

The StarLight mission: a formation-flying stellar interferometer

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ABSTRACT

The StarLight mission is designed to validate the technologies of formation flying and stellar interferometry in space. The mission consists of two spacecraft in an earth-trailing orbit that formation fly over relative ranges of 40 to 600m to an accuracy of 10 cm. The relative range and bearing of the spacecraft is sensed by a novel RF sensor, the Autonomous Formation Flyer sensor, which provides 2cm and 1mrad range and bearing knowledge between the spacecraft. The spacecraft each host instrument payloads for a Michelson interferometer that exploit the moving spacecraft to generate variable observing baselines between 30 and 125m. The StarLight preliminary design has shown that a formation-flying interferometer involves significant coupling between the major system elements - spacecraft, formation-flying control, formation-flying sensor, and the interferometer instrument. Mission requirements drive innovative approaches for long-range heterodyne metrology, optical design, glint suppression, formation estimation and control, spacecraft design, and operation. Experimental results are described for new technology developments.

Keywords: formation-flying control, stellar interferometry, heterodyne metrology, formation-flying sensor

1. INTRODUCTION

NASA's long-range vision includes the search for life in the universe¹. The scientific belief that detection of biosignatures may be more likely where liquid water is present motivates the search for terrestrial planets in habitable zones around stars in our solar neighborhood. One mission envisioned for the direct detection of these extrasolar terrestrial planets is the Terrestrial Planet Finder (TPF)². A formation-flying nulling IR interferometer is one mission architecture being considered for TPF, in which four 3.5 meter collecting apertures located on 4 spacecraft spaced along a baseline of up to 200 m direct light to a central combiner on a fifth spacecraft, where light from the central star is nulled and the light from a dim off-axis planet is directly detected. Two new technologies required to make this mission feasible are *formation flying* and *stellar interferometry* on moving platforms. The StarLight mission (Figure 1) was proposed as a technology demonstration mission within the NASA Navigator Program to validate these two technologies in space.

Formation-flying astrophysics missions³ other than TPF may benefit from the StarLight technology demonstration: these missions include the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS), Stellar Imager, the Micro-Arsecond X-ray Imaging Mission (MAXIM) and the MAXIM Pathfinder.



Figure 1: The StarLight mission configuration, showing the Combiner (lower) and Collector (upper) spacecraft.

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The StarLight project was first proposed under the New Millennium Program as the New Millennium Interferometer (NMI)⁴, later renamed Deep Space 3 (DS-3)⁵ and even later renamed Space Technology 3 (ST-3)⁶. The StarLight project implementation calls for Ball Aerospace & Technologies Corporation to provide the two spacecraft buses and system integration and test. Management, system engineering, formation flying control and sensors, interferometer instrument and mission operations are performed by the Jet Propulsion Laboratory. The StarLight mission was originally scheduled for a 2006 launch; however, the flight development activities of StarLight were terminated in March 2002 (late in the project Mission and System Definition Phase). Since then, the StarLight project has been merged with the Terrestrial Planet Finder Project and will continue to develop ground technologies for formation-flying interferometry, with the goal of supporting the selection of a single architecture for TPF in 2006. For the remainder of this paper, we will describe StarLight as the point design developed at the time of the termination of the flight aspects of the project.

This paper describes the mission system design, the flight system design including spacecraft, interferometer, formation-flying and AFF sensors, and mission operations. A description of technology development results are provided elements of the formation-flying and interferometer payloads. The reader can use this mission overview paper as a guide to companion papers in this conference and elsewhere in the literature to find greater detail on specific topics of the StarLight mission or technology development.

2. MISSION OVERVIEW

The StarLight flight system consists of two spacecraft, the Combiner and Collector (Figure 1). The Combiner supports the interferometric combining optics while the Collector supports a siderostat to steer stellar light to the Combiner. The spacecraft are launched on a single Delta II 7925 with a 10-foot fairing. The Delta II third-stage solid motor directly injects the two spacecraft into an Earth-trailing heliocentric orbit and then separates from the two-spacecraft cluster configuration. Shortly after third-stage separation the spacecraft separate from one another and perform formation flying over relative distances of 30 to 600m to an accuracy of 10 cm. Relative range and bearing (to a one-sigma accuracy of 2 cm and 1 arcmin, respectively) is provided by a novel Ka-band sensor called the Autonomous Formation-Flying Sensor (AFF)^{7,8}. Optical (1.3 μ m) laser metrology between the two spacecraft provides higher precision angular and relative linear knowledge. Stellar light collected by small 12 cm optics on each spacecraft is combined in a Michelson beam combiner on the Combiner spacecraft to generate interference fringes over a range of interferometric baselines (Figure 2) which ultimately provides validation of the end-to-end technology. The mission duration is baselined to be 6 months, with a possible 6 months of extended mission operations.

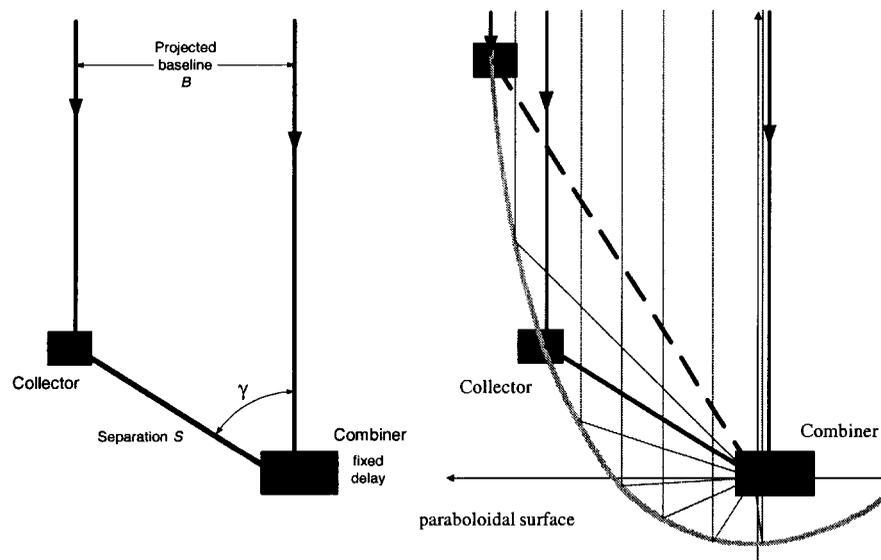


Figure 2 - Parabolic Geometry

Interferometry on StarLight will be performed both in single spacecraft mode with a fixed 1.3 m baseline for initial checkout, and then in formation-flying mode, in which the two spacecraft operate in a novel parabolic configuration⁹ (Figure 2). 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). The Combiner spacecraft, carrying 14 m of fixed optical delay on the right arm of the optics, is located at the focus of a virtual paraboloid (7 meters from the vertex of the parabola). The Collector spacecraft then maneuvers to various positions along the paraboloid, maintaining equal path lengths for the two arms of the interferometer over a variety of separations and bearing angles. With just 14 m of fixed delay, projected baselines of 30-125 meters can be achieved with spacecraft separations of 40-600 m. When operating in combiner-only mode, a shunt mechanism will bypass the fixed-delay line to give a symmetric configuration with a baseline of 1.3 m, limited by the extent of the optical bench.

The performance of the StarLight interferometer will be characterized by measuring visibility curves for a sample of approximately 20 stars with a range of angular diameters and stellar magnitudes ($M_v = 2-5$), as illustrated in Fig. 3. The passband for fringe measurements will be in the visible/near-IR (600-1000 nm) over 5 baselines in the range 30-125 m.

