An Overview of Formation Flying Technology Development for the Terrestrial Planet Finder Mission

The objective of the Terrestrial Planet Finder (TPF) mission is to find and characterize earth-like planets orbiting other stars. Three architectural options are under consideration for this mission: a formation-flying interferometer (FFI), a structurally-connected interferometer, and a coronagraph. One of these options will be selected as the TPF baseline design in 2006. This paper describes the technology task underway to establish the viability of precision formation flying for the FFI option. In particular, interferometric science observations require autonomous precise control and maneuvering of five spacecraft to an accuracy of 2 cm in range and 1 arc-minute in bearing. This precision must be maintained over inter-spacecraft ranges varying from a few meters to hundreds of meters. Autonomous operations, ranging from formation acquisition and formation maneuvering to high precision formation flying during science observations, are required. Challenges lie in meeting the demanding performance requirements as well as in demonstrating the long-term robustness of the autonomous formation flying system. These challenges are unprecedented for deep space missions. To address them, research is under way in the areas of formation control algorithms, relative sensor technologies, system design, end-to-end real-time system simulation, and ground-based and micro-g end-to-end system demonstrations. Four interrelated testbeds are under development concurrently with the FFI system design. The testbeds include the Formation Algorithms & Simulation Testbed (FAST), the Formation Sensor Testbed (FST), the Formation Control Testbed (FCT) and the Synchronized Position Hold Engage Re-orient Experimental Satellites (SPHERES) experiment. Formation flying technologies developed under the StarLight project and the NASA Distributed Spacecraft Technology (DST) program (under Code R) are being leveraged and expanded to meet the TPF requirements. This paper provides an overview of the ongoing precision formation flying technology activities.

Authors: M. Aung, A. Ahmed, M. Wette, J. Tien, D. Scharf, G. Purcell, B. Landin, M. Regehr.

1.0 Introduction

The objective of the Terrestrial Planet Finder (TPF) mission is to find and characterize earth-like planets orbiting distant stars. Three architectural options are under consideration for this mission: a formation-flying interferometer (FFI), a structurally-connected interferometer, and a coronagraph. Each of these candidate architectures is trying to achieve the same goal, namely to resolve a planet that is a million to a billion times more faint than its parent star at angular separations on the order of milliarcseconds. The two battles being fought are those of contrast and angular resolution. The following architecture descriptions can also be found on the TPF website at http://planetquest.jpl.nasa.gov/TPF/tpf_technology.html. Further information can be obtained from the recently published TPF Technology Plan.

At visible wavelengths, the coronograph has the difficult task of blocking the light from a star that is a billion times brighter than the elusive planet. This contrast reduction is achieved by blocking the direct and diffracted light, allowing observation of the faint planet nearby. Using this technique to study the area around a nearby star requires manipulating the diffraction of light around the edges of the telescope, which detracts from the potential angular resolution of the image. The diffraction pattern of a simple round telescope, for example, is a series of concentric rings with a bright central spot. Blocking the light from a star in order to see an orbiting planet requires suppressing the first several bright rings without blocking out the planet. By using masks to simulate a telescope with a different effective shape, the diffraction pattern can be controlled so that the starlight is much dimmer closer to the center in some areas, and brighter in others. The telescope can be rotated about its line-of-sight so that the planet image passes in and out of the regions where the starlight is dim. There are many different masking techniques that can accomplish this task. A more critical issue for TPF is wavefront control. This includes correcting for imperfections in the optics, which scatter light and degrade image contrast. To correct for its own internal imperfections, the coronograph would use active optics, similar to the technology that the Keck Observatory and other ground-based telescopes use to correct for wavefront distortion in the Earth's atmosphere. Coronograph designs operating at visible wavelengths offer several advantages. At shorter wavelengths, a smaller telescope can be used to obtain the required resolution. Additionally, optical detectors require less thermal control than their infrared counterparts, reducing the need for onboard cooling.

