemblies are mounted to the side of the bus: the Interferometer Control Electronics (ICE-1) and Drive and Signal Conditioning Electronics (DSCE-1). The ICE-1 (to be described in more detail later) contains a computer which will host the interferometer flight software and also provide data handling interfaces with the spacecraft computer and an interspacecraft communications link with the interferometer hardware on the collector. The large wedge shaped object on top of the bus is the Interferometer Main Bench Assembly. In this drawing, the Main Bench can be seen to be enclosed by a tent of thermal blankets. Figure 5 provides a side view of the combiner Main Bench (blankets have been removed for clarity). The multiple

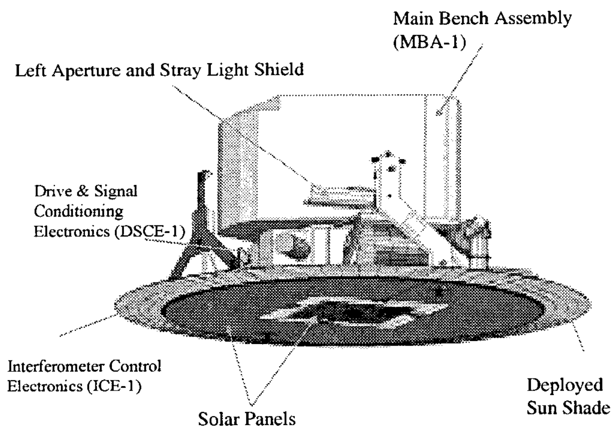



**Figure 4 - Combiner Satellite**

"stalks" are thermal-blanket supports. The bench supports all of the opto-mechanical hardware for the Stellar and Metrology subsystems, an overview of which is provided in the upcoming walkthrough of the right and left arms of the interferometer.

*Collector Hardware*

Figure 6 depicts the collector spacecraft. The collector is a less complex version of the combiner. It hosts a smaller set of interferometer electronics (ICE-2 and DSCE-2) and the collector Main Bench Assembly. The collector Stellar and Metrology hardware is limited to a single siderostat and retro-reflector, a transfer flat, and the Metrology Pointing Sensor (MPS). Unlike the combiner bench, the collector bench is not surrounded by a thermal blanket tent (instead, the blankets directly cover the bench).

*The Right Arm (refer to figure 7)*

Starting with the right arm of the interferometer on the underside of the combiner main bench, incoming light from the star is collected by the right combiner Siderostat, which provides precision tip/tilt pointing control and a 12 cm aperture. The starlight then passes through a Beam Compressor, which provides 4:1 reduction in beam diameter (to allow smaller downstream optics) and stray light control via a shuttered and baffled pinhole. The 3cm starlight beam is then transferred to the top of the main bench through a periscope arrangement of fold mirrors. The top fold mirror in the periscope (referred to as Right Apex Mirror 1) also provides in-flight precision tip/tilt adjustment to remove quasi-static misalignments of the stellar boresight/line-of-sight . In formation-mode the stellar beam then enters the Fixed Delay Line (FDL) which contains the 14 meters of optical path necessary to support the combiner spacecraft's position at the focus of the parabola. Alternatively, in combiner-only mode, the FDL is bypassed by a shunt mirror mechanism which deflects the beam into a short cats-eye, thus supporting the 1 meter baseline in combiner-only mode. After leaving the FDL (or shunt), the stellar beam is routed by

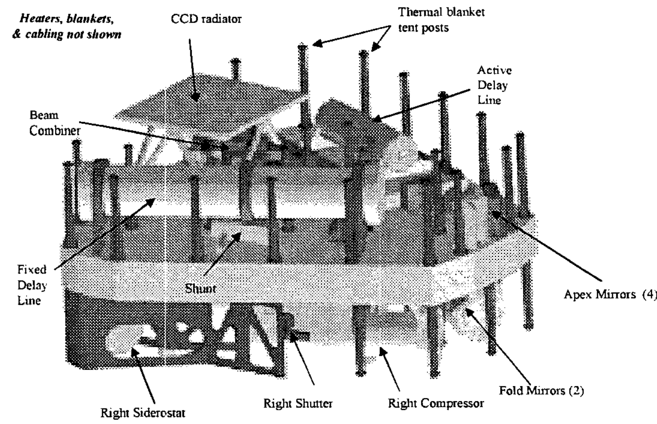



**Figure 5 - Combiner Main Bench**

Right Apex Mirror 2 (also actuated for alignment control) to the Beam Combiner Assembly. The Beam Combiner will be described in more detail in Section 4. Briefly, however, the Beam Combiner houses the optics which combine the two arms of the interferometer, generating left and right pointing spots, white light fringe spot, and dispersed fringe spots on the camera focal plane for detection. The dispersed spots refer to a 4 channel spectrometer capability used to augment fringe tracking and measurement.

While the above description concentrated on the incoming stellar beam, linear metrology of both arms of the interferometer is also critical. For the right arm, the 1.3 µm metrology laser beam (details to be provided in Section 5) is injected via a Beam Launcher on the Beam Combiner sub-bench. The metrology beam is injected at the center of the stellar beam and occupies the inner core (this fraction of the beam is not available for stellar photons). The Metrology beam is directed out of the Beam Launcher (Figure 8) towards the right siderostat and retro-reflector, then returns to the Beam Launcher where it continues on to a retro-reflector mounted on a spider near the Beam Combiner beam splitter, before returning to the Beam Launcher for detection.