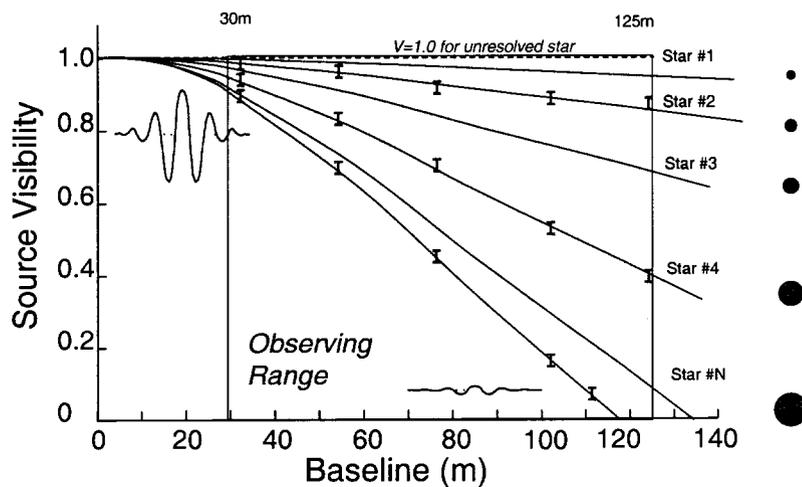


Figure 3: StarLight performance will be validated by measurements of visibility on a number of target stars with known angular diameters

It is anticipated that making 5 visibility amplitude measurements on a single target will take approximately 1 day, most of which is spent moving the spacecraft, stabilizing the formation and reacquiring fringes¹⁰. At any one epoch the formation is able to observe stars within +/- 25 degrees of the normal to the sun vector, constrained by the size of the sun shields designed to keep the instrument shaded during all observations. Over the course of 6 months all targets on the sky are observable, with some stars within 25 degrees of the ecliptic poles continuously observable. Baseline rotations of +/- 25 degrees are possible for stars only in a direction normal to the sun vector.

The target stars required to characterize the interferometer performance set demands on the aperture size. Candidates were selected from the Hipparcos Bright Star catalog, and filtered to exclude close binaries and variable stars. The stars were binned by angular diameter, the goal being to identify approximately 6 candidate stars in each of 5 size ranges. The stars in Bin 1 are marginally resolved, with source visibility > 0.8 on the 125 m baseline; those in Bin 5 are well resolved, with source visibility < 0.25. For compact targets, the fringe visibility is high and the interferometer can detect relatively faint stars; larger targets have lower visibility and must be correspondingly brighter for detection. If the target is too large, it is over-resolved and undetectable. The sensitivity required for the StarLight mission is therefore driven by the need to identify sufficient target candidates in the low visibility bins. The sensitivity depends primarily on the rate at which target photons reach the detector, the degradation of the fringe visibility due to the instrument (wavefront, path jitter, dispersion, etc.) and the fringe search rate (discussed below). Collecting apertures of 0.12 m diameter deliver a sufficient number of photons for fringe detection. Sizes much larger than this become less agile and difficult to accommodate; smaller sizes do not meet the photon requirement, and diffraction effects become a problem over the large 600 m inter-spacecraft separation.

Table 1 lists performance parameters which StarLight will validate on orbit. Formation-flying control performance levels are required to permit optical acquisition between the spacecraft. Once the optical links between the spacecraft

are established (both metrology and stellar light) more precise measurements of the formation geometry are possible; the precision formation knowledge requirements are necessary to initiate a fringe search with the optical delay line within the available delay line range. Interspacecraft absolute range is measured only by the AFF sensor; metrology only measures relative changes in range to the 10 nm level. Because the fringe search for StarLight does not require better knowledge in absolute range, the metrology system design was not designed to provide additional absolute range accuracy in order to minimize complexity and cost. Acquisition of the stellar interference fringe validates the end-to-end system operation; tracking the fringe over time and for different stars of known source visibility allows characterization of instrument stability and performance.

Table 1: Performance parameters to be validated by StarLight

Formation Flying Control (requirements apply at all separations)	
Minimum separation	at most 40m
Maximum separation	at least 600m
Range control accuracy	+/- 10 cm
Range rate control accuracy	+/- 1 mm/s
Relative bearing control accuracy	+/- 4 arcmin
Precision Formation Knowledge (requirements apply at longest separation)	
Maximum separation	at least 600m
Range knowledge accuracy (1 sigma)	2 cm
Range rate knowledge accuracy (1 sigma)	200 um/s
Bearing knowledge accuracy (1 sigma)	20 arcsec
Bearing rate knowledge accuracy (1 sigma)	0.02 arcsec/sec
Optical Stellar Interferometry	
Variable baseline dynamic range	at least 4
Longest projected baseline	at least 125m

3. FLIGHT SYSTEM DESIGN

3.1. Spacecraft system design

The two-spacecraft StarLight concept is shown stacked in the launch fairing in **Fig. 4** while **Fig. 5** shows an oblique side view of the deployed Combiner spacecraft and **Fig. 6** shows an oblique side view of the deployed Collector spacecraft. The general spacecraft mass budget is shown in **Table 2**. More detailed descriptions of the Combiner and Collector can be found in references^{11, 12}.

The main performance characteristics of the two spacecraft include a total launch mass of approximately 866 Kg, an attitude control capability of 0.67 arcmin, relative velocity control in formation flying mode of 42 micron/s, and jitter characteristics above 10 Hz of better than 0.05 arcsec. The maximum Earth-spacecraft distance is reached at the end of the mission and is expected to be ~0.06 AU. Primary communications with Earth is through the 34 m DSN using the Combiner X-band system high gain antenna.

Component and subsystem commonality are maximized between the two spacecraft buses to simplify integration and test and ensure low cost. Both spacecraft have identical formation and attitude control systems (FACS), avionics, cold gas propulsion and spacecraft control computers. The structure and power subsystems are virtually identical, with the Combiner having a larger solar array area (5.1 m²). The Collector spacecraft has a fixed sunshade with an outer diameter equal to the inner diameter of the Delta II ten foot fairing dynamic envelope. Since the Combiner solar array occupies the Delta II ten foot fairing diameter, the Combiner spacecraft uses a deployable sunshade. The sun-shades are sized to

keep the formation flying sensors and interferometer instrument optics, along with the rest of the spacecraft, in shadow and reduce glint between the two spacecraft. The Combiner propulsion module thruster stalks are angled to maintain clear fields of view for the interferometer apertures.

Table 2. StarLight Flight System Mature Mass Budget.

