Formations of Tethered Spacecraft As Stable Platforms for Far IR and Sub-mm Astronomy

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ABSTRACT In this paper we describe current research in tethered formations for interferometry, and a roadmap to demonstrating the required key technologies via on-ground and in-orbit testing. We propose an integrated kilometer-size tethered spacecraft formation flying concept which enables Far IR and Sub-mm astronomy observations from space. A rather general model is used to predict the dynamics, control, and estimation performance of formations of spacecraft connected by tethers in LEO and deep space. These models include the orbital and tethered formation dynamics, environmental models, and models of the formation estimator/controller/commander. Both centralized and decentralized control/sensing/estimation schemes are possible, and dynamic ranges of interest for sensing/control are described. Key component/subsystem technologies are described which need both ground-based and in-orbit demonstration prior to their utilization in precision space interferometry missions using tethered formations. Defining an orbiting formation as an ensemble of orbiting spacecraft performing a cooperative task, recent work has demonstrated the validity of the tethering the spacecraft to provide both the required formation rigidity and satisfy the formation reconfiguration needs such as interferometer baseline control. In our concept, several vehicles are connected and move along the tether, so that to reposition them the connecting tether links must vary in length. This feature enables variable and precise baseline control while the system spins around the boresight. The control architecture features an interferometer configuration composed of one central combiner spacecraft and two aligned collector spacecraft. The combiner spacecraft acts as the formation leader and is also where the centralized sensing and estimation functions reside. Some of the issues analyzed with the model are: dynamic modes of deformation of the distributed structure, architecture of the formation sensor, and sources of dynamical perturbation that need to be mitigated for precision operation in space. Examples from numerical simulation of an envisioned scenario in heliocentric orbit demonstrate the potential of the concept for space interferometry.

KEYWORDS: Tethered Spacecraft, Formation Flying, Dynamics, Control, Pointing, Retargeting, Astrophysical Detectors, Variable Baseline

1. INTRODUCTION

NASA's future Earth and Space science missions involve formation flying of multiple coordinated spacecraft. Several space science missions (e.g., Terrestrial Planet Finder [1], Terrestrial Planet Imager, Starlight, LISA, SPECS) include distributed instruments and a large phased array of lightweight reflectors and antennas, and long variable baseline space interferometers. A collection of collectors and combiner/integrator spacecraft will form a variable-baseline optical space interferometer for a variety of science applications. Formation flying spacecraft must conform to extremely stringent control and knowledge requirements. The control system for space interferometry, for example, must provide precision station-keeping from coarse requirements (relative position control of any two spacecraft to less than 1 cm, and relative attitude control of 1 arcmin over a large range of separation from a few meters to tens of kilometers) to fine requirements (nanometer relative position control, and .01 milliarcsec relative attitude control).

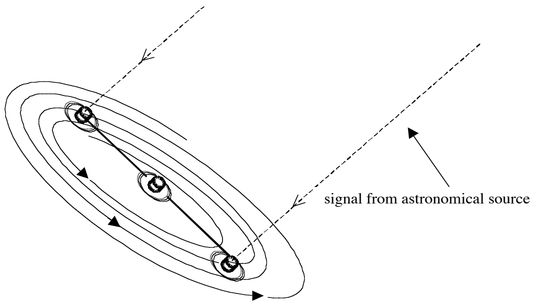


Figure 1. Tethered Interferometer Operation during Source Observation

Apertures of kilometric size are realized by connecting two or more light collecting spacecraft by means of one or more tethers. The advantage of using the tethers is that a variable controllable baseline can be achieved by reeling the tethers in or out, with a much smaller fuel consumption for reconfiguring the spacecraft as compared to the case of separated spacecraft in formation, in which on-board thrusting is continuously required. The idea of connecting the spacecraft to each other by means of a lightweight deployable tether is particularly attractive because: a variable baseline for interferometric observations can be achieved by deploying or retracting the tether; the coverage of the observation plane can be done continuously by spinning the whole system; the high levels of propellant consumption currently demanded by the ACS (Attitude Control System) of separated spacecraft in formation can be dramatically reduced by clever tension control of the interconnecting tethers; and two-dimensional and three-dimensional architectures can be constructed. Figure 1 depicts a configuration of a tethered interferometer in heliocentric orbit currently being considered by a joint JPL-Smithsonian Astrophysical Observatory (SAO) research study ([2]). These spinning tethered configurations are stable and can be tested in LEO. However, to mitigate the thermal dynamics ensuing in the system at each terminator crossing, a near polar sun-synchronous orbit would be preferred. Additional off-the-shelf ACS and tether deployer technology could be used at a relatively low cost. This would make a LEO demonstrator of a tethered formation for space interferometry possible in the near term. Rather than directly analyzing the feasibility and dynamical behavior of a complex tethered interferometer such as the proposed SPECS (Submillimeter Probe of the Evolution of Cosmic Structure), we propose to deal with the simpler architecture of Figure 1 as a precursor to SPECS, but which has the essential features required for its operation: variable baseline, spin dynamics, tether dynamics, multiple light collectors and a central light combiner.