An alternate technique that can be used to decrease contrast and achieve extremely high angular resolution is long baseline interferometry. Using interferometers to study distant planets allows smaller, widely separated mirrors to work together as a giant virtual telescope. The resolution obtained is the same as that garnered from a telescope with a diameter equal to the separation between the individual telescopes. To collect enough of this information to build up a good picture, the interferometer must rotate around its line of sight to different relative positions and repeat the "exposures." As well as taking a picture, an interferometer can obtain spectra of the targets it is looking at, allowing the same instrument to determine the presence or absence of particular bio-markers. Contrast reduction is achieved by using a beam-combining technique known as nulling, and

further signal to noise enhancement can be obtained by chopping the signal to remove spurious background interference. A second architecture being considered by TPF is a mid-infrared, structurally connected interferometer utilizing four apertures mounted on a rigid beam with a baseline up to 40 meters. Operating in the mid-infrared gives the interferometer a thousand-fold advantage over the visible light coronograph in the contrast realm. Infrared telescopes, however, must be cooled to cryogenic temperatures.

To even further increase the resolution of such an interferometer, the four apertures and the beam combining optics can be removed from the structure tying them together to form a free-flying formation. This formation flying interferometer (FFI) allows increased aperture size and longer (variable) baselines, allowing the FFI access to more stars in our stellar neighborhood. The over-arching goal of the following formation flying technology work is to provide a stable, safe, autonomous platform for these observations.In 2006, one of these options will be selected as the baseline for the TPF mission. This paper describes the technology development underway to establish the viability of precision formation flying for the FFI option.

2.0 Precision Formation Flying to Enable Interferometry

To enable the TPF FFI, five spacecraft are flown in precise formation and collaboratively operated as a single instrument. The target star is observed with the spacecraft in a linear array configuration as shown in Figure 1. The array baseline, defined as the distance between the two furtherest Collector spacecraft, is variable between 70 m and 150 m. Each spacecraft is approximately 15 m wide due to its thermal shield. Inter-spacecraft separation between adjacent spacecraft will vary between 8 m and 35 m. During observation of a target star, the array is rotated at a fixed baseline length. It is rotated slowly (e.g. 12 hours per revolution or slower) while maintaining inter-spacecraft formation control to accuracies of 2 cm in range and 1 arc-minute in bearing. The array can be re-sized to different baselines and re-configured to point to new target stars.

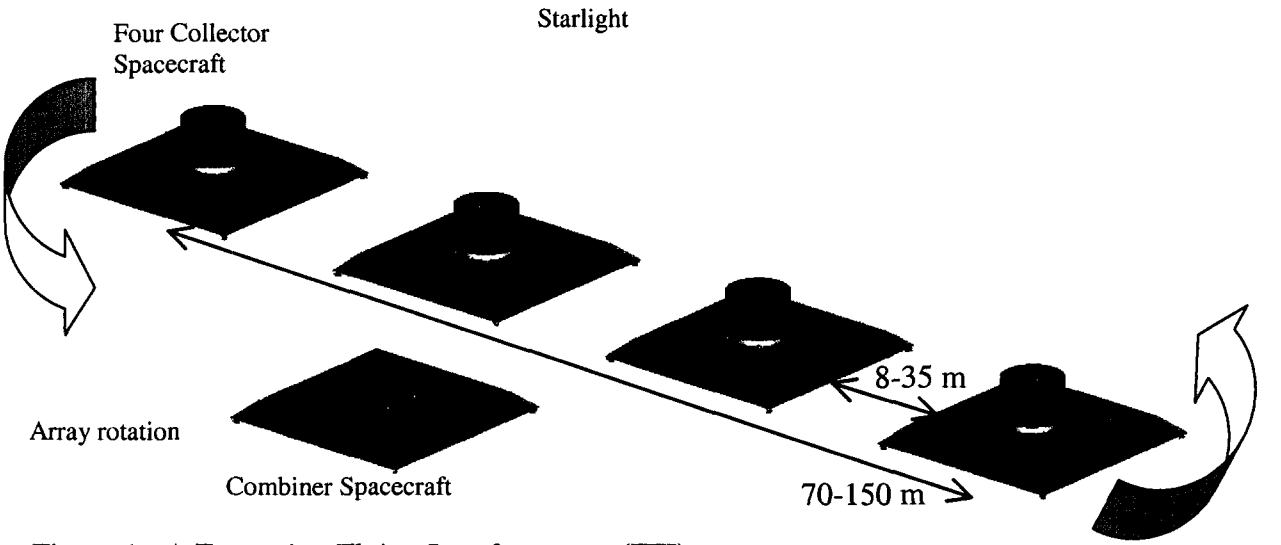
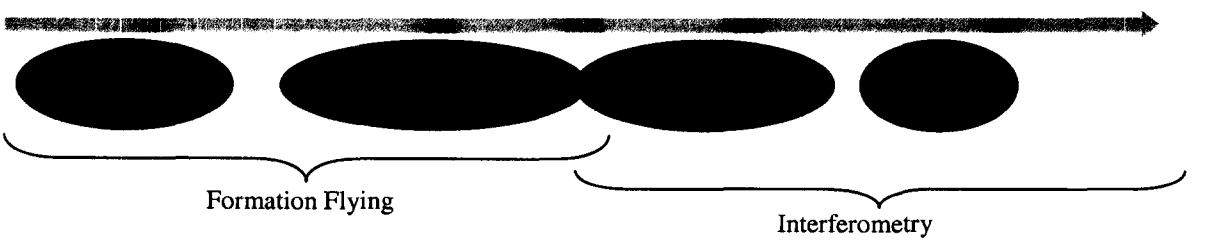