Item	Mass (Kg)
Combiner bus subsystem (dry)	272.8
Combiner AFF package	18.0
Combiner interferometer & electronics	176.2
Combiner propellant	47.8
Combiner spacecraft total (wet)	514.8
Collector bus subsystem (dry)	243.7
Collector AFF package	18.0
Collector interferometer & electronics	41.3
Collector propellant	47.8
Collector spacecraft total (wet)	350.8
Total flight system stack mass	865.6

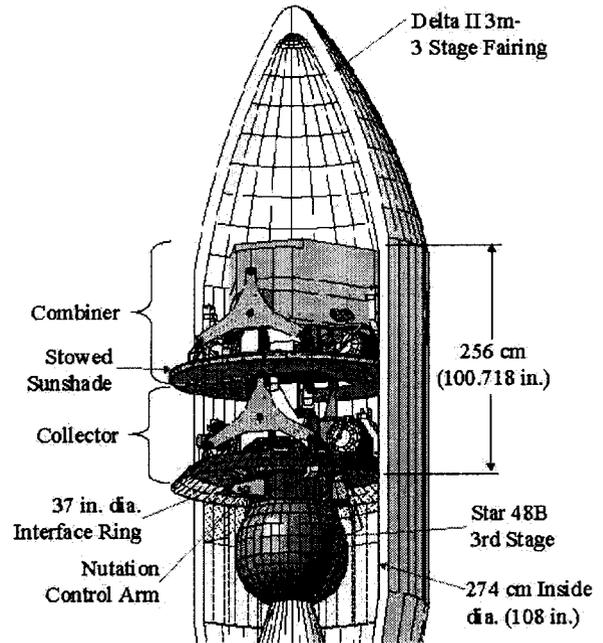


Figure 4. StarLight Launch Stack in the Delta II 7925, Ten Foot Fairing.

General Description and Functional Architecture

The StarLight constellation consists of two three-axis stabilized spacecraft buses with integrated interferometer and autonomous formation flying (AFF) sensor instrument suites. Each StarLight spacecraft consists of separate, functionally distinct subsystems—structure; mechanisms; electric power and distribution subsystem (EPDS); telecommunications (TTC); command and data handling (C&DH), FACS; software, thermal control system (TCS); and propulsion—along with the formation flying and interferometer instruments suite. The Collector spacecraft is largely the same as the Combiner except for the following differences: 3.2 m² of solar array area, diverse secondary structures, no HGA or gimbal, inclusion of the interface to the launcher PAF, and the Collector payload instruments.

The architecture for both the Combiner and Collector spacecraft is based on Ball’s spacecraft control unit (SCU) avionics suite. The SCU is a modular, rack-based system that uses circuit cards in a central electronics unit for all spacecraft control functions. The SCU utilizes both cPCI and VME backplanes interconnected with a bridge chip. Hardware interfaces are standardized (RS-422), which simplifies mission-specific modification. The largely single-string StarLight configuration provides critical redundancies. Hardware design is also modular, enabling parallel manufacturing, integration and test flows.

The telecommunications systems on each spacecraft are similar. Both use identical UHF systems for inter-spacecraft communications at data rates of up to 512,000 bps. Primary flight system – ground communications are done using the Combiner X-band system high gain antenna at maximum range data rates of 39,816 bps. Both spacecraft have identical X-band low gain communications systems for commanding and safe mode.

StarLight’s formation and attitude control subsystem (FACS) provides six-degree-of-freedom spacecraft formation control. The FACS estimates and controls vehicle inertial attitude, angular velocity, and the formation’s range and

bearing angles. The FACS architecture for both the Combiner and Collector spacecraft is identical. The spacecraft's control system architecture implements a slow drift between attitude and formation control deadbands, while the interferometer control system counter-steers the instrument's siderostats and delay lines to maintain precision pointing at the target star and to acquire and track the starlight interference fringe pattern.

Out of consideration for contamination concerns, the cold gas propulsion system layout was designed to be a modular stand-alone entity that could be integrated as a complete system to the primary bus structure. The idea was to ensure the entire system could be integrated and checked out in a contamination free environment before being fitted to the bus. The assembly consists of the top deck of each spacecraft, the propulsion frame, thruster stalks (with 2 clusters of 4 thrusters each), plumbing and other hardware needed.

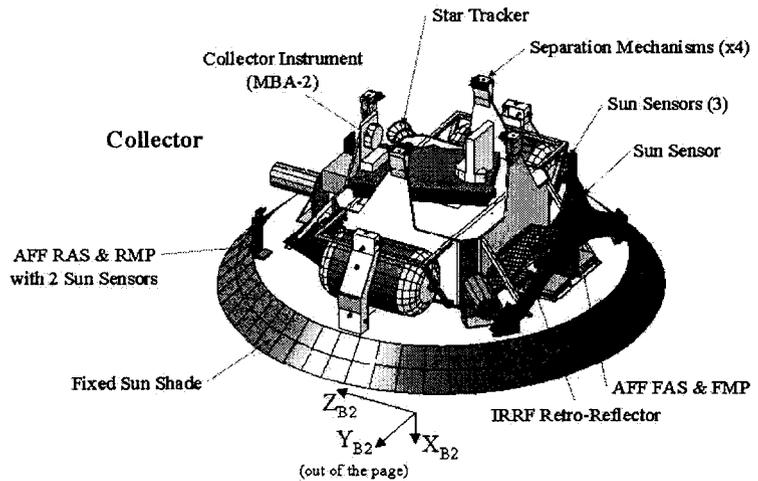


Figure 6. The deployed collector spacecraft.

Interferometer Instrument and AFF Accommodation

Composite top decks on both spacecraft provide the support needed for interferometer instruments (see **Figs. 5 and 6**). These composite top decks also provide the required dimensional stability and stiffness, along with completely unobstructed fields-of-view (FOV). The front AFF antennas on both spacecraft are located on ground plane plates at the edge of the solar panels maximizing horizontal and vertical separation distances without any deployments. This placement also minimizes multipath interference. The single-piece, structural, ground plates also enable precise thermal control of the formation flying components.

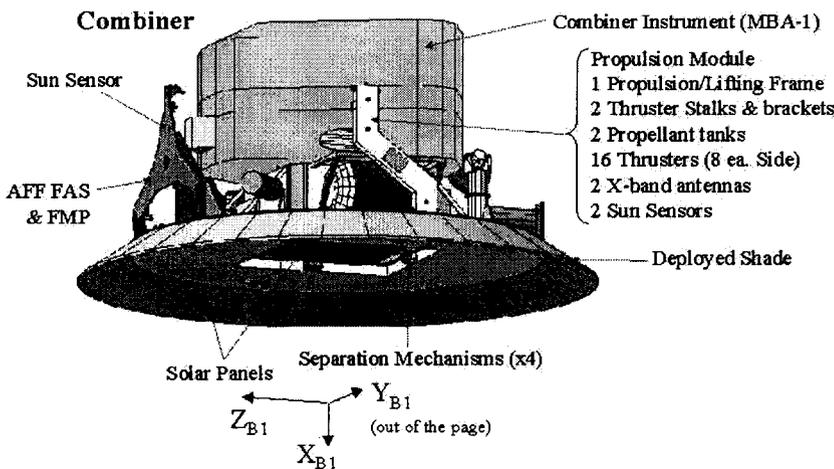


Figure 5. Deployed Combiner Spacecraft.

Figure 7 shows the two-spacecraft-constellation in operation and the 25° half-angle shadowing (defined as the maximum allowed rotation about any axis in the YZ-plane) provided by the sunshades. Each spacecraft is designed to fully accommodate its StarLight instrument suite.

The deployable sunshade on the Combiner provides complete blockage of the sun about any axis over a 25° angle (see **Fig. 5**) for the interferometer instrument and has an outer diameter of 338 cm. It is made from RF-transparent, non-reflecting materials to minimize AFF multipath effects.

The fixed Collector sunshade provides complete blockage of the sun and glint

about any axis over a 25° angle (see Fig. 6) and has an outer diameter of 274 cm. It is also made from RF-transparent, non-reflecting materials to minimize multipath effects. It has a “knife edge” and cants down from the mounting plane to reduce multipath effects and provide cleaner FOV. The “knife edge” minimizes edge glint towards the Combiner spacecraft, see Ref. 14. The cant angle is defined to ensure reflected light from the remaining portion of the launch adapter ring does not reach the Combiner spacecraft.