In this paper, first, we describe the drivers and constraints for tethered formations designed for space interferometry, and explain why tethered formations can play a major role in space interferometry. Next, we discuss the approach to predicting the performance using dynamics models and control, sensor and estimation models required by a tethered system. Next, we identify the key sensing/control authority levels which space interferometry demands of tethered formations, and outline a roadmap for ground testing and in-orbit testing of key tethered formation component technology.

2. DRIVERS AND CONSTRAINTS OF TETHERED FORMATIONS

There are several potential drivers and constraints that affect a tethered interferometer system design [2]:

- *pointing stability:* The pointing direction of the interferometer is required to be held within one arc minute (at 1 km baseline) with respect to the line of sight throughout the period of an observation.
- *distance collectors-combiner:* The distances collector1-combiner and collector2-combiner must never differ more than 10 cm from each other.
- *minimum and maximum tether tension:* For a tether to be controlled at the cm level a minimum tension of about 100mN is required so that inner residual tensions and hysteresis phenomena can be limited. Moreover a higher tension is an asset for the stability of the interferometer subjected to solar pressure, whereas depending on the diameter of the tether the tension should be at least one order of magnitude less than the material yield tension.
- *maximum tangential velocity:* The minimum number of photons of the observed source to be collected at a certain baseline length and orientation provides a limit for the maximum tangential velocity of the end mirrors. This velocity should be of the order of 1-5 m/s, provided that sufficiently large mirrors and advanced photon detection systems are employed.
- *boresight with respect to the Sun:* The angle between the anti-Sun direction and the boresight axis must be kept under 20-30 degrees to prevent the solar radiation noise from degrading the measurement.
- *u,v plane coverage:* The Fourier plane would need to be fully sampled from short lengths to 1000m baseline and as rapidly as possible. The high-resolution area (from 100 m to 1000 m baseline) is scientifically the most important.
- *fuel consumption:* The thrusting maneuvers should be reduced as much as possible. The ideal solution would be to keep the magnitude of the angular momentum constant throughout the observations and be able to fulfill all the requirements.
- *survivability:* The tether has to be able to survive in a micrometeoroids environment with high probability (more than 95%) for a 4-5 years mission.

3. WHY TETHERED FORMATIONS CAN PLAY A MAJOR ROLE IN SPACE INTERFEROMETRY

The building block of the formation is a tether connecting two (or more) telescopes on a line. Our teams at SAO and JPL have analyzed in details the orbital perturbations acting on a linear formation in heliocentric (Earth trailing) orbit and the resulting dynamics for the last one-year [2]. The conclusions of our study are that the contributions of disturbances associated with the tether dynamics forced by external perturbations to the overall pointing and relative positioning of the formation are negligible when compared to the effect of the same perturbations acting on the satellites. A steady-state pointing (of less than 1 arcmin) and positioning accuracy requirements (of less than 1 cm) specified for the free-flying formations can be met by a tethered configuration in heliocentric orbit. Figure 2 shows the pointing angular errors of a 1-km-baseline tethered system formed by two collectors and a central combiner on a line. This figure was derived for a specific initial orientation that drives the out-of-plane hard but not the in-plane. For other initial orientations, the in-plane angle is more perturbed than the out of plane but the overall pointing errors of the tethered interferometer in heliocentric orbit are always below 1 arcmin over periods of many months without requiring any overall attitude formation control during the observations.

A comparative analysis of the perturbations acting on the spacecraft of a configuration such as the TPF one vs. those associated with the tether itself indicates that the satellite sun shields contribute 99% of the relevant environmental perturbation forces while the tether only contributes 1%. In conclusions, the contribution of the tether to the formation errors is negligible when compared to the effect of the perturbations acting on the satellites sun shields. Geometric and/or optical asymmetries of the sun shields will produce the lion share of the differential-mode noise components that will impact the control of the free-flying formation. The tethered configuration is actually more robust than the free-flying formation at tolerating those effects because thanks to the possible higher spin rates, it has a higher angular momentum and greater stability.