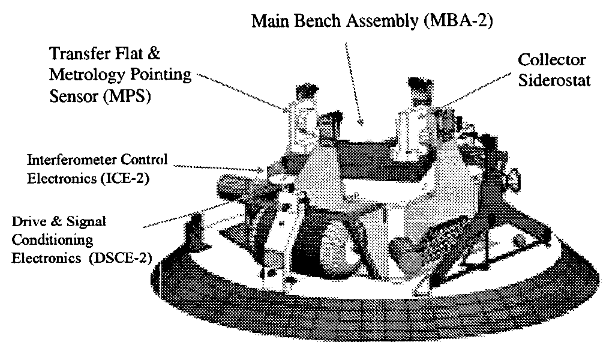



**Figure 6 - Collector Satellite**

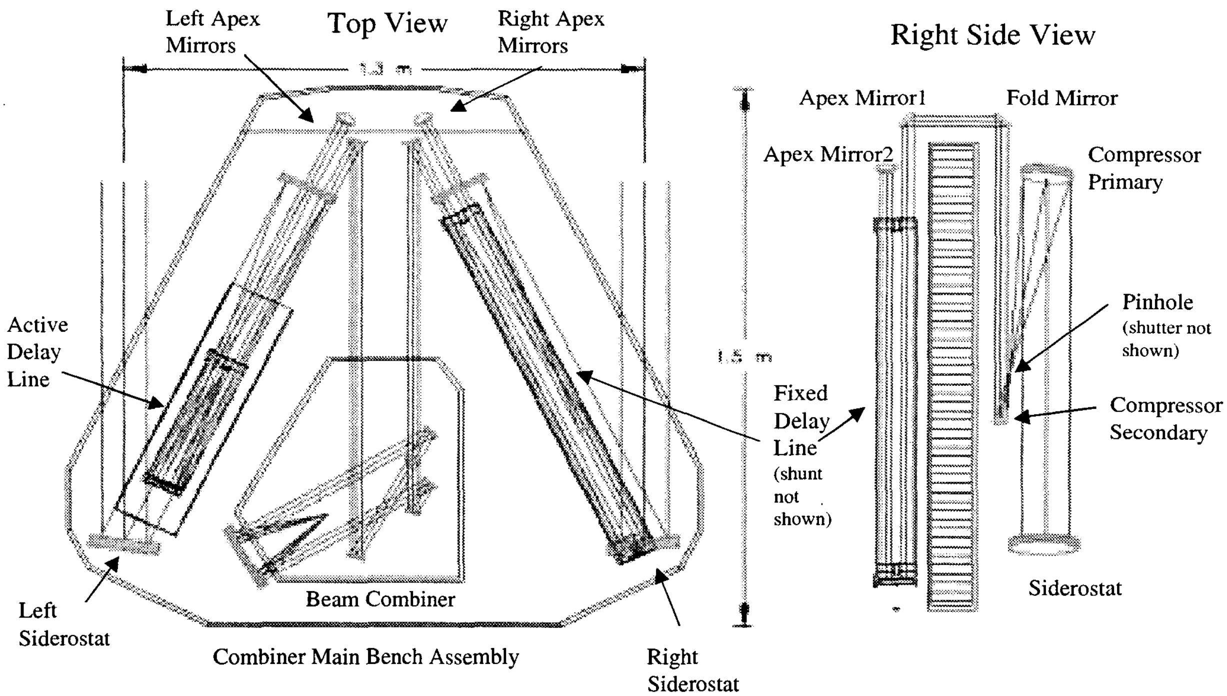



**Figure 7 - Combiner Stellar Optical Layout**

*The Left Arm (refer to Figures 3, 7, & 8)*

The left arm of the interferometer is similar to the right but with additional complexity. The collector siderostat serves the same purpose as the right combiner siderostat (i.e., points at the star). The stellar beam is relayed to the combiner via a Transfer Flat mirror. Pointing control of Stellar and Metrology beams between the two spacecraft is provided by a combination of Angular Metrology and the Left Combiner Siderostat. Light from the metrology laser (the same source used for linear metrology on the right arm), is injected from a Beam Launcher on the left arm of the Beam Combiner on the combiner spacecraft. In addition to the internal, combiner-only linear metrology, the left metrology beam also monitors the inter-spacecraft path (external metrology) and is used as component of the left pointing control loop (angular metrology). This is accommodated as follows. The outbound left metrology beam is intercepted by a beam-splitter before reaching the left combiner siderostat, at which point part of the beam is directed to a corner cube near the left siderostat, thus supporting left arm combiner linear metrology. The other part of the left metrology beam continues on to the left siderostat and is directed toward the collector spacecraft. An angular metrology acquisition sequence uses the left siderostat to center the metrology beam on the collector transfer flat via feedback from the MPS over the interspacecraft comm link. This allows the left combiner siderostat to track relative motion between the two spacecraft. The left metrology beam also continues past the collector transfer flat to a retro-reflector on the collector siderostat. In this fashion, the inter-spacecraft portion of the left arm optical pathlength is also sampled. Alignment of the left arm stellar and metrology beams is critical (1.4 arcsec level).

The linear metrology function is based on phase measurements of the retro-reflected signals. Phase modulation is used to solve the "dual-target" problem on the left side. More details on Metrology will be presented in Section 5 of this paper.

The only other difference on the left arm is the delay-line. Unlike the FDL and shunt on the right arm, an Active Delay Line (ADL) is included in the left arm. The ADL will be described in more detail below.

*Other tricks*

In addition to the hardware already described for support of the primary interferometer function (observing stars), an Internal Test Source (ITS) is included in the design. The driving requirements for the ITS are as follows:

1) Support a built-in capability to make assessments of combiner-mode interferometer throughput, visibility, and alignment at various stages of the pre-launch integration effort (the original idea was to employ a fairly portable piece of test equipment known as the "traveling pseudo-star", basically an inverse interferometer...but there were difficulties accommodating it).

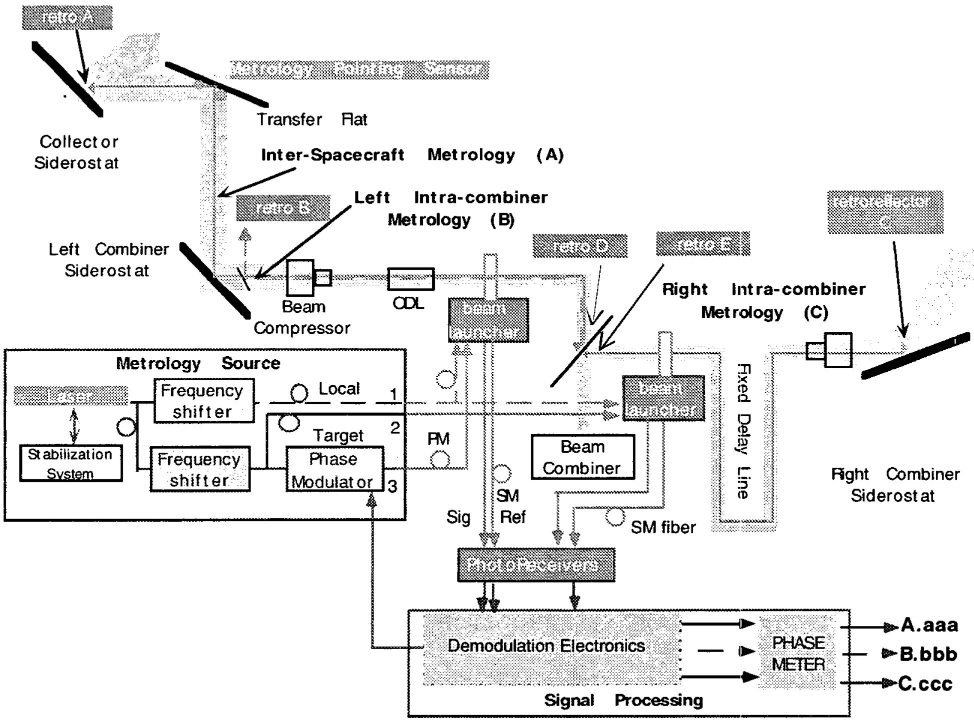



**Figure 8 - Metrology Subsystem Architecture**

2) Provide the same capability for in-flight alignment and calibration of the interferometer in combiner-mode.

A preliminary concept for the ITS is shown in Figure 9. In this concept, two independent sources are used to inject light into two arms of the interferometer through optical fibers at or near the pinhole in each beam compressor.
In this concept, two sources are necessary due to the large dynamic range required to support both alignment and fringe generation.

Source 1 consists of a fairly broadband LED (850± 25 nm) to produce "white-light" fringes. This will allow white-light fringe tracking both on the ground and in flight but doesn't provide sufficient spectral width to support dispersed fringe tracking (that capability will be tested in our Formation Interferometer Testbed using a non-portable full white-light pseudo-star). The light is injected outwards through the pinhole, hits the combiner siderostats which can turn inward in a "narcissus mode", and is then reflected back into the interferometer arms like real starlight and thus travels to the focal plane for detection.

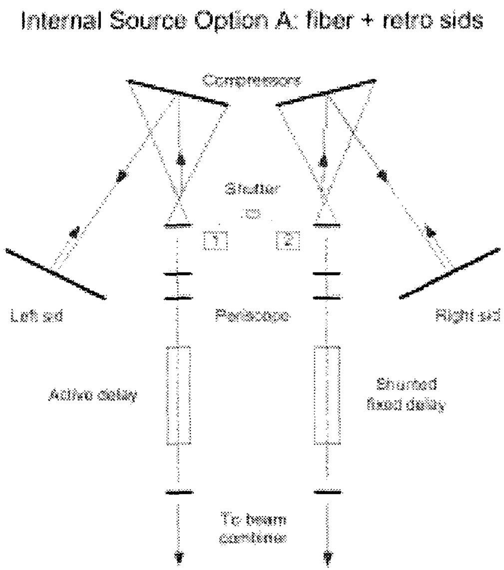
Source 2 consists of a normal diode laser which is used to illuminate the inner side of the closed shutters (i.e., source 1 and 2 can't be used simultaneously). The laser beam on the shutter is imaged by the camera as a defocused spot and used as an internal alignment reference. Adjustments can then be made using the apex mirror actuators in the periscope. Alternative ITS architectures are being studied.