The use of composites enables tailoring of the interferometer mounting environment to minimize vibrationally- and thermally-induced distortions. The easily accessible external mounting interfaces for the optical instruments on both StarLight spacecraft and AFF antennas enable rapid and simple alignments during I&T.

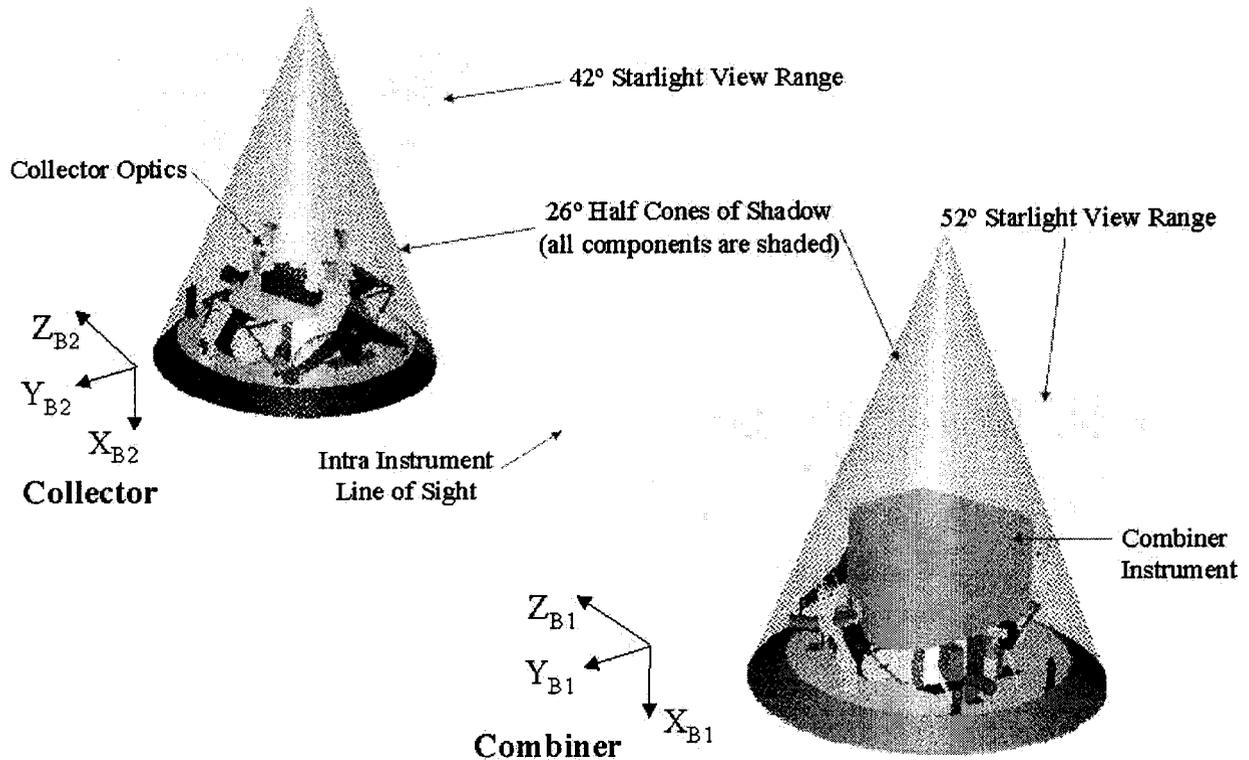


Figure 7. Two StarLight spacecraft flying in formation and conducting separated spacecraft interferometry. The 25-degree shadowing provided by the sunshades is shown along with the instrument’s field-of-view.

3.2. Formation Flying

Operation of the optical interferometer requires alignment of the relative optical path delay to nano-meter level accuracy. In StarLight, this is achieved in multiple steps. In order of operation, they are: a coarse acquisition to bring the two spacecraft from lost-in-space to a relative error of XXX cm in range and XXX arcmin in bearing angle; fine acquisition to further align the two spacecraft to XXX cm in range and XXX arcmin in bearing angle; siderostats to align the starlight, and finally a delay line align that starlight to a nanometer-level of accuracy. Each stage brings the relative alignment of the two spacecraft to within field-of-view of the next stage. Each stage is achieved by a closed-loop control system composed of control algorithms, relative formation sensors with increasingly stringent requirements in estimation accuracies, inertial sensors, and appropriately fine actuation.

The Starlight mission is designed to demonstrate a number of key FF technologies enabling a new class of future separated spacecraft missions. The scope of these technologies include the development of a unique RF sensor system for inter-spacecraft range and bearing sensing, and the design of the an Formation and Attitude Control System (FACS) architecture and avionics to enable precise control of the Starlight two spacecraft formation meeting prescribed performance - enabling first-ever space based separated spacecraft optical interferometer. Starlight FF Avionics system is also required to be scalable to future separated spacecraft missions with more than two spacecrafts in the constellation. These FF technologies areas are broadly classified under the categories of: 1) Architecture, 2) Function, and 3) Performance.

Formation-flying architecture:

The FF avionics architecture requires a number of architectural features to support the distributed nature of separated spacecraft formations, as well as, the need for enhanced on-board autonomy and robustness. A key Starlight requirement for the FF Avionics architecture to be scalable to five spacecrafts (TPF) requires special considerations for the Starlight Avionics architecture. Starlight FF architecture is shown in Figure 3.1.

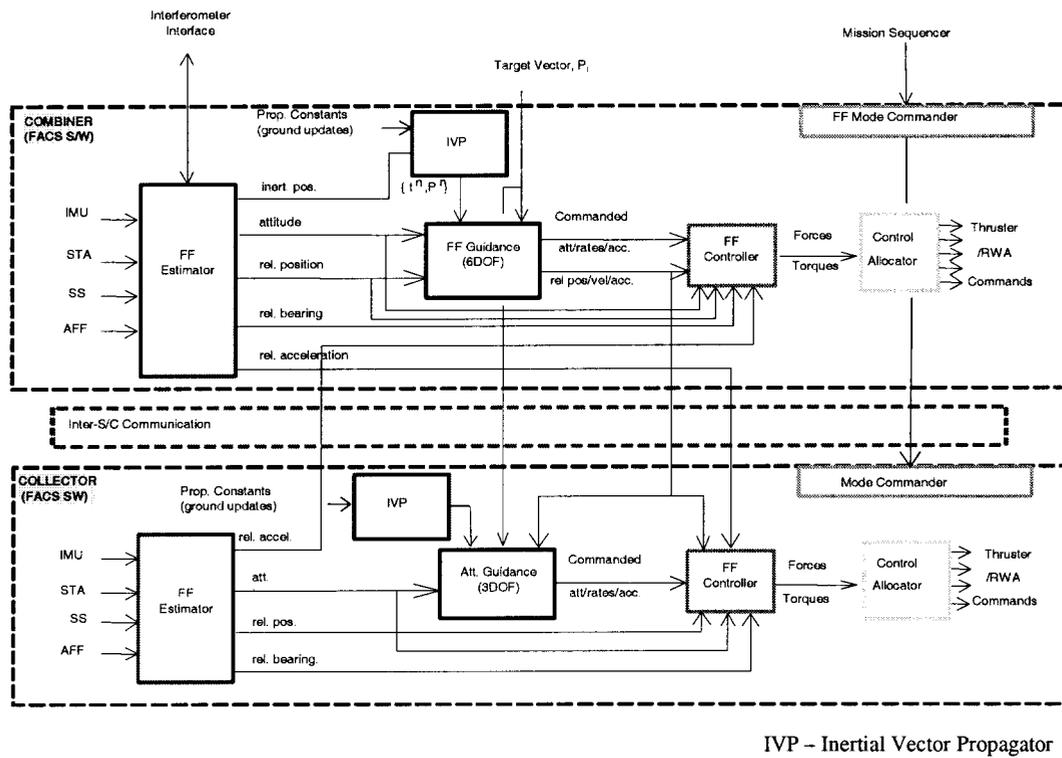


Figure xx.x: StarLight Formation and Attitude Control System (FACS) Architecture

In the case of Starlight, the two spacecraft have functionally identical FF avionics system. As such a Peer-to-Peer architecture would be the natural choice. However the differences due to the interferometer payload and configuration (hardware, optics, functions) makes it suitable to adopt a master/slave architecture, where combiner spacecraft is designated as the formation master. This would largely be true for future space interferometer mission.