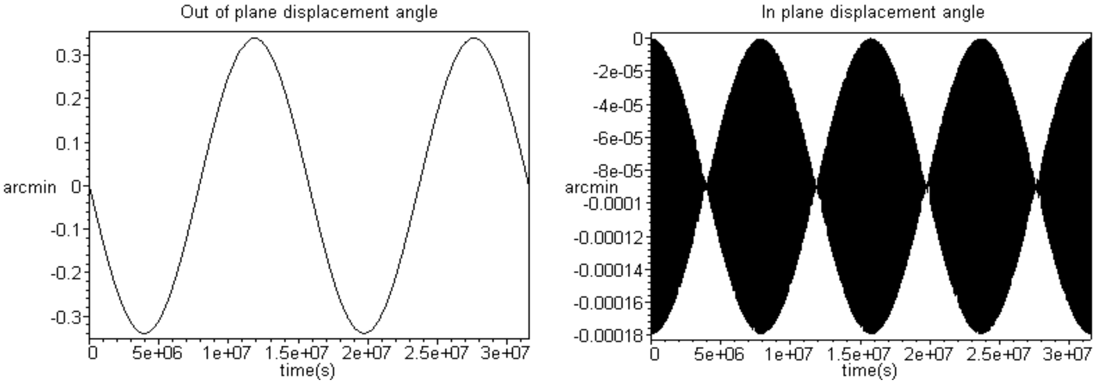
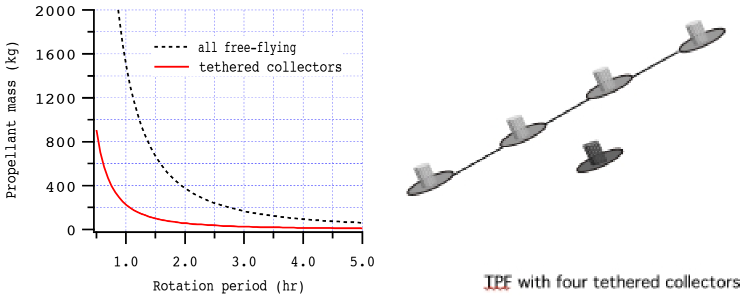


Figure 2 Pointing angular errors of tethered interferometer in solar orbit (over 1 year). Baseline length = 1km; rotation period = 2 hr 20 min; symmetric sun shields on collectors

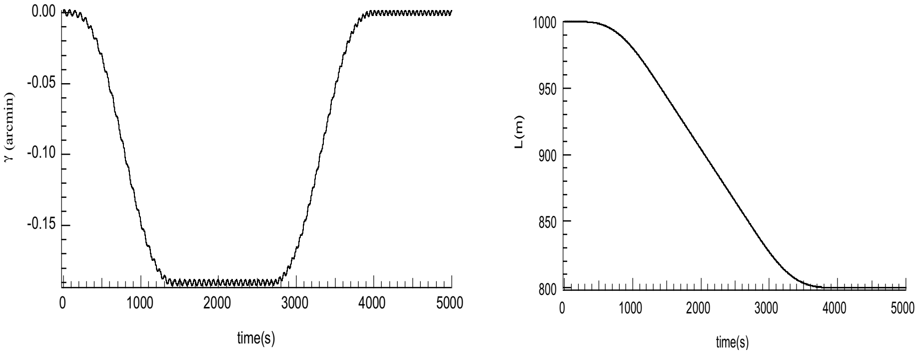
Another important point is that besides being very small the noise brought about by environmental perturbations acting on the tether is a common-mode type of noise, that is, it alters equally the optical path lengths of the interferometer and consequently it does not require differential corrections of the optical path lengths. Differential-mode noise can be produced by retargeting maneuvers that excite odd modes of lateral tether vibrations. The amplitudes of these modes are proportional to the retargeting speed and are strongly limited by the tether tension. Retargeting maneuvers of the tethered interferometer and techniques for damping out those modes will be one the subject of our future research. Finally, the spectral content of a tether for TPF in the length range 100 m to 1 km is at low frequency. Natural longitudinal (i.e., stretching) modes are readily damped out by material damping or simple tether attachment damping devices and they are not a concern. Natural lateral modes have first-harmonic frequencies in the range 0.1 Hz to 0.03 Hz assuming a 1-hr rotation period as a reference. The frequency of external perturbations acting on the tether are also very low, appearing at one or twice the rotation frequency and orbital frequency. This low frequency content points to the fact that the decreasing-amplitude higher-order harmonics should not be a problem for the fine control system of delay lines which is typically designed for a 1 kHz frequency range.