*Thermal and Structural Support*

The Optical Bench Subsystem (to be described in detail in Section 3) is responsible for supporting the components of the Stellar and Metrology Subsystems. Minimizing misalignments is a critical and challenging requirement (i.e., few arcsecond scale changes are allowed). The Optical Bench Subsystem also provides the thermal control system for the interferometer. Among the key requirements in this area is a need to maintain both the temperatures of the combiner and collector main benches to 20 ± 1 degC during observations. Also, the camera CCD must be kept cool (-60 degC) to reduce dark current. De-contamination and spot heaters are also provided in discrete locations. Note, survival heater control of the optical benches and operational/survival thermal control of the interferometer electronics is provided by the spacecraft bus.

*Enough about photons – on to electrons (and bits)*

Electrical support for this assortment of opto-mechanical hardware is provided by the Electronics Subsystem, which includes a total of four assemblies, two each on the Combiner and Collector spacecraft bus. The Electronics subsystem will provide power, control, and signal conditioning and processing for the Stellar, Metrology, and Optical Bench components; support a high speed (< 1 msec latency) interspacecraft communication function to close the left pointing control loop; and also host the Flight Software in a dedicated interferometer computer




1 source 1: broadband LED (850 ±25 nm) to produce white-light fringes

2 source 2: diode laser to illuminate the back of the shutter for alignment

**Figure 9 - Internal Test Source**

(one each on the combiner and collector). More details on the Electronics Subsystem will be provided in Section 6.

Flight Software will execute command and data handling, fault protection, and interferometer control algorithms, to be covered in detail in Section 7.

*Operational Design*

The StarLight mission operational design is still undergoing study but we present our current assumptions used to guide the system design. The minimum mission duration is 6 months (extendable to 12 months). After a month or so of initial spacecraft separation, checkout, and formation-flying experiments, we will perform checkout and calibration of the interferometer in combiner-only mode, followed by more formation flying checkout, followed by several months of formation-flying interferometry (with a requirement of obtaining at least 100 UV points and goal of 500).

A typical observation sequence consists of the following key activities (Figure 10):

1) Slew: Collector spacecraft maneuvers to the desired formation geometry (i.e., the proper separation/range and bearing angle corresponding to a given baseline) – this is the most time-consuming event (moving 100 meters takes 60 minutes). During the slew, the interferometer remains in SLEW mode, which maintains system thermal stability. Towards the end of the slew, each spacecraft will make the necessary attitude adjustments to point the interferometer boresights near the target star. When the slew maneuver ends, the formation flying system will null out residuals (we assume this settle time will be one minute or so). At this point, the spacecraft reaction-wheels will be shut down to reduce jitter. Spacecraft attitude control during observations will be maintained with thrusters.

2) FM_ACQ/OBS: each Formation-Mode Acquisition and Observation will take about 30 minutes on average (the following algorithms are discussed in more detail in Section 7).

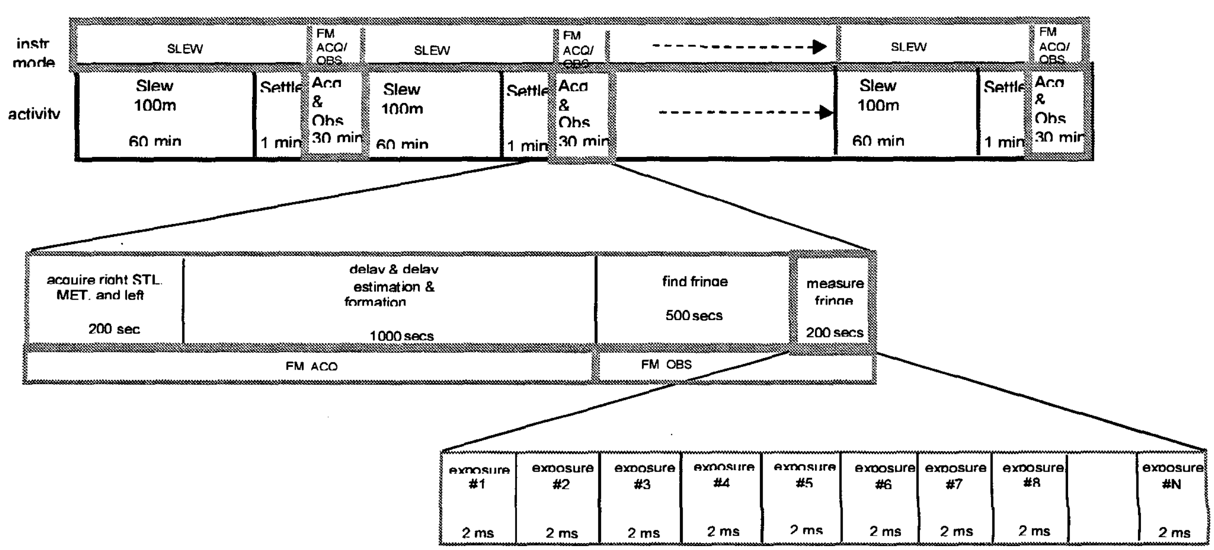



**Figure 10 - Typical Observation Timeline**

a. Acquire right and left starlight + Angular Metrology: involves performing spiral searches with the three siderostats until the star (and Metrology laser spot) are centered in the FOV. This step is expected to take about 200 seconds.

b. Delay/Delay Rate Estimation & Trim Formation: since the Slew will have some residual range and bearing angle rates (formation flying system only has 2 cm and 1 mrad precision, respectively) some "fine tuning" is necessary before fringe acquisition can be attempted. This is because the aforementioned residuals will result in an uncertainty about where the fringe is located (in delay space) and the fringe will be moving at some unknown rate (which means even if acquired, it will be difficult to follow). Hence, the need to perform delay and delay rate estimation and, if necessary, ask the formation flying system to trim the formation again – iterating until residuals are at an acceptable level. This process is still under study but for now we assume it could take 1000 seconds to complete (if there's some iteration).

c. Find Fringe: Finding the fringe involves using the coarse and fine "stages" of the Fringe Tracker algorithm to lock onto the fringe.

d. Measure Fringe: once lock is achieved on the fringe, visibility measurements commence at the 500 Hz CCD frame rate. Therefore, each measurement consists of a 2 ms exposure with the White Light fringe pixel and 4 dispersed fringe pixels serving as the observable. This process continues for about 200 seconds (under review). Spacecraft attitude control requires thruster firings which will result in momentary loss of fringe lock. The thruster firings are therefore confined to 3 second windows every 30 seconds. Following each thruster firing, fine fringe lock is automatically re-established and fringe measurement continues.

When complete, this process repeats with the formation Slewing to another baseline configuration. Our current plan is to complete all baseline configuration observations on a single target before moving on to the next.

*Summary of Interferometer System Capabilities*

A list of key interferometer properties is provided in Table 2 below. This, together with Table 1, provides a high-level summary of the StarLight Interferometer capabilities.

| **Property** | **Quantity** |
|---|---|
| Actuators | 18 |
| Control Loops | Six total<br>• three 50 Hz pointing servos<br>• three delay-line servos (1, 60, 300 Hz BW) |
| Primary sensors | 20 (including one CCD camera) |
| Engineering sensors | 185 |
| Internal Test Source | White light fringe and alignment capability |
| Optical elements | 29 |
| Laser Metrology | 1.3 μm, multi-pumped |
| Optical Bench | High-conductivity Composite facesheets w/honeycomb cores |
| Heaters | 38 |
| Electronic Boards | 24 (in 4 assemblies) |
| Main Processor | GD603R, 240 MHz |
| Flight S/W | C++, VxWorks, with 22 modules (some inherited) |
| Interferometer Mass | Combiner: 146 kg<br>Collector: 36 kg |
| Interferometer Power | Combiner: 310 W<br>Collector: 87 W |
| Field of Regard | Left Arm: 5 x 42 deg<br>Right Arm: 5 x 52 deg |
| Field of View | Stellar Pointing: 1 arcmin<br>Metrology Pointing: 1 deg |

**Table 2 - Interferometer System Properties**

## 3. OPTICAL BENCH SUBSYSTEM

The Optical Bench subsystem (refer to Figures 5 and 6) will consist of a composite structure on each spacecraft, providing a precision support structure (alignment stability of several arcseconds over several minutes to days). Both Main Bench Assemblies are composed of high conductivity graphite-composite facesheets. The Combiner Main Bench has a graphite composite honeycomb core. The Collector Main Bench has an Aluminum honeycomb core. Both will each be mounted to their respective spacecraft busses with three bipods made of Titanium thin-walled tubes.