Figure 1: A Formation Flying Interferometer (FFI)

The four stages of an FFI are illustrated in Figure 2. The stages are grouped into two FFI phases: formation flying and interferometry. In the formation flying phase, which is composed of the formation acquisition and precision formation flying stages, spacecraft relative positions are acquired and are used to precisely control the spacecraft into the desired formation. The interferometer acquisition stage begins when the spacecraft are in the science formation and precisely controlled (to accuracies of 2 cm in range and 1 arc-minute in bearing). When these two conditions are met, the narrow field-of-view inter-spacecraft laser metrology system can achieve lock. Then, using the inter-spacecraft laser metrology, siderostats and fast steering mirrors, the starlight collected at the Collector spacecraft is relayed to the Combiner spacecraft. Finally, at the Combiner spacecraft, this starlight is combined with nanometer-level closed-loop precision using optical delay lines to acquire and lock fringes;. Subsequently, nulling is performed.

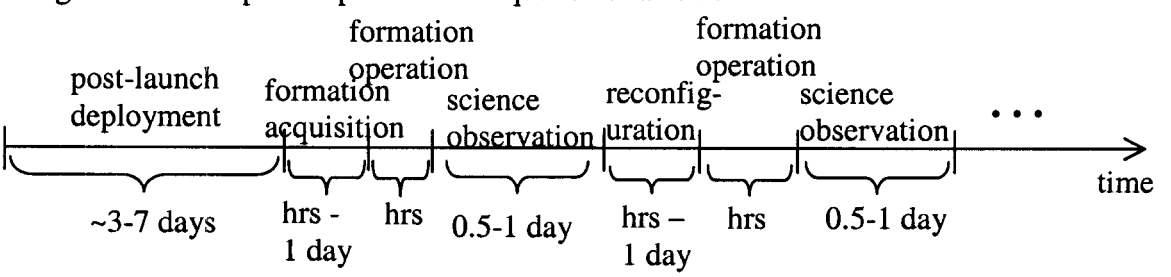
Figure 2: Four Control? Stages of Formation Flying Interferometry



The TPF FFI will be operated in deep space, either in an earth-trailing orbit or in a Halo orbit about the Earth-Sun L2 point. FFI operations are required to be autonomous with aid from the Earth-based Global Positioning System (GPS). *Therefore, the formation flying system is a real-time, autonomous precision system that provides a stable multiple-spacecraft platform for an interferometer to operate across the array of spacecraft.*

The nominal operational scenario of formation flying begins with the multiple spacecraft launched together in a single stack. After launch, the spacecraft deploy sequentially. The deployment phase is done slowly and meticulously; it is currently envisioned to last from a few days to a week. A deployed spacecraft will move to a safe distance of a kilometer or more before the next spacecraft is deployed. Post-deployment, each spacecraft will establish communication with the ground. When all the spacecraft are deployed safely, the autonomous formation flying stage will begin. The first mode is the "formation acquisition" mode in which relative spacecraft communication and position knowledge is acquired. Next, in the "formation operation mode," the spacecraft will be reconfigured from their post-deployment relative positions into a precise formation, ready for science observation. In the third mode, the "science observation" mode, the array is precisely rotated as the target star is observed by the FFI. Each observation lasts on the order of 12 to 24 hours. After observation of a target is complete, the array is reconfigured for the next observation. For illustration purposes only, a conceptual time-line is shown in Figure 3.