Consider an interferometer configuration in which the four in-line collectors of TPF could be connected by a light (a few kilograms) tether with a relatively simple mechanization while leaving the combiner free flying. In this case a very large portion of propellant can be saved for station-keeping the four collectors during observations (only the combiner needs to be propelled). We have estimated, based on the geometry of TPF, that the propellant for station keeping can be reduced by a factor of 6.7 in a tethered collector formation with respect to the free-flying configuration. Because of the lower propellant consumption, the spin rate of TPF could be increased from the present 8 hours to, let us say, 2 hours or even 1 hour (as indicated in [1]) by enabling the observation of a larger set of target stars for planets search. Figure 3 shows the propellant required exclusively for planets detection for the free-flying TPF and the four-tethered-collector configuration as a function of the rotational period. Planet detection (for which propellant estimates are available from the TPF study [1]) accounts only for a portion of the total propellant expenditure of TPF. Imaging astrophysical sources, which requires continuous covering the u-v plane, can also be readily accomplished in a tethered formation. The tether simply removes the limitations imposed on TPF by the propellant consumption which limits the observation spin rate (that is the number of targets) and builds more flexibility into the mission operation by adding a propellant-free actuation capability for baseline reconfiguration



(a) (b)

Figure 3 (a) preliminary estimate of cumulative propellant (adapted from Ref. [1] required for planet detection only for a TPF with all free flying elements and a TPF with four tethered collectors as depicted in (b).



(a) (b)

Figure 4 (a) spacecraft bearing error during a reconfiguration maneuver with (b) the baseline length varying from 1000m to 800m.

and u-v plane coverage. Similar considerations would apply in comparing the fuel performance of a tethered vs. non-tethered SPECS interferometer. Reconfiguring the baseline from one length to another can also be accomplished by reeling in (or out) the tether with the use of energy and almost no propellant. Figure 4 shows the simulated dynamics of a baseline reconfiguration from 1000 m to 800 m (with a perfect actuator) and the associated bearing angle error (produced by Coriolis forces) of one collector with respect to another. The tether, if attached off the center of mass, produces substantial restoring torques that stabilize the bearing angle of the spacecraft.

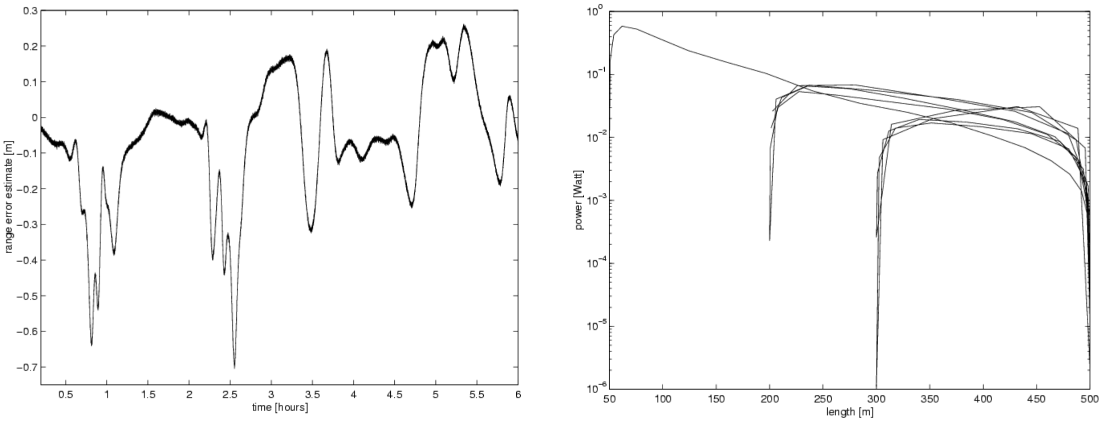


Figure 5. (a) Error between true and estimated range. (b) Tether deployer power as a function of system's length.

Figure 5a shows shows that the error between the true and estimated range between a collector and the combiner is of the order of tens of centimeters, consistent with the expected performance of the Autonomous Formation Flying radio-frequency metrology sensor. Additional laser metrology will be needed for higher precision metrology. Figure 5b shows a tether deployer power utilization as a function of the baseline length in the range of 10^{-2} Watt, provided most of the reconfiguration required for U-V plane coverage occurs at intermediate baselines. Figure 6a shows the trace of coverage in the normalized U-V plane achieved with the baseline reconfiguration program depicted in Figure 6b. From Figure 6 one can determine the advantage of the tethered system in providing high density U-V plane coverage. Figure 7a shows the tether temperature profile as a function of the position in the orbit, suggesting that ways to isolate the tether will be required to avoid thermal perturbations. Figure 7b shows the interferometer baseline rate to be in the range of cm/s for spin rates of the order of 0.01 rpm. In conclusions, the results of our analysis for a tethered formation in heliocentric orbit indicates that the steady-state dynamics of the tether forced by the environmental perturbations is small and its effect on the pointing and separation of the formation are well within the specified requirements. Moreover, tether dynamics produce low-frequency noise that should be handled readily by the broad-banded fine control system of proposed interferometers such as SPECS and TPF.