The operational thermal control system includes an array of patch heaters on the Main Bench assemblies. For example, the Combiner Main Bench Assembly contains 16 heater zones (8 per side), each composed of 4 patch heaters and 1 thermistor controlled by a dedicated heater circuit. There are also a number of spot heaters for local thermal control plus de-contamination heaters on the Camera CCD and Siderostats for burn-off of any molecular contaminants.

## 4. STELLAR SUBSYSTEM

The Stellar Subsystem includes the optics, mechanisms, and sensors necessary for collecting stellar photons, supporting Metrology photons, and for providing precision pointing and pathlength control. The interferometer optical train has already been described from a system perspective in Section 2. We now present a detailed description of the primary components, including:

1) 3 Siderostats
2) 2 Beam Compressors (&shutters)
3) 4 Apex Mirrors (actuated)
4) 1 Fixed Delay Line (& shunt)
5) 1 Active Delay Line
6) Beam Combiner sub-bench
7) Sundry optics (fold mirrors, transfer flat, etc)
8) Camera
9) Internal Test Source (described in Section 2)

*Siderostats*

Each of the three siderostats consists of a 12 cm flat mirror mounted on a fine-stage, tip/tilt gimbal which is in turn mounted on a coarse stage "turn-table". The coarse stage is used to provide wide-angle pointing (maximum of 52 degrees of motion in azimuth) in support of the various formation geometries. The coarse stage is actuated with a DC stepper motor with feedback provided by a precision optical encoder. Coarse stage control accuracy is 1 arcmin and knowledge accuracy is 0.6 arcsec, 1 sigma. The combiner coarse stages have the ability to point inward (aka "narcissus mode") to provide retroreflection for the Internal Test Source and also provide protection against direct sunlight down the boresight. The fine stage is actuated by voice-coil type mechanisms over a range of ± 20 arcmin in azimuth and elevation. Precision encoders support open-loop control accuracy of 9 mas, 1 sigma, per axis.

*Beam Compressors*

Each of the two beam compressors consists of an off-axis telescope composed of primary and secondary mirrors. The 12 cm beam is brought to a focus inside the compressor and re-collimated at the secondary, resulting in a 4:1 compression (i.e., 3cm exit diameter). Off-axis light is reduced by the inclusion of a field-stop "pin-hole" at the focus of the compressor. Actuated shutters are provided outboard of the pinhole to provide contamination protection during launch, support in-flight alignment, and prevent damage of the pinhole due to accidental sunlight down the compressor boresight. The assumption is we'll use a metallic pinhole designed for high power laser operation. Preliminary analysis shows focussed sunlight (~1 W/mm2 power density) results in pinhole damage for relative short exposures (< 50 msec). Shutter closure will be triggered by warnings from the spacecraft computer in the event attitude deadband failures or sun sensor threshold triggers. Commanding the combiner siderostats to narcissus mode is another potential mitigation technique. The shutter actuator architecture is currently being studied, with stepper motors and brushless DC motors being the leading candidates, with limit switches for sensing the state.

*Apex Mirrors*

A total of four Apex Mirrors reside on the top side of the Combiner Main Bench Assembly (two each on the left and right arms). They serve three primary purposes: serve as the top of the periscopes used to transfer the Stellar and Metrology beams between the bottom and top of the Main Bench, serve as relay optics between the delay lines and the Beam Combiner, and allow removal of quasi-static misalignments in the combined Stellar/Metrology beam.

Each Apex Mirror consists of a precision optical flat supported by a tip/tilt actuator. The current actuator design is based on 3 Piezo-Electric Transducers (PZTs) with strain gauge feedback. However, this is still under study and is likely to change (the PZTs require constant power to hold position).

The Apex Mirror Alignment Requirements are as follows:

1) Mechanical Range: ± 2 arcmin/axis
2) Mechanical Resolution: 0.45 arcsec
3) Angular Drift: < 0.07 arcsec/100 secs
4) Piston jitter: <= 2.5 nm, 0 – 300Hz

These requirements address two primary effects: large (> 1 arcmin) shifts in beam alignment from ground to orbit (gravity release, launch loads, etc) and smaller, but significant in-flight thermal drift (instability).

We expect to make a one-time correction for the former alignment error and will perform frequent calibrations to compensate for the thermal drift. The frequency of these periodic calibrations is still under study. However, the baseline assumption is stability will be sufficient to keep the Apex Mirrors fixed during an observation (although we may end up doing a calibration prior to the start of each observation).

*Fixed Delay Line (& shunt)*

For formation mode operations, the Fixed Delay Line (FDL) packs 14 meters of optical path delay into a 1 meter package. The FDL is a 15 reflection delay line based on three prime-focus cat's eyes.

For combiner-only mode, the FDL is bypassed by means of a shunt. The shunt consists of an actuated flip mirror which intercepts the beam in front of the FDL and diverts it to a 3 reflection, single cat's eye delay line (to limit the baseline to the separation between the left and right combiner siderostats, or approximately 1.3 meters). The current shunt actuator design is based on a stepper motor and limit switches.

*Active Delay Line*

The Active Delay Line (ADL) is based a proven design developed by JPL's Interferometry Technology Program and shares a common heritage with a number of ground testbed interferometers and the Space Interferometery Mission [5], [6].

The ADL provides a 3-stage (motor, voice-coil, PZT) *cat's-eye* capable of controlling the optical path delay to a precision of 35 nm, RMS with closed loop bandwidths of 300 Hz over a optical path delay range of ±20 cm at fringe search speeds of 100 µm/sec. During fringe acquisition, the ADL is servoed until fringe visibility is maximized and then is dithered across the fringe according to a predetermined waveform while the fringe is tracked and visibility measurements are collected. There are actually 4 PZTs on the PZT stage. The dither PZT is mounted on the servo PZT. The servo PZT provides the fringe search and tracking capability. The dither PZT provides the modulation necessary to dither the delay back and forth across the fringe. A duplicate set of servo and dither PZTs and mirror are mounted in a symmetric fashion on the outside of the delay line and re-actuated to provide momentum cancellation.

The ADL is equipped with a launch lock mechanism to prevent movement of the coarse stage trolley during launch. The launch lock consists of an electronically driven, spool-initiated sep-nut connected to a threaded rod on the trolley.

*Beam Combiner*

The purpose of the beam combiner is to bring various components of the right and left stellar beams onto the focal plane of the camera for detection. In terms of overall requirements, the focal plane must provide:

1) feedback for control of the left and right stellar pointing loops
2) feedback for control of left and right beam shear
3) feedback for fringe acquisition, tracking, and visibility measurement

As a minimum, this implies the production of two fairly compact (several pixel diameter) pointing spots, a single pixel white-light fringe spot, and 4 adjacent pixels containing a spectrally dispersed fringe. The white-light (WL) fringe spot is chosen to allow fringe acquisition in an Avalanche Photo Diode (APD) like mode, in which the left and right arms of the interferometer are overlapped onto a single camera pixel in order to provide some spatial filtering. The dispersed fringe consists of light in the fringe passband (600-1000nm) split into 4 spectral channels, forming a coarse spectrometer. A "4 bin algorithm" (as used by the Keck and Palomar Testbed Interferometers) generates visibility amplitude and phase which is used for group delay estimation for improved fringe tracking (both the WL and dispersed fringes are used both in tracking as well as being the ultimate observable).