Figure 3: Conceptual Operational Sequence of an FFI



3.0 Technical Challenges in Formation Flying

The fundamental requirement for the precision formation flying system is to provide a stable platform of multiple spacecraft across which the FFI is to operate. While there are many individual technical challenges, the primary challenge of formation flying lies in its system complexity, as opposed to a single break-through technology. The key technical issues are:

- Initial Acquisition of the Formation
- Collision Avoidance
- Precision Formation Control
- Observation-on-the-fly
- Integrated End-to-end System

The enabling technologies associated with these issues are described below and summarized in Figure 4. They technologies are categorized in formation flying technologies, and system-level infra-structure technologies.

3.1 Initial Acquisition of the Formation

After launch, separation and stabilization of the spacecraft, the first step is to acquire knowledge of the relative position of the other spacecraft. The key technology to enable this is a formation acquisition sensor that provides range and bearing measurements to accuracies on the order of centimeters (cm) in range and arc-minutes in bearing. The acquisition sensor needs to operate with a full 4π-steradian field-of-view coverage about each spacecraft. Also, complexities associated with sensor calibration across spacecraft need to be minimized. For example, complex calibration maneuvers need to be eliminated through advanced techniques.

3.2 Collision Avoidance

With relative spacecraft position knowledge, the formation can be maneuvered into a desired configuration. In doing so, collisions must be avoided. On-board autonomous guidance and control algorithms are critical for enabling collision avoidance maneuvers.

3.3 Precision Formation Control

After the spacecraft are configured, the array is precisely controlled for interferometric observation. All inter-spacecraft positions in the array will be controlled with a precision of 2 cm in range and 1 arc-minute in bearing. Multiple-spacecraft control architectures and algorithms, taking into account the end-to-end system, are key enabling technologies.

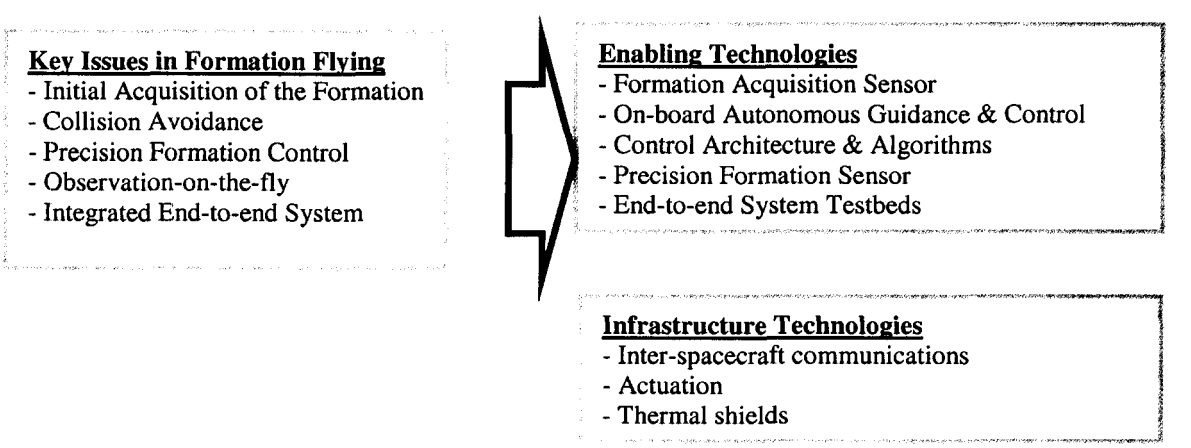
3.4 Precision Formation Control while Rotating the Array during Observation

In the observation mode, the array is rotated with a fixed baseline. During the rotation, the inter-spacecraft control precision of 2 cm and 1 arc-minute is maintained. In addition, the thruster firings are synchronized to allow maximum stable time for the observation. Precision sensors and control architecture design are key enabling technologies.

3.5 End-to-end System Design

Formation flying is a synthesized capability of architecture design, algorithms, system implementation and many component technologies operating as an autonomous, real-time, distributed system. Therefore, end-to-end system testbeds are necessary to verify and validate the system design.

Figure 4: Key Formation Flying Issues and Enabling Technologies



3.6 Infrastructure Technologies

A solid infrastructure is required to support the formation flying distributed spacecraft interferometer. This infrastructure includes: inter-spacecraft communications, actuation and thermal shields.

A reliable inter-spacecraft communication system with sufficient bandwidth and tolerable latency is required for closed-loop control of the spacecraft formation as well as for closed loop control of the inter-spacecraft metrology loops for interferometer operations.