Formation-flying functions:

Lost-in-space acquisition:

StarLight is required to have the capability to re-acquire formation knowledge (AFF based relative range/bearing) from any relative orientation and relative position (within the operating capability of the sensor). This ensures operational robustness in case of partial or complete system resets. Lost-in-space acquisition levies stringent requirements on the Formation and Attitude Control System (FACS) to autonomously perform a full search of the relative attitude and position space, taking into account the relative sensor (AFF) capabilities (FOV, blind spots, etc.).

Constraint Avoidance:

A single spacecraft mission typically imposes a number of pointing constraints for spacecraft attitude. These pointing constraints ensure protection of critical instrument bore-sights against planetary albedo or solar radiation. Earth communication pointing and tracking requirements may also impose additional antenna pointing constraints. Aside from such static pointing constraints there are kinematic constraints on maximum maneuver slew rate and acceleration dictated by the capabilities of on board sensor and actuators e.g., celestial sensor (star tracker) or reaction wheel performance.

Due to additional relative degrees-of-freedom (inter-spacecraft relative range/bearing), separated spacecraft missions, such as StarLight, impose a number of additional constraints. These constraints are typically relative range and relative attitude (bearing) dependent. Starlight FACS software provides the on-board capability to account for multiple constraints, capturing both inertial pointing as well as relative pointing and range constraints.

- a) Collision Avoidance Constraint (range constraint)
- b) Sensor (relative) operating range constraint (range/bearing constraint)
- c) Glint constraint (bearing constraint)

Plume constraints (significant for thruster effusion based contamination at close ranges, range/bearing constraint)

3) On-board Autonomy:

The baseline design of the StarLight flight system requires autonomous observations of a list of uploaded target stars. Ground generated list of target stars is sequenced to minimize consumption of on-board consumable resources as well as for time efficiency. On board mission sequencer implements the observation sequence. FACS guidance and control algorithms are designed to accept high level target star pointing vectors and desired baseline commands from the mission sequencer and autonomously profile any necessary translation and pointing maneuvers to achieve the desired observation geometry. These maneuvers are performed on-board based on the selected optimality criteria for minimum time or fuel, and fuel equalization between the two spacecrafts, while staying within the capabilities of on-board sensors and actuators and meeting pointing, glint, and solar/thermal constraints.

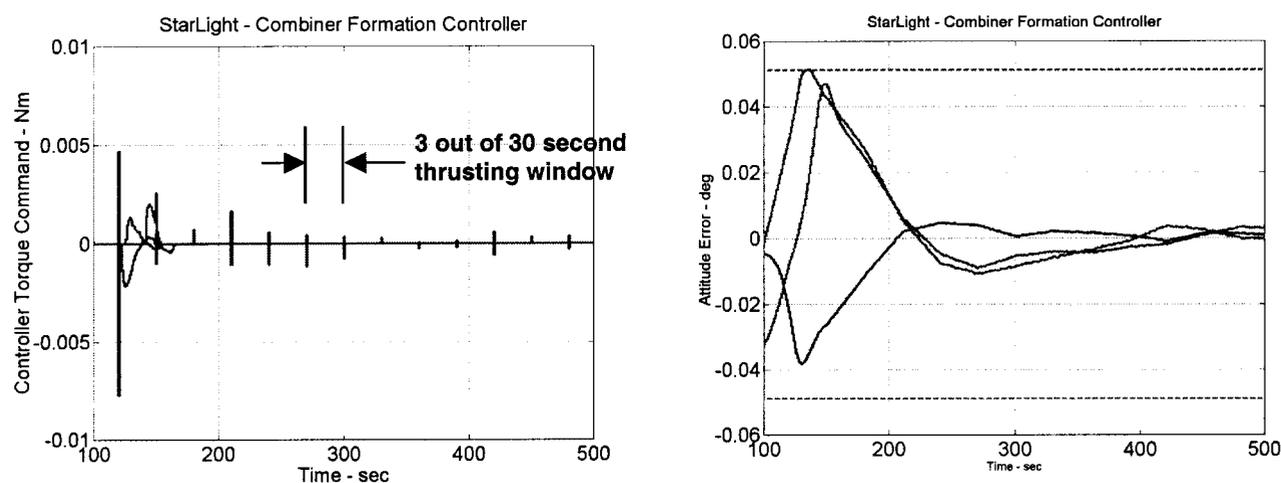
Formation-flying performance:

The requisite level of performance is achieved through incremental performance improvements by successively calibrating out errors from various contributing sources (sensors, alignments, offsets, etc.).

1. Gyro to star tracker calibration
2. AFF sensor calibration
 - a) Instrumental calibration
 - b) Phase constant calibration
 - c) Antenna phase center and gain pattern calibration
3. AFF bearing to inertial calibration
4. Combiner Instrument internal alignment & calibration (stellar alignment/shear)
5. Instrument siderostat pointing to inertial alignment
6. AFF bearing to angular metrology calibration

StarLight interferometry observation campaign is initiated after the initial on-orbit checkout and calibration is completed and full performance of the StarLight formation flying is achieved.

One of the key performance requirements for the FF system is to minimize any on-board disturbances during interferometer observation (with fringe lock). To avoid harmonic disturbances & jitter, reaction wheels are not used during interferometer observation. Additionally, any thruster firing (for inertial attitude and baseline hold) on either spacecraft, is required to be limited to a narrow window of 3 seconds within each contiguous 30 second period. Thruster activity is synchronized across both spacecrafts for all control degrees-of-freedom (attitude and range/bearing). A new formation (inertial attitude and relative range/bearing) control law was developed to meet this deterministic thruster firing requirement across all controlled dofs, while meeting the formation control performance requirements. Unlike traditional dead-band control law, which can result in random firing of thrusters as control dead-band limits are reached for each controlled dof, the new control law enables synchronized control of all dofs across the two spacecraft while meeting inertial attitude, and relative range/bearing control requirements. Simulation results are shown in Figure xx.xx below:



Figures 9, 10: Synchronized formation control performance with thruster firing constraint

3.3. Autonomous formation-flying sensor

The Autonomous Formation Flyer (AFF) sensor^{13, 14} provides key knowledge of the relative spacecraft separation for coarse acquisition of the multi-spacecraft formation. Key challenges of the AFF sensor stem from simultaneous satisfaction of the following requirements for:

- a wide field-of-view (FOV), $\pm 70^\circ$ cone coverage, for recovery from the lost-in-space scenario;
- unprecedented accuracy in estimation of spacecraft separation, (2cm, 1 arcmin) 1- σ uncertainty in range and bearing angle estimates, when within a $\pm 2^\circ$ cone angle of bearing angle, for handoff to the laser metrology system;
- autonomous operations for deep space application, with no real-time interaction from ground, and no aid from the GPS satellite system;
- real-time estimates; and
- independence from the spacecraft and interferometer operations.