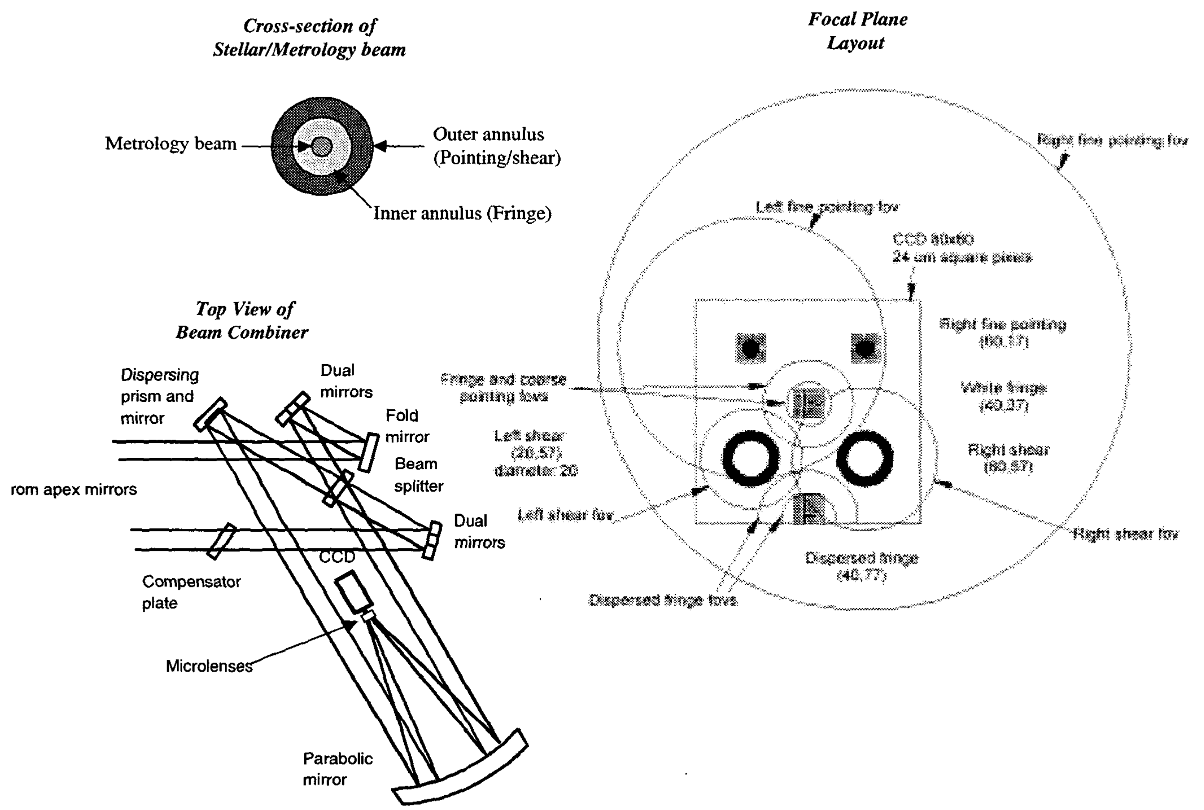



**Figure 11 - Spatially Separated Beam Combiner Concept**

There currently are two competing designs for the Beam Combiner: a spatially separated approach (using annular optics) and a spectrally separated approach (using a dichroic).

The baseline design uses a spatially separated approach and is depicted in Figure 11. This approach makes use of annular wedges, implemented using custom-designed dual mirrors, to separate the outer annulus of starlight from the inner annulus of starlight. The outer annulus for each arm is brought to the focal plane as an unfocused ring for use in beam shear feedback. It is also focused by a microlens array into a more compact spot for pointing feedback. The inner annulus for each arm is directed to a beam-splitter where it interfered with the inner annulus of the other arm. One output of the beam splitter goes directly to the focal plane (via the microlens array) where it appears as the single pixel WL fringe spot. The other output of the beam splitter goes to a prism where it is split into the 4 spectral channels before arriving at the focal plane as the dispersed fringe (across 4 adjacent pixels). The inner core of the Stellar beam is dedicated to the Metrology laser, although the Metrology beam is retro-reflected before reaching the beam splitter (not shown in Figure 11) at which point the inner core of the beam is "empty". The resulting focal plane layout consists of 2 (right and left) pointing spots, 2 (right and left) shear rings, 1 WL fringe spot, and 1 dispersed fringe.

Several challenges with the baseline design (namely, the many overlapping Fields Of View (fov) on the focal plane which represent algorithmic and stray light problems and the assembly complexities associated with the microlens array and dual mirrors) encouraged investigation into possible alternatives.

One promising option involves the use of a dichroic periscope. In this design (Figure 12), the incoming left and right beams (shown here in green and blue) first encounter a dichroic plate. The short wavelength (400-600 nm) light in each beam is reflected while the long wavelength (600-1000 nm) light is transmitted. The short wavelength light then encounters a fold mirror (M1) which shunts the light into the "upper level" of the Beam Combiner, thus missing the beam splitter (BS). The short wavelength light continues on to the flat (M2) and parabolic (M3) mirrors and brought to the focal plane (Camera) without use of microlenses. This results in a right and left pointing spot as in the baseline design but no shear rings (shear sensing is done with intensity measurements from pointing spots). Meanwhile, the long wavelength light encounters the BS (which is actually half compensator plate, half beam splitter), producing two fringe outputs which are focused by M3 onto the focal plane – as before, as a single WL fringe spot and a dispersed fringe. Note: Figure 12 does not explicitly show the required dispersion prism. The advantages of this design include a much simplified focal plane (no overlapping fovs), easier assembly (no microlenses or dual mirrors) and more photons (higher SNR). It is highly likely we will adopt this architecture as the new baseline.

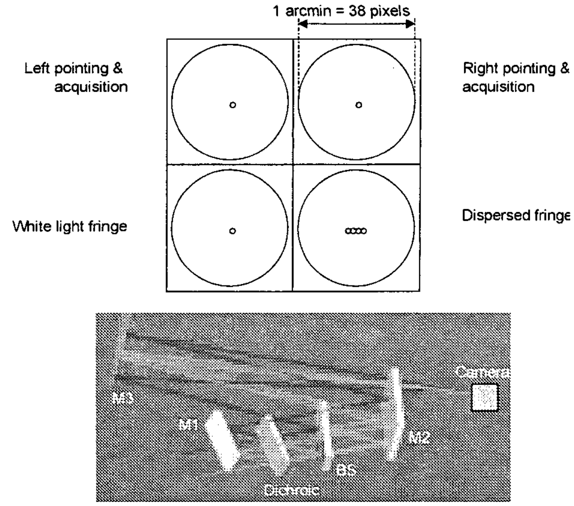



**Figure 12 - Spectrally Separated Beam Combiner**

In either Beam Combiner configuration, the optics are mounted on a sub-bench composed of Invar. Other hardware located on the Beam Combiner sub-bench include the Metrology Beam Launchers (one on each arm of the interferometer, near the Beam Combiner entrance) and the camera head (CCD). The CCD radiator is mounted over the top of the Beam Combiner sub-bench.

*Sundry Optics*

In addition to the optics described above, the Stellar Subsystem provides folding mirror flats for the bottom half of the Apex periscopes and also the transfer mirror flat on the collector spacecraft.

*Camera*

The stellar camera's driving requirements are:

1) frame rate: 500 Hz
2) read noise: 10e- RMS/pixel/frame

We have baselined the EEV CCD39, a single four-quadrant, 80x80 pixel CCD as the detector. The Camera Head, located at the Beam Combiner focal plane, will house the CCD and pre-amps. In order to reduce dark current, the CCD will be passively cooled to –60 degC via a cold-finger connected to the radiator mounted above the Beam Combiner.