Actuation is required to control the formation. Considerations for actuator selection include: contamination of the optics; choice of cold gas versus electric given the cold (~40K) environment necessary for infra-red operations; fuel-efficiency for the long mission lifetime; and ability to vary thruster impulse to support the control algorithms.

Thermal shields are required to protect the interferometer optics. The design of thermal shields needs to take into consideration thermal requirements, requirements derived from the interferometer and requirements derived from formation flying. For formation flying, the sources of thermal shield requirements include the required field-of-view of inter-spacecraft communication antennas and sensors, radio-frequency (RF) acquisition sensor performance and RF inter-spacecraft communication performance.

4.0 Formation Flying Technology Development

Precision formation flying is enabled by system design and the combination of the technologies above. To establish the viability of the FFI mission architecture for TPF, system design activities and technology testbeds are currently under development. These activities are highly interrelated, and all contribute to establishing the feasibility of the end-to-end formation flying system.

The system design activities include formulation of the end-to-end formation flying system and analysis of viable infrastructure technologies, such as the inter-spacecraft communications and thermal shield design.

The technology testbeds develop formation flying algorithms, component technologies, and demonstrate and validate the end-to-end system as summarized in Table 1.

Table 1: Technology activities for formation-flying system.

	Technology Activity	Description	Key Intended Result
1	Formation Algorithms and Simulation Testbed	Algorithm development and high-fidelity distributed real-time software testbed to demonstrate end-to-end TPF formation-flying system	Demonstrate full TPF performance of 2 cm and 5 arcmin in range and bearing control, off-nominal scenarios
2	Formation Sensor	Hardware development and	Demonstrate range and bearing

	Technology	demonstration of the formation acquisition sensor at S-band	determination with 4π-steradian field-of-view coverage with maximum uncertainty of 50 cm and 1 degree in range and bearing
3	Formation Control Testbed	Ground-based laboratory using multiple mobile vehicles equipped with flight-like avionic hardware and air-bearings on a raised floor	Demonstrate end-to-end autonomous formation-flying in a 1-g environment with near-full TPF performance with control accuracies of 5 cm in range and 5 arcmin in bearing
4	SPHERES Flight Experiments (MIT)	Three soccer-ball-sized "spacecraft" on the International Space Station with ultrasonic range and bearing sensors and gas thrusters	Demonstrate feasibility of formation-flying in micro-g environment, perform TPF-like array maneuvers
5	Thermal Shield Technology	Thermal shield material selection and testing	Select material acceptable for TPF based upon RF, thermal and optical performance
6	Formation Interferometer Testbed	An optical interferometer distributed over separate, moving platforms representative of a formation-flying interferometer	Demonstrate optical interferometer fringe acquisition and fringe tracking across two platforms with 30 μm/s relative velocity

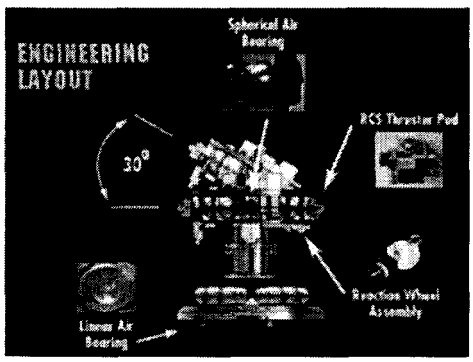
The **Formation Algorithms & Simulation Testbed (FAST)** is a distributed real-time testbed implemented across multiple independent computational platforms for end-to-end simulation of the TPF formation-flying system. Fundamental formation flying algorithms will be developed for the five-spacecraft TPF mission based in part upon the two-spacecraft algorithms developed for StarLight mission. StarLight was a two-spacecraft formation flying interferometer mission, a precursor mission to TPF. As of 2002, it has been cancelled as a flight mission and the technology development has been continued under TPF. The algorithms will be demonstrated in a high-fidelity end-to-end simulation environment to the full TPF performance of 2 cm and 1 arcmin accuracy in range and bearing control. Realistic mission scenarios will be demonstrated, including formation acquisition, formation calibration (?), formation maneuvering, re-configuration, and nominal observation. The simulation will be further exercised with system fault scenarios to verify the long-term robustness of formation-flying missions. Fault scenarios will include collision avoidance, evaporation of the spacecraft formation, and system-level failures (e.g. thrusters, sensor). The FAST simulation results will be validated in hardware by the Formation Control Testbed, described below.