In response to these requirements, the AFF sensor has been designed as a distributed radio-frequency (RF) system at Ka-band. The system is composed of virtually identical hardware and software on each spacecraft, transmitting to and receiving from the other spacecraft. Estimates of the range and the bearing angle are derived from signal processing of the exchanged signals, with algorithms based upon the basic Global Position System (GPS) signal processing design.

Technical challenges lie in antenna design to simultaneously satisfying requirements for a wide FOV and rejection of multipath and self-jamming signals; microwave transceiver design with complex frequency schemes and stability requirement; real-time digital signal processing; and a system design for the different components to operate together as a stable, reliable system. Further challenges lie in autonomous calibration of system variations due to thermal and structural variation, and pre- and post-launch variations, to meet and maintain the stringent performance requirement.

Because the AFF sensor is an integral part of the precision formation flying system and the RF nature of the instrument, a strong inter-dependence exists between the AFF sensor design, the spacecraft structural design, the inter-spacecraft acquisition algorithm, and the optical interferometer requirements, including:

- Mutual physical, optical, and electrical accommodation of the AFF Sensor and the spacecraft;
- Electrical, mechanical and thermal stability;
- Ground- and space-based calibration;
- Inter-spacecraft acquisition;
- Communication between the AFF sensor and the spacecraft.

3.4. Interferometer instrument

The interferometer instrument is described in more detail in two companion papers in these proceedings, covering the architecture and operations¹⁰ and the optical design¹⁵. Here we briefly describe some of the issues that drove the design.

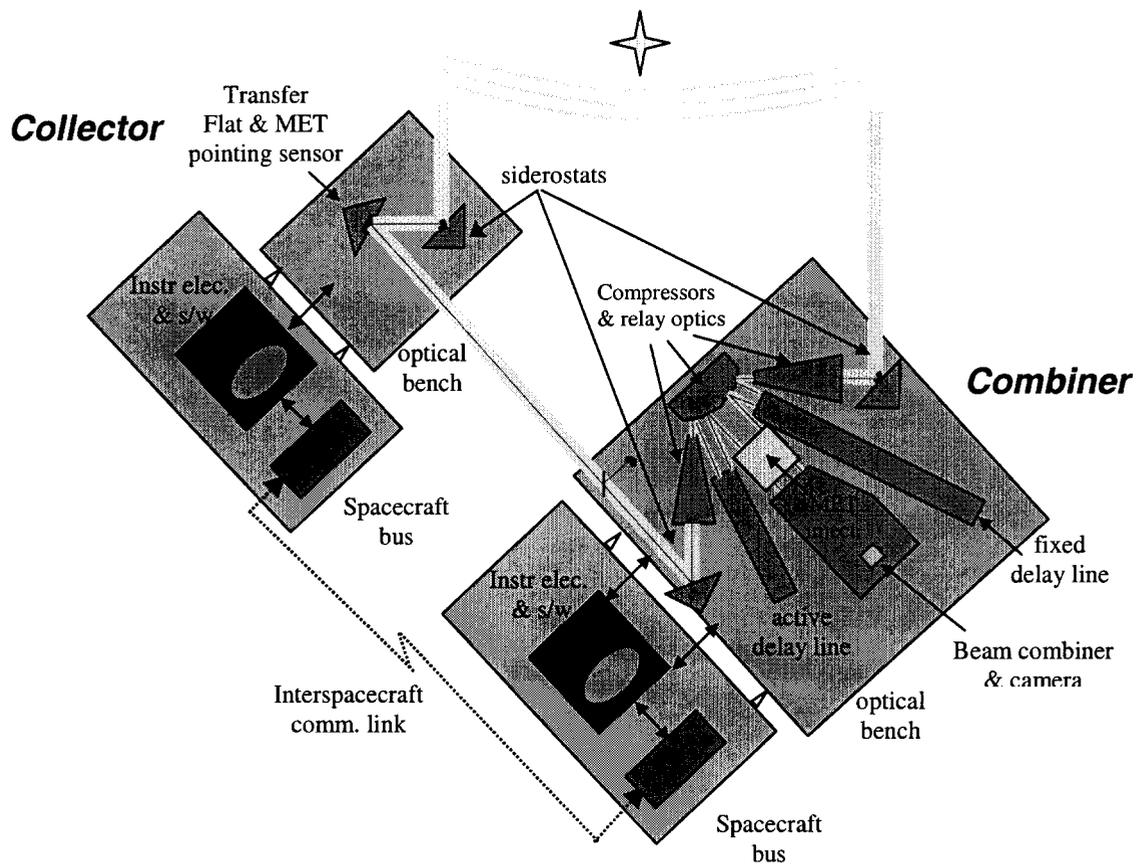
The decision to go to a 2- instead of a 3-spacecraft configuration was driven by cost. Demonstration of a projected baseline of at least 100 m is important for the Terrestrial Planet Finder, and a fixed optical delay much longer than 14 m becomes difficult to accommodate with bulk optics on a small single spacecraft. With a 14 m fixed delay, the maximum projected baseline length of 125 m then requires a separation of 600 m. A functional diagram of the interferometer instrument is shown in Figure X.

With 0.12 m apertures, the input beams must be compressed to a manageable size before passing through the fixed and active delay lines, and into the beam combiner. A compressed diameter of 3 cm was chosen as a compromise between compact size and diffraction effects. An early design for the optical layout had all the optics attached to one side of a graphite epoxy bench. The large area of this bench required a large solar shade to prevent illumination by the sun, and the lack of stiffness was undesirable for the instrument stability. A bench populated with optics on both sides is both easier to shade and more stable. Siderostats and beam compressors are located on the bottom (spacecraft-side) of the optical bench, and the alignment mechanisms, delay lines, metrology injection and beam combiner are located on the top surface.

StarLight will use a single 80x80 pixel CCD camera for acquisition, fringe detection and angle tracking operations. Earlier designs called for multiple cameras and an Avalanche Photodiode for white light fringe detection. Cost played a large role here, but the final architecture for the beam combiner meets the requirements with an elegant simplicity¹⁵. The camera frame rate is related to the accuracy with which the rate of change of combiner-to-collector bearing angle (γ in Fig. 2) can be measured. This angular rate uncertainty is the dominant source of error in estimating the rate of change of the optical path difference between the two interferometer arms – the delay rate. The fringe search rate through delay space is chosen to be five times the 1σ uncertainty in delay rate, in order to minimize the probability of the fringe running away ahead of the search. The camera must be read out fast enough to sample the modulations of the photon rate in the interference pattern, a frequency proportional to the fringe search rate. For StarLight, an angular rate uncertainty of 14 milliarcseconds / s gives a delay rate uncertainty of approximately $10 \mu\text{m} / \text{s}$ at a separation of 600 m. With a factor of two in performance reserve, this becomes $20 \mu\text{m} / \text{s}$, requiring a fringe search rate of $100 \mu\text{m} / \text{s}$. The white light fringe spacing of $\sim 0.8 \mu\text{m}$ should be sampled approximately 4 times per cycle to avoid too much smearing, corresponding to a camera frame rate of $(4 \times 100 \mu\text{m} / \text{s} \div 0.8 \mu\text{m}) = 500 \text{ Hz}$. Faster frame rates can substantially increase camera read noise, thereby decreasing sensitivity; lower frame rates demand more accurate measurement of the angular rate. The high frame rate also minimizes the latency of the readout (the camera is a frame transfer device), which is important for maintaining high bandwidth in the path length and angle-tracking control loops.