The Camera Signal Chain Electronics, consisting of sample and hold and analog/digital conversion, will be located near the Beam Combiner on the Main Bench Assembly.

The VME/Camera Interface Module will be located in the Instrument Control Electronics chassis on the combiner spacecraft bus and will provide clock waveforms to the Camera Signal Chain Electronics and store the resulting full frame image data in local memory for access by the Interferometer Flight Software over the VME backplane.

## 5. METROLOGY SUBSYSTEM

The Metrology Subsystem (Figure 8) will supply a 1.3 μm laser, along with optics, sensors, and electronics necessary to support precision bearing angle determination and optical path-length knowledge. Since a detailed description of the Metrology Subsystem theory and components is presented in a companion paper [7], this section will instead discuss some high-level concepts pertinent to the overall Interferometer System architecture. As mentioned in Section 2, there are effectively two types of Metrology on StarLight:

1) Linear Metrology
   - Right Intra-Combiner Liner Metrology
   - Left Intra-Combiner Linear Metrology
   - Inter-Spacecraft Linear Metrology
2) Angular Metrology

Note that Linear Metrology includes three distinct "branches".

*Right Intra-Combiner Linear Metrology*

This branch consists of a standard heterodyne metrology gauge which provides *relative* knowledge (i.e., changes in) the right arm optical path delay. A qualitative description of this standard gauge (i.e., heterodyne interferometer) follows – refer to Figures 8 and 13. The gauge produces two optical beams derived from the single laser source: a *local* beam and a *target* beam which is frequency shifted relative to the local signal. Both the local and target beams are combined interferometrically in a Metrology Beam Launcher (an integrated assembly of beam-splitters, polarizers, and other optics residing at the entrance of the Stellar Beam Combiner). The resulting optical beat signal is sampled by a *reference* photo-diode (PD) (converted to an analog voltage). Meanwhile, the local and target beams continue on through the Beam Launcher, where the target beam is launched outwards (in this case, towards Retroreflector C located on the right combiner siderostat). The target beam returns, passes through the beam combiner, encounters Retro E located on a spider mount near the Beam Combiner beam-splitter , then returns to the Beam Launcher where it is combined with the local signal on the *unknown* PD. Again, the resulting optical beat signal is converted to an analog voltage. The two sinusoids (unknown and reference) are then compared by phase meter electronics. The ultimate product is a delta-phase measurement which is equivalent to delta-pathlength.

*Left Intra-Combiner Linear Metrology*

The combiner-only portion of this branch (the path between Retro B and Retro D in Figure 8) is identical to the right arm, with the exception of the previously

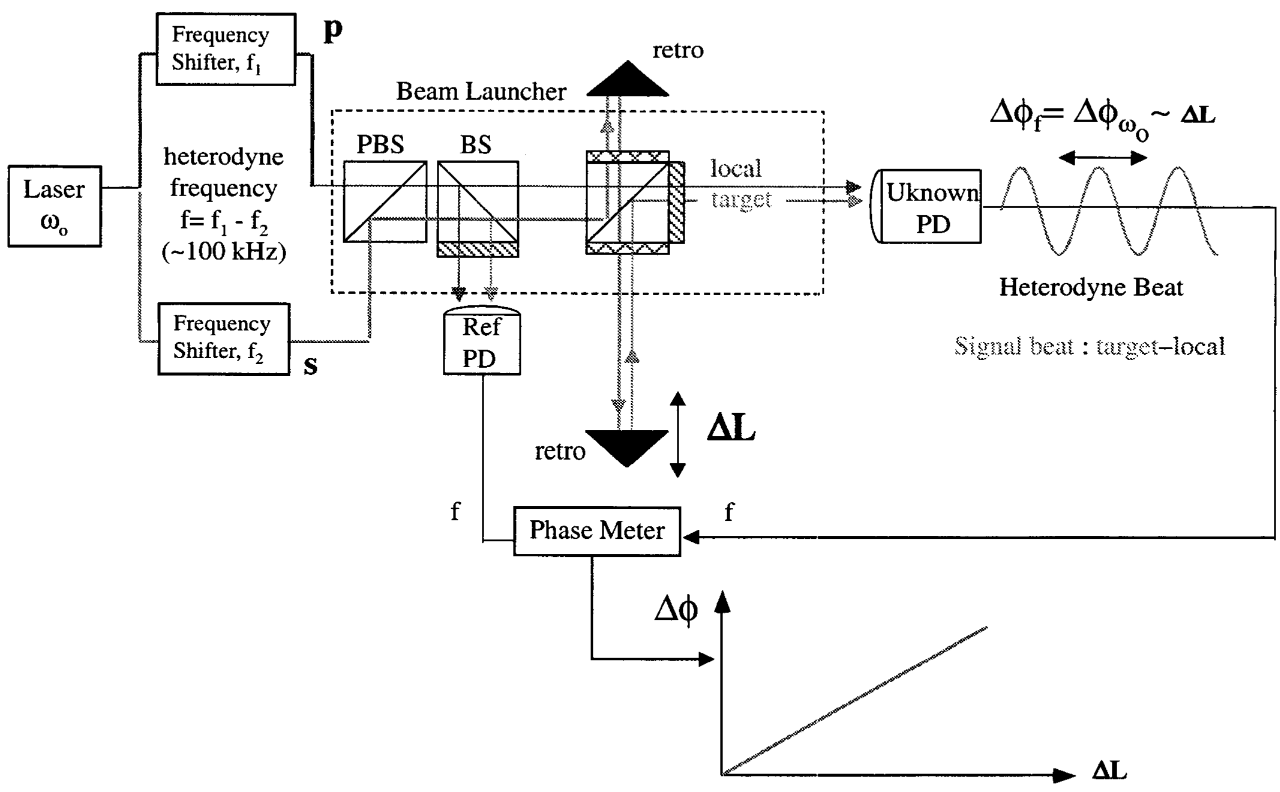



**Figure 13 - Heterodyne Metrology Gauge**

described beam-splitter which allows the left beam to continue on to the collector.

*Interspacecraft Linear Metrology*

The linear metrology aspects of this branch are similar to that described above (measuring changes in path length between Retro A on the collector siderostat and Retro D on the left arm of the Beam Combiner) – with one major difference. The single beam and two outer retros represent a unique challenge known as dual-target metrology. This ambiguity is removed by adding phase modulation to the left beam. A detailed description is provided by Dubovitsky, etal [7].

*Interspacecraft Angular Metrology*

The same laser beam used for interspacecraft linear metrology illuminates the collector Transfer Flat mirror on its way to the collector siderostat. The Metrology Pointing Sensor (MPS) is located on the transfer flat. The MPS is an Intensity Gradient Detector (basically a set of 4 photo-diodes in an "quad-cell" like configuration). The 4 voltage levels corresponding to intensity of the MPS are sampled by the collector electronics, forwarded via the Interspacecraft Comm link to the combiner interferometer computer, where they are used to compute an equivalent centroid of the laser spot on the transfer flat and used for closing the interspacecraft pointing control loop.

## 6. ELECTRONICS SUBSYSTEM

The Interferometer Electronics of course supports all of the aforementioned active components of the Optical Bench, Stellar, and Metrology subsystems. This subsystem consists of a total of 4 independent assemblies. Refer to Figure 14 for a conceptual drawing for the two assemblies on the combiner (the controller electronics configuration is similar).