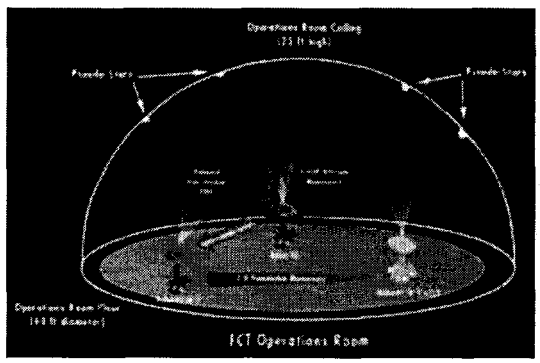
The **Formation Sensor Testbed (FST)** will provide a hardware demonstration of the formation acquisition sensor, demonstrating th ability to provide an instantaneous 4π-steradian field-of-view relative position determination among multiple spacecraft. This capability is required for initial acquisition of the formation and for collision avoidance. Maximum range and bearing uncertainty will be 50 cm and 1 degree, respectively, over the full coverage. The acquisition sensor is a radio frequency (RF) sensor, based upon the StarLight Autonomous Formation-Flying (AFF) Sensor.[i] This FST will develop new sensing algorithms needed for multiple spacecraft operation (with more than two spacecraft), and a passive radar mode for added robustness against collision avoidance, and to eliminate the need for time-consuming calibration maneuvers. RF performance with a TPF-like structural environment and accommodation constraints will be evaluated. FST will also provide sensor models to be used in the FAST system simulation.

The **Formation Control Testbed (FCT)** [3] will demonstrate end-to-end autonomous formation-flying in a 1-g environment with near-full TPF performance of 5 cm maximum uncertainty in range and 5 arcmin in bearing control accuracy. It will emulate real spacecraft dynamics using three mobile test vehicles moving on air-bearings and equipped with flight-like avionic hardware and inter-spacecraft communication. The FCT is illustrated in Figure 5.. FCT will also provide validation of the FAST. FCT algorithms and prediction of FCT system performance will be developed in FAST. FCT system performance will be compared to the FAST predictions, thus validating FAST modeling capability to predict TPF performance.

Figure 5: Formation Control Testbed

(a) Robert Engineering Concept (b) Testbed





The Synchronized Position Hold Engage Re-orient Experimental Satellites **(SPHERES)** experiment[ii], developed and managed by the Space System Laboratory at the Massachusetts Institute of Technology, will perform TPF-relevant maneuvers with three soccer-ball-sized "spacecraft" in the International Space Station (ISS). Each SPHERE is self-contained with ultra-sonic relative sensors, ultrasonic global position sensing, thrusters and inter-spacecraft communication. The experiment will demonstrate functional feasibility of formation-flying over a 3m x 3m x 3m test area. It will provide lessons-learned for formation-flying.

The **Thermal Shield Testbed** will characterize the impact of different thermal shield materials on the RF sensor performance, inter-spacecraft stray-light performance and thermal performance.

Technology Development Approach

The testbeds and the design team activities are highly interrelated, and address the first two formation flying stages of FFI as illustrated in Figure 6. The FST will demonstrate the critical technology required for initial acquisition of the formation by providing instantaneous 4π-steradian field-of-view relative range and bearing knowledge. The FAST develops formation flying algorithms and provides an end-to-end simulation of the formation flying system on a distributed, real-time platform, thereby demonstrating the full TPF FFI performance. The FF system design, inter-spacecraft communications models and thermal shield models from the system design team and the sensor models