The 500 Hz camera frame rate fixes the maximum fringe search rate at $100 \mu\text{m} / \text{s}$. A fringe search range of five times the 1σ uncertainty in delay should intercept the fringe 96% of the time. At the short 40 m separation, the 10 mm uncertainty in delay is dominated by the range uncertainty of 20 mm, measured using the Autonomous Formation Flying sensor (the geometry of the configuration dilutes the impact of range on delay). Searching through 50 mm of delay at the maximum fringe search rate then takes a total of 500 s.

A challenge with any optical interferometer is the large number of mechanisms involved. StarLight will have a total of 24, including 12 cm tip/tilt mirrors on the collector and combiner, a 3-stage active delay line, a bypass shunt for the fixed delay line, a set of 4 alignment mirrors for the stellar optics and alignment for the metrology injection. As a result of this, and a desire for design simplicity, low mass and low cost, the StarLight interferometer is essentially a single-string system, with very little built-in redundancy.



4. MISSION OPERATIONS

StarLight will be launched on a Delta II 7925-10 from the Eastern Test Range. The launch period opens on 2006 June 06 and lasts a total of 20 consecutive days. The orbital energy of the trajectory relative to the Earth is just large enough ($0.6 \text{ km}^2/\text{s}^2$) to inject the spacecraft onto an Earth-lagging solar orbit; the spacecraft will slowly drift away from the Earth, following the Earth in its orbit around the Sun. This type of trajectory was selected in lieu of an Earth-centered orbit because it provides a more stable environment with regards to thermal environment, viewing conditions for interferometry, and dynamic conditions for formation flying. Once the spacecraft are safely in orbit and are checked out, the technology validation begins. The primary mission has a six month duration during which time the spacecraft will always remain less than 0.1 AU from the Earth.

The mission operations have been partitioned into five phases: 1) launch and initial acquisition, 2) checkout and initial calibration, 3) formation flying calibration and interferometer checkout, 4) formation interferometry preparation, and 5) formation interferometry. A possibility for a sixth phase is being maintained in the event that an extended mission is eventually viable.

Launch and Initial Acquisition Phase: This phase begins with liftoff and ends with successful signal acquisition of the spacecraft by the Deep Space Network (DSN) after the spacecraft have injected into the solar orbit. One day has been allotted for the duration of this phase. Continuous coverage from DSN is required.

Checkout and Initial Calibration Phase: This phase begins with cluster checkout and spacecraft separation. Once the spacecraft separate and each is checked out, initial calibrations for the FACS, AFF and range-finding instrument are performed. This includes flying the spacecraft in formation at ranges between 30 m and 250 m and achieving a relative bearing knowledge of 10 arcmin. This phase lasts two to four weeks and requires continuous 24 hour coverage from DSN.

Formation Flying Calibration and Interferometer Checkout Phase: This phase builds on the success of the previous phase and further explores the formation flying technology. This is achieved through AFF range validation and rotation calibration as well as a set of “coarse” formation flying experiments. Additionally, the interferometers begin their respective checkouts. The Combiner performs a “right” and “left” interferometer checkout followed by a coordinated right and left checkout. This phase culminates with fringe acquisition and measurement by the Combiner followed by subsequent observations. Successful completion of this phase will yield 5 arcmin bearing knowledge in the same ranges as the previous phase, i.e., 30 m to 250 m. This phase lasts four to six weeks and requires eight hours of DSN coverage per day.

Formation Interferometry Preparation Phase: This phase is primarily centered on right, left, and coordinated starlight interferometer checkout for the formation mode interferometry. Also included in this phase is AFF bearing calibration using angular metrology (as opposed to spacecraft maneuvers per the previous method of bearing calibration). Successful execution in this phase culminates with bearing knowledge of 1 arcmin at the same ranges as in the previous phases and will also include successful formation mode interferometry at a range of 30 m. This phase lasts four to eight weeks and requires eight hours of DSN coverage per day.

Formation Interferometry Phase: Having successfully completed the previous phases, this final phase includes multi-spacecraft interferometry observations at ranges between 30 m and 600 m with a bearing knowledge of 1 arcmin. This phase lasts six to 14 weeks and requires eight hours of DSN coverage per day.

Extended Mission Phase: Providing the mission objectives are met and approval is given, a number of exciting demonstrations are considered. These additional demonstrations further exhibit the robustness of the technologies. They include additional observations of different starts, characterization of visibility stability, “observe on the fly,” variations of formation control and estimation criteria, long and short range and rear-facing formation flying demonstrations, and a change in formation master. The formation flying experiments would take place at ranges between 10m and 1000m while the additional interferometry observations would occur at ranges of 30m to 600 m. Again, the bearing knowledge would be at the 1 arcmin level. This phase would last six months and would require eight hours of DSN coverage per two days.

5. DISCUSSION OF SYSTEM COUPLING AND COMPLEXITY

...and how treated in requirements and design

AFF: spacecraft accommodation issues

AFF to metrology handoff

Delay and delay rate estimate: requires interferometer metrology, but then trimming of formation to set delay

Limits on interferometer magnitude: function of (read noise, delay rate, throughput, visibility)

Delay line length

Implications of using only AFF, only metrology, and the addition of stellar light.

The mission drivers included:

- formation flying accuracies of 10 cm over separation distances of up to 600 m,
- maintaining fields-of-view for multiple apertures,
- packaging of the two spacecraft onto a single launcher with adequate mass margins and mass properties,
- keeping the instruments and formation flying sensors in shadow over 25° rotation angles,
- developing two spacecraft which work together and have overlapping requirements[z],
- and maintaining a low onboard jitter environment to enable the interferometer to lock on and track fringes.

The mission presents a number of challenges at the system level. Since the interferometer is distributed across multiple spacecraft, there are many inter-dependencies between the interferometer instrument, the spacecraft busses and the formation flying system. The formation-flying system and instrument are particularly tightly coupled. Some of the following examples are developed in more detail in the following sections and companion papers. Coarse position sensing to be performed with the Autonomous Formation Flying Sensor (AFF), operating at 32 GHz with modulation codes based on GPS, is hampered by the presence of the solar shades needed to keep sunlight off the instrument. The solar shades must be both opaque to visible and infra-red light and at the same time transparent and minimally reflective at radio wavelengths. Once the instrument metrology system is acquired, the formation flying system takes inputs from the spacecraft startrackers (inertial attitude), AFF (range, coarse bearing) and the interferometer (range rate and precision bearing) to trim the relative positions and speeds of the spacecraft and bring them within the control authority of the instrument's tip/tilt mirrors and delay line. At the same time, the instrument will be taking the same data to estimate the delay and delay rate in order to initiate a search for the fringe. While finding and measuring fringes, it is important to the instrument that the platform is vibration-free, and thruster firings by the formation-flying system (on either spacecraft) are therefore restricted to windows no closer than 30 s apart. Complicating these interactions is the large number of possible states that a combination of two spacecraft can find themselves in, a problem that increases rapidly with the number of additional spacecraft that are added to the formation¹⁶.