*Combiner Interferometer Control Electronics (ICE-1)*

ICE-1 is a VME chassis containing the interferometer computer (the GD603R processor) board, Non-Volatile Memory (NVM) board, and many modules for input/output (I/O). Some of this I/O includes things like the control modules for the two combiner siderostat fine stages and the camera (all 3 of which are delivered by the Stellar Subsystem to Electronics for integration into ICE-1). Other I/O consists of stepper motor controllers, timing/waveform generation, engineering telemetry collection (analog and discrete inputs), serial interfaces with DSCE-1, Metrology control and phase meter, etc. The processor board provides two independent RS-422

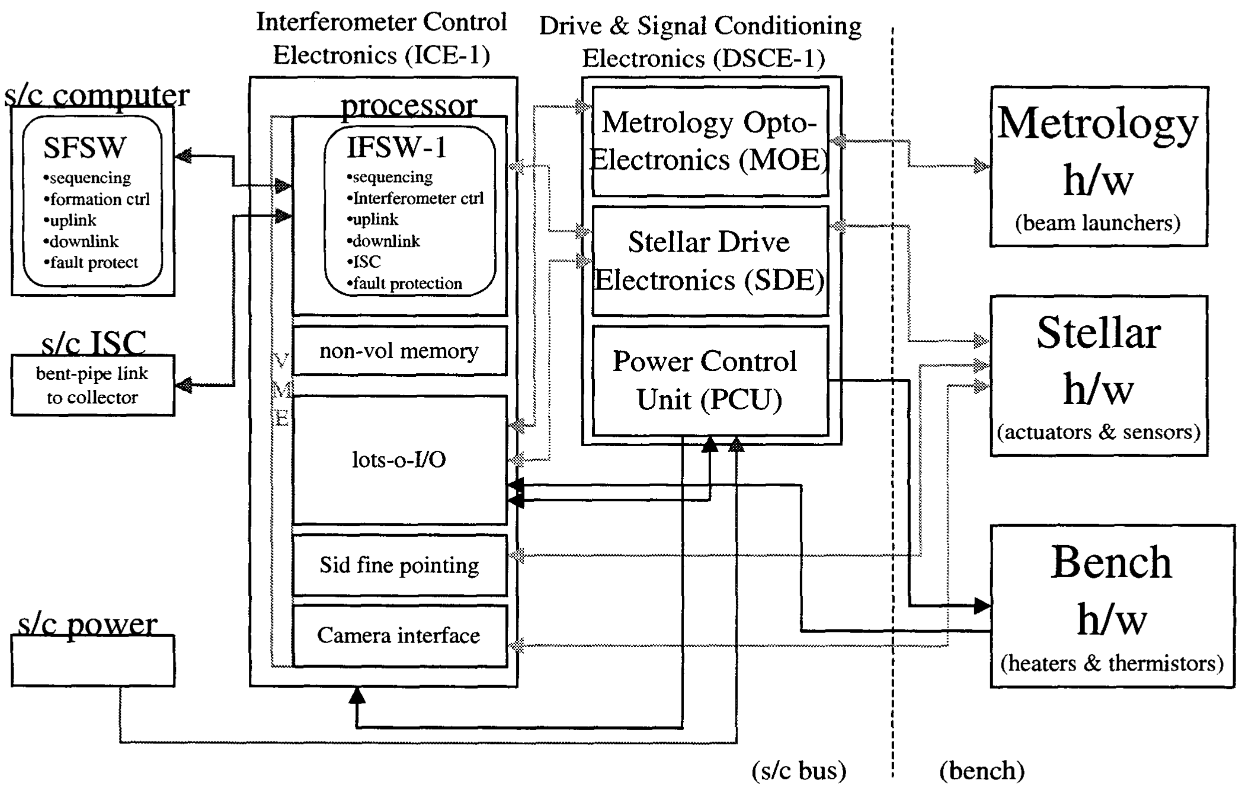



**Figure 14 - Combiner Electronics**

serial interfaces with the combiner spacecraft avionics. One provides a Command & Data Handling (C&DH) interface between the spacecraft computer and interferometer computer. The other is a bent-pipe, high speed interface with the spacecraft Interspacecraft Comm (ISC) UHF transponder used for low latency (< 1msec) transfer of interferometer control system data and commands between combiner and collector. ICE-1 is mounted on the spacecraft bus structure.

*Combiner Drive & Signal Conditioning Electronics (DSCE-1)*

DSCE-1 is a custom assembly consisting of several different modules which share a common mounting frame but otherwise do not share a backplane. DSCE-1 receives the single 28V DC interferometer power feed from the spacecraft and provides secondary power conditioning and switching for the interferometer subsystems on the combiner (including backplane power for ICE-1). It also supplies control electronics for the bench operational heaters and a substantial amount of "front-end" I/O electronics for the Stellar and Metrology components. DSCE-1 resides next to ICE-1 on the combiner spacecraft bus structure.

*Collector Interferometer Control Electronics (ICE-2)*

ICE-2 is a simplified version of ICE-1. The main differences are it only has a microcontroller instead of a full-blown computer board and the I/O is significantly reduced (mainly has to support the C&DH and ISC functions, MPS data handling, and collector siderostat fine stage control). ICE-2 is mounted on the collector spacecraft bus structure.

*Collector Interferometer Drive & Signal Conditioning Electronics (DSCE-2)*

DSCE-2 is a much simplified version of DSCE-1. It includes scaled-back versions of the power control electronics, heater control electronics, and only has front-end signal conditioning for the MPS and collector siderostat coarse stage.

## 7. ALGORITHMS AND FLIGHT SOFTWARE

The Interferometer Flight Software (IFSW) will provide the following core functions for the interferometer:

1) Basic Command & Data Handling
    - real-time uplink command execution
    - uplink command sequence loads
    - downlink telemetry
2) Fault Protection
3) Interferometer Control

The IFSW architecture uses a combination of inherited Real-Time Control (RTC) software developed for other JPL interferometry projects along with significant custom code, all of which is supported by the VxWorks commercial real-time operating system. All code is implemented in C++ (object-oriented).

The baseline control system architecture is shown in Figure 15. The key control algorithms are as follows:

1) Camera control & image analysis
2) Delay Line Controller
3) Right Pointing Controller
4) Left Pointing Controller
5) Interferometer Estimator
6) Fringe Tracker

*Camera Control & Image Analysis*

The camera plays two distinct roles on StarLight. First, it serves as a "star tracker" (the camera head and electronics and the IFSW together work to support left and right stellar pointing control loops). This software module reads the full-frame and/or sub-windowed raw camera data and generates centroids for the left and right pointing spots. Second, the camera (including the IFSW) provides intensity measurements of the White-Light and Dispersed fringe spots. Those intensity measurements constitute the ultimate observable for the interferometer. In addition to being used in real-time for fringe tracking, the raw data will also be recorded and converted to visibility measurements a posteriori (on the ground).

*Delay Line Controller*

The delay-line control servo uses the Active Delay Line to control the optical path delay in the left arm of the interferometer. Initially, feedback is provided strictly by metrology (11 nm knowledge at 3 KHz sample rate). However, during fringe acquisition and tracking, feedback is also provided from the fringe tracker servo, which incorporates white-light and dispersed fringe spots on the camera CCD at a 500 Hz sample rate.

*Right Pointing Controller*

The right stellar pointing servo is responsible for acquiring and tracking the target star on the right arm to the required accuracy (0.25 arcsec, 1 sigma, on the sky). It receives right pointing spot centroids from the camera imaging analysis module and outputs commands to the right combiner siderostat coarse and fine stages. Control of the siderostat coarse stage (setup for acquisition) requires the right pointing controller to read the coarse stage optical encoders. Control of the siderostat fine stage (star acquisition and tracking) is easier in some ways since the siderostat fine stage control is handled by an electronics board delivered with the fine stage (i.e., just send the desired position command and receive residuals – no need to deal with raw fine stage encoder data or maintain a "local" siderostat loop).