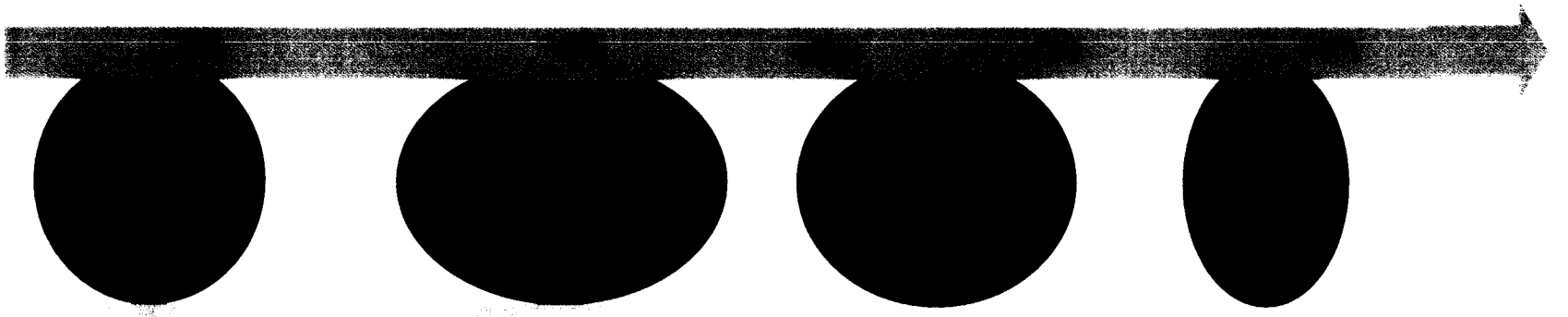
from the FST are incorporated in FAST. The FCT will validate the FAST algorithms and simulation in a physical ground-based testbed with 6 degree-of-freedom robots moving on air-bearings and equipped with flight-like avionic hardware. The FAST algorithms can be refined based upon FCT experiment results. The SPHERES experiment will demonstrate functionality of formation flying in a micro-g environment, performing TPF-like maneuvers within the ISS. The lessons learned from the SPHERES experiment will benefit formation flying system design. Thermal shield design and material selection will be taken into account in all the technology activities.

Through this integrated approach, we expect to establish a system design as well as develop critical technologies to support TPF. The implementation will be incremental across each testbed, and closely correlated across other testbeds and system activities. The implementation is summarized in Figure 7, and further detailed in [?[, [?] and [?] (FAST, FST and FCT papers). In the FAST, the algorithms and real-time, distributed simulations will be developed for two spacecraft first based upon StarLight and Code R research, and then extended to five spacecraft. Initially, algorithms for nominal scenarios will be developed. Subsequently, the faults scenarios will be addressed. In the FST, the multiple spacecraft sensing algorithms are first implemented on table-top testbeds to establish, verify and refine the algorithms, and then the algorithms are migrated to an outdoor end-to-end system test. In the FCT, the first robot will be verified before adding another robot to perform a two-robot formation flying validation. Subsequently, a three-robot demonstration will be performed. For the SPHERES experiment, a two-SPHERE experiment will be performed first and a third will be added if launch of the third SPHERE is possible; the SPHERES were originally to be launched on the Shuttle.

5.0 Conclusion

Through an integrated approach across the design team and testbed activities, the viability of precision formation flying is being established. The implementation is incremental. By mid 2006, a complete system design will be established, supported by algorithms, and performance and functional validation of the end-to-end system and component technologies. These results will be directly applicable to TPF and further applicable to other multiple-spacecraft precision formation flying missions such as: MAXIM, Stellar Imager (SI), SPECS, Constellation-X, SMART-3 (ESA), DARWIN Space Infrared Interferometer (ESA), Magnetospheric Multiscale (MMS), Global Precipitation Mission (EOS-9), Living with a Star (LWS), Soil Moisture and Ocean Salinity Observing Mission (EX-4), Time-Dependent Gravity Field Mapping Mission (EX-5), and Vegetation Recovery Mission (EX-6).

Figure 6: Integrated Approach for FF Technology Development



Formation Sensor Testbed (FST)

Formation acquisition sensor hardware & algorithms – scalable to 4π-steradian coverage.
Demonstrate & validate the functionality and performance in a hardware testbed

FAST

Formation control architecture & algorithms in an end-of-end high-fidelity formation flying simulations in a distributed real-time environment