The Interferometry Performance Model (IPM) is a system engineering tool developed by the StarLight team to address these issues. The model propagates the Level 2 performance requirements (length of baselines, number of targets, etc.) to Levels 3 and 4. The complex problem is broken down into a large set of relatively simple analyses, much like a complex software task is reduced to a number of simple functions. Each block of analysis connects a set of input and output requirements, in most cases using an Excel spreadsheet. These functions may be resource allocations, error budgets, or operational sequences. Examples range from target star selection to the acquisition of angular metrology, the instrument visibility budget and alignment stability budgets, all integrated together using commercial database software. As with the software analogy, there is as much information content in the links between the functions – a complex web of connections – as there is within the functions themselves, and all requirements can be traced back to their Level 2 origins.

Glint

Separated-spacecraft interferometry presents a new challenge in space astronomy: for the first time, we are trying to observe stars while a sunlit object sits near the field of view. A white-painted paperclip in direct sunlight seen from roughly 70 km away is as bright as a magnitude zero star. For any astronomical telescope, it takes some care to reject

adequately the stray light from such a bright object near the star of interest. For the StarLight mission, the sunshades present the same kind of stray light challenge as that paperclip.

For StarLight, there are two principal pathways for stray light; others are believed to be less important.¹⁷ First is the scatter from the edge of the collector sunshade directly into the left aperture of the combiner instrument ("one-way"); second is the scatter from the combiner sunshade reflecting off the face of the collector spacecraft and instrument and into the combiner instrument ("two-way"). The one-way stray light enters the combiner about 1 degree off-axis at 40 m range, and 4 arcminutes at 600 m. With a moderately sharp edge on the fixed collector shade (100 micron radius), and modest surface quality on the first two combiner instrument mirrors (CL 500), the arcminute-diameter field stop limits the one-way stray light contribution to less than 1% of the stellar interferometry signal. Similarly, with flat black surfaces on the collector (10% albedo), the two-way stray light is less than 1% of the stellar signal, despite the unfavorable stray-light geometry of the combiner shade.

6. TECHNOLOGY RESULTS

6.1. Formation flying

A number of key enabling FF technologies needs to be developed for the class of deep-space FF missions addressed in this paper. A candidate list of FF technologies are listed below with relevant references highlighting work-in-progress:

- 1) Formation Flying Control architecture to address distributed sensing, communication, and control of multiple spacecrafts in a constellation in a robust manner.
 - a. "StarLight - Formation Flying Control Architecture", to be presented at International Symposium Formation Flying Missions & Technologies in Toulouse, France, October 28-31, 2002.
- 2) Collision avoidance under all nominal operating conditions
 - a. "Collision Avoidance Guidance for Formation Flying Applications", AIAA Guidance, Navigation, and Control Conference, Montreal, Quebec, Canada, August 6-9, 2001.
- 3) Robust strategy and algorithm for formation acquisition (relative range/bearing knowledge) with realistic sensing capabilities and constraints (FOV constraints).
 - a. JPL Internal Presentation: "StarLight – AFF Acquisition Strategy", April 30, 2001.
- 4) Resource optimal on-board algorithms to enable minimum fuel usage and fuel balancing across the formation, while meeting pointing (solar/thermal/glint) and range/bearing constraints.
 - a. "Path-Planning for Formation Flying Applications", 5th SIAM Conference on Control and its Applications, San Diego, CA, July 11-14, 2001
- 5) Robust hierarchical synchronized control methodology across multiple spacecraft to enable high precision space based interferometry.
 - a. "Multi-Mode Synchronized Control for Formation Flying Interferometer", to be published.

6.2. Autonomous formation-flying sensor

To assess the feasibility of meeting the stringent requirements, a performance model consisting of multiple error trees have been developed for the AFF sensor. Further, a prototype of the AFF sensor has been developed and is under test to verify that components of the error tree allocations are met. The prototype system is also used to verify the algorithmic and calibration designs. Results will be reported in¹⁸

6.3. Linear and angular metrology

The performance of the key metrology systems has been demonstrated in the lab and shown to meet the requirements of the StarLight mission. A more detailed description of the metrology system can be found in Dubovitsky et al.¹⁹.

Dual target linear metrology uses a single metrology beam to monitor independently the pathlength internal to the combiner optics at the same time as the external path between the combiner and collector spacecraft, with a precision of

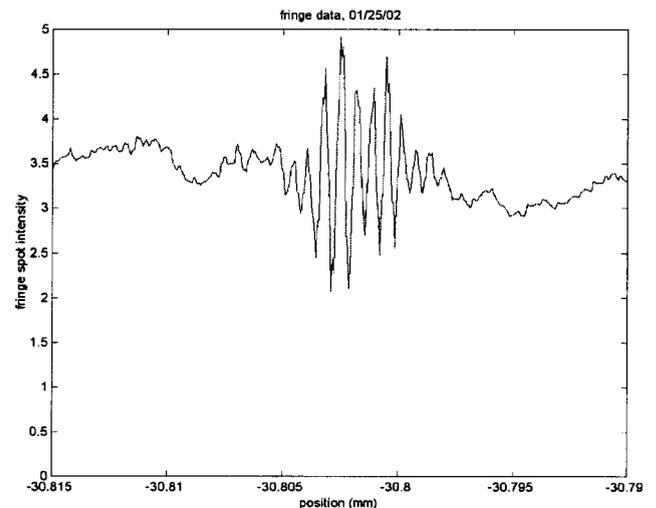
10 nm. The challenge is to separate the weak return signal from the collector, up to 600 m away, from the much stronger return within the combiner spacecraft. Modeling of the beam propagation, supported by lab experiments, was used to predict the return signal strengths. These levels were reproduced on a bench-top experiment, where the output of a metrology beam launcher was split. One output was retro-reflected to represent the internal combiner path; the other was coupled into a 400 m spool of optical fiber. The fiber output was re-collimated and retro-reflected back through the fiber and into the beam launcher. The optical fiber provides the correct time delay for a 600 m spacecraft separation, which is important for the demodulation process that separates the prompt (internal combiner) and delayed (collector) returns. The system met or exceeded all the requirements. In the process, a new technique for reducing the polarization leakage that leads to cyclic error was discovered²⁰ which proved essential to meeting the performance.

The Metrology Pointing Sensor (MPS) is a set of 4 infra-red photodiodes, and their associated electronics, located at the center of the transfer flat on the collector spacecraft. The sensor measures the offset of the laser metrology beam from the combiner spacecraft. The requirements call for a bias of no more than 5 mm, an rms noise of 50 μm , and a drift rate of no more than 10 $\mu\text{m} / \text{s}$ for a spacecraft separation of 600 m. A prototype sensor is currently being tested in the lab using a Gaussian beam with the size and power predicted for flight operation, and looks set to meet the requirements.

The 1320 nm laser that will be used for the StarLight metrology system is described by Asbury et al.²¹ and features multiple pumps to provide redundancy and prolonged lifetime. The linear metrology system uses independent gauges to monitor disturbances in the left and right arms of the interferometer. With the large asymmetry in path length, the laser output frequency must be stabilized, and new system was developed and tested to demonstrate this²².

6.4. Formation interferometer testbed

- Purpose
- Configuration
- Recent results, reference to Udo²³, refs to Joel²⁴
- Limits to performance
- Figures below



7. SUMMARY

Technology feedforward to TPF: concepts of FF, PFE, FFI
 - delay and delay rate estimate

- limits on performance
- AFF hand off to optical
- Schemes, ops for optical acquisition and handoff to fringe search
- We may fly again

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