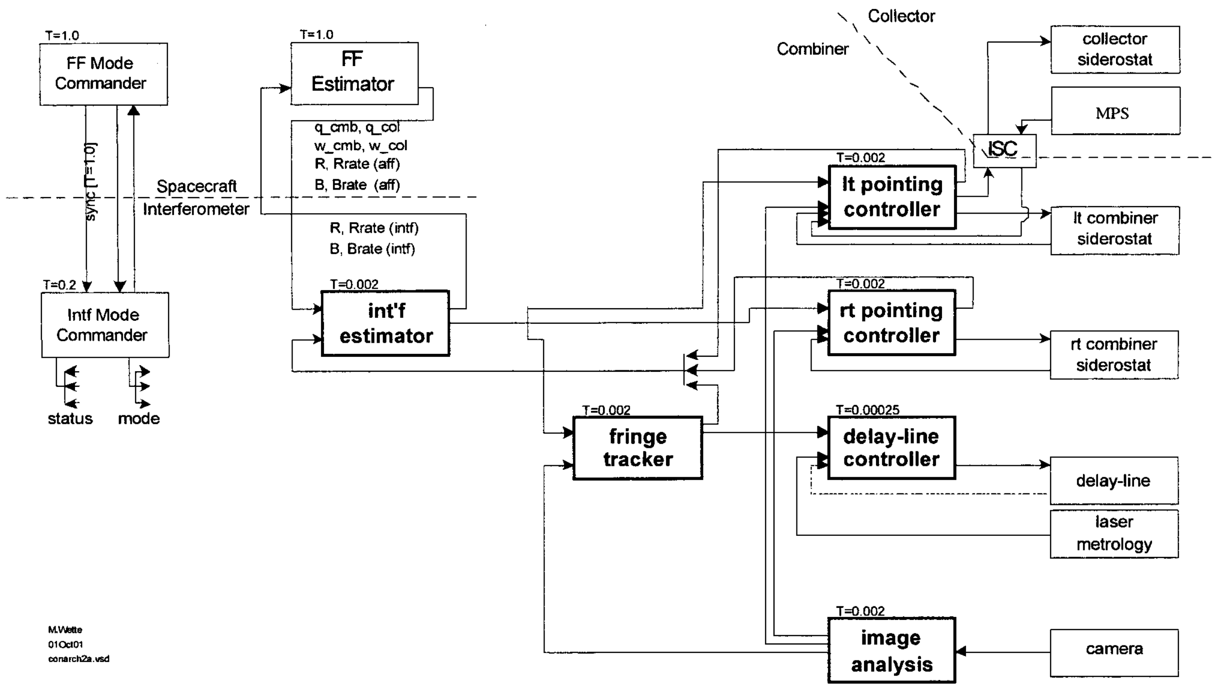



**Figure 15 - Control System Architecture**

Initial analysis suggests a closed-loop bandwidth of 50 Hz is required for all pointing loops on StarLight. Recent work suggests it may be somewhat less (maybe 10-20 Hz) but sensor latencies call for extra margin so the ultimate camera sample rate will still probably be around 500 Hz for pointing control.

Performance test results on a prototype stellar pointing control algorithm recently implemented in our Formation Interferometry Testbed (FIT) at JPL are presented in Shields' companion paper [8].

*Left Pointing Controller*

The left pointing control servo actually has two components. The left stellar pointing control loop is closed around the collector siderostat and the left pointing spot centroids. This is handled as described above for the right pointing controller. The new part is the interspacecraft pointing loop (also referred to as the Metrology Pointing Loop). This uses the Metrology Pointing Sensor (Intensity Gradient Detector) centroids for feedback and the left combiner siderostat for control. The left stellar and metrology pointing loop are ultimately integrated to cover left side pointing.

Performance test results on a prototype metrology pointing control algorithm recently implemented in our Formation Interferometry Testbed (FIT) at JPL are presented in Shields' other companion paper [9].

*Interferometer Estimator*

The Interferometer Estimator uses information from the Formation Flying (FF) Estimator on the spacecraft computer as well as the other interferometer controllers to derive delay and delay rate estimates which are used to guide formation trimming (see Section 2 for description). These estimates are later refined by feedback from the Fringe Tracker, which provides extremely precise validation of the Formation Flying solutions. This estimator also uses spacecraft attitude data from the FF Estimator (based on star-tracker and IMU observables) to assist with stellar pointing acquisition.

*Fringe Tracker*

The fringe tracker uses delay and delay-rate solutions from the Interferometer Estimator (the residuals following formation trimming) to provide a starting point for Coarse Fringe Acquisition– the ADL puts the delay in the "ball-park" (within a ± 20 mm window). The ADL then begins scanning at rates of 100 μm/s using the camera white-light fringe spot for feedback with a visibility variance algorithm. Once delay and delay-rate knowledge have been refined to the ±10 μm and 3 μm/s levels, respectively, the Fringe Tracker transitions to Fine Fringe Acquisition. At this point, the dither PZT modulation is activated to provide a pre-programmed "stair-case" pathlength modulation across the estimated fringe position. The spectrometer data is used by a "4 bin" algorithm to estimate fringe phase and improves the knowledge of fringe position [10]. At this point, fringe measurement begins. The single white-light and 4 dispersed fringe pixel data will be buffered at 500 Hz for downlink (along with error estimates from the other control loops and various engineering data). The white-light fringe data is co-phased with the dispersed fringe data a posteriori to improve overall fringe SNR.

The fringe measurement stage of an observation typically lasts about 200 seconds. We expect to momentarily lose fine fringe lock during thruster firings (every 30 seconds) but the Fringe Tracker will maintain 1.3 μm/s delay rate knowledge and automatically restart fine fringe acquisition over an ADL search range of ± 10 μm following thruster firing (expandable to ± 30 μm if fringe lock isn't quickly re-established).

## 8. SUMMARY

The StarLight formation flying stellar interferometer will demonstrate new technologies necessary for TPF and other future astrophysics missions. By carefully characterizing the system in-flight performance by obtaining fringe visibility measurements on a variety of stellar targets over a range of baselines, we will validate our components, algorithms, and processes.

In this paper, we summarized the overall interferometer system architecture and its subsystems along with their key capabilities. Although the design can be expected to evolve over time, this paper provides a snapshot of the baseline design at this phase of the project. The Interferometer Preliminary Design Review and Critical Design Review are currently scheduled for June 2002 and January 2003, respectively, and represent important milestones in freezing the interferometer design.

Our system design poses many challenges, both in detailed component level design and assembly as well as system-level integration, test, and operations. Future papers will elaborate on these and other challenges.

## 9. ACKNOWLEDGEMENTS

The authors gratefully acknowledge contributions from the entire StarLight Interferometer Team and in particular, Steve Gunter, Matt Wette, Stefan Martin, Serge Dubovitsky, Randy Bartos, and Paul MacNeal. Spacecraft configuration drawings were provided by our partners at Ball Aerospace.

The research described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the National Aeronautics and Space Administration.

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## BIOGRAPHY

Riley Duren received a BSEE in 1991 from Auburn University. He also pursued graduate studies in astronomy and physics at UCLA and the Florida Institute of Technology. He worked for NASA at the Kennedy Space Center from 1988-1995, where he prepared five space shuttle science instruments for flight. He joined JPL in 1996 where he worked on the Shuttle Radar Topography Mission (SRTM) and the Space Interferometry Mission (SIM) filling a variety of lead roles spanning system engineering, integration and test, mission operations, and data reduction. He is currently the Interferometer System Engineer for the StarLight mission, a formation-flying stellar interferometer precursor for the Terrestrial Planet Finder project. His interests include the search for extra-solar terrestrial planets and developing space-based interferometers.

Oliver Lay obtained his undergraduate degree in Physics (1991), followed by a PhD in Radio Astronomy (1994), both at Cambridge University. His thesis project involved linking the James Clerk Maxwell Telescope and the Caltech Submillimeter Observatory to form the first submillimeter-wave interferometer. During postdocs at Caltech and Berkeley, his subsequent research interests included star formation and protoplanetary disks, and the propagation of signals through the atmosphere, in addition to interferometry. He came to JPL in 1998, and became the Interferometer Architect for the StarLight mission. He is also involved in the design of the metrology system for this mission.