FCT

Validate FAST algorithms in an end-to-end hardware testbed with multiple robots

SPHERES

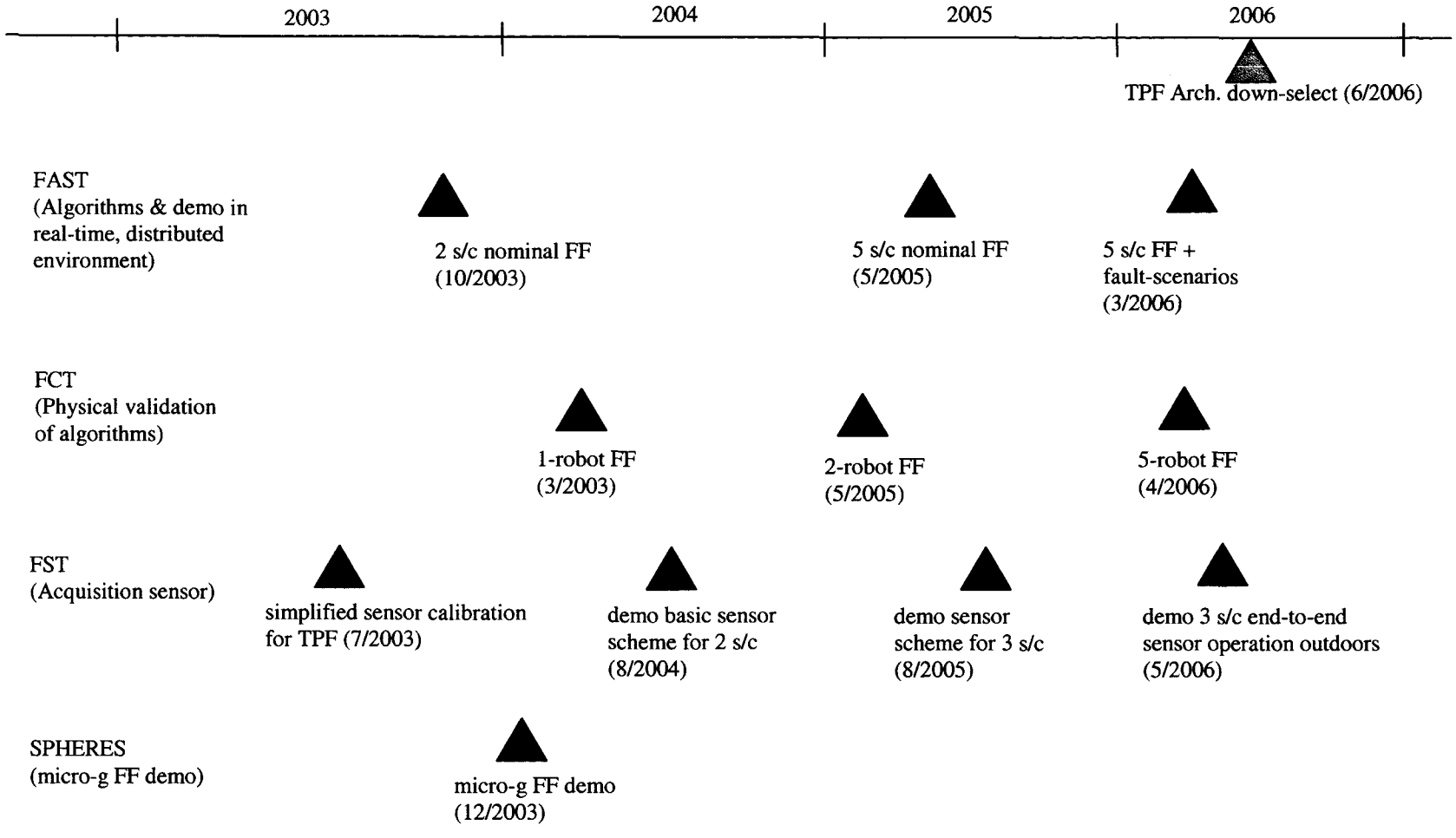
Lessons learned from TPF-representative formation maneuvers.

FIT

Interferometric fringe acquisition and tracking across relatively moving platforms

Infrastructure: FF system design, inter-s/c communications, actuation, thermal shields

Figure 7: Formation Flying Technology Implementation Plan



[i] Aung, M. et al., "Autonomous Formation Flying Sensor for the StarLight Mission," *International Symposium on Formation Flying Missions and Technologies*, Toulouse, France, October 29-31, 2002.

[ii] Saenz-Otero, A., Chen, A., Miller, D. W., Hilstad, M., "SPHERES: Development of an ISS Laboratory for Formation Flight and Docking Research," *IEEE Aerospace,* 2002.

[3] Martin W. Regehr, Ahmet B. Acikmese, Asif Ahmed, Richard Bailey,Clayton Bushnell, Kenneth C. Clark, Anthony Hicke, Brent Lytle, Paul MacNeal, Richard E. Rasmussen, Joel Shields, Gurkirpal Singh, "The Formation Control Testbed," *IEEE Aerospace Conference*, Big Sky, Montana, March 6-13, 2004