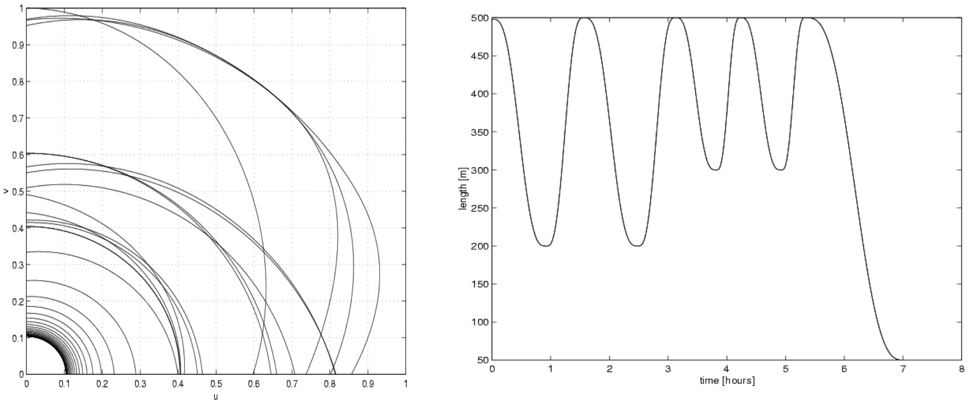


Figure 6. (a) U-V plane coverage trace. (b) Interferometer variable baseline program to cover U-V plane.

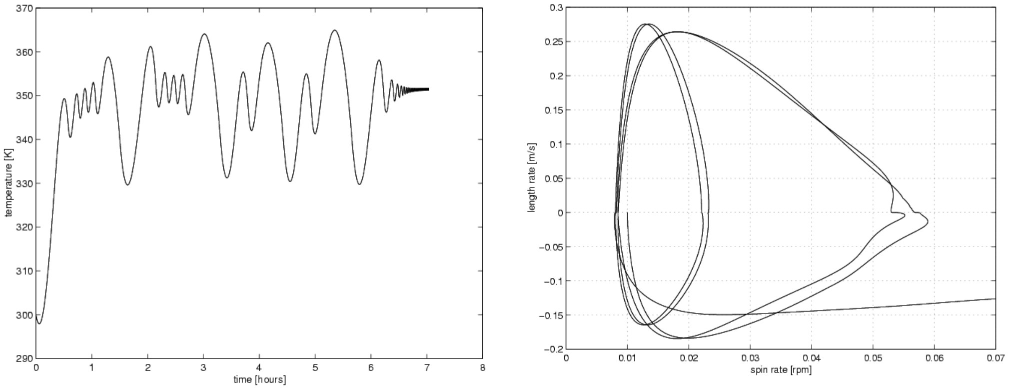


Figure 7. (a) Tether temperature profile. (b) Interferometer baseline rate vs. spin rate.

4. SYSTEM ARCHITECTURE

4.1 Modeling and Dynamics

From a dynamical standpoint, a formation of tethered spacecraft is characterized by a wide dynamic range (from less than 1 Hz in the spacecraft dynamics to KHz in the operation of the instrument synthesized by the formation), and by spatial scales ranging from sub-micron to kilometers. The formation can be thought of a *virtual truss* ([3], [4], [5]) in which the stiffness and dissipation levels of the connecting links are dictated by the control action on the relative sensing and actuation between two or more neighboring spacecraft. The dynamic model of this virtual truss suffers from undesired deformation modes caused by sensor noise, actuator non-linearity, dynamic uncertainties, and environmental disturbances.

4.2 Sensing/Estimation

Figure 8 depicts various sensing/estimation schemes required by tethered formations. Formation Estimation plays a key role in formation flying control of distributed spacecraft. In order to fully appreciate the complexity of the formation estimation problem, consider the illustration in Figure 8, which depicts four possible architectures for information exchange for a formation of four spacecraft. The arrows denote the relative state measurement made by the spacecraft located at the tip of the arrow. For the simplest case (A) each member of the formation uses only the relative state with respect to a designated master. In the second case (B), a centralized solution is the only possible architecture. Architecture (C) allows any member of the formation to make, visibility permitting, relative state measurements with respect to any other member. In architecture (D) the master and another member of the formation, labeled Reference, form a "baseline". The Reference receives information only from the Master, while all other spacecraft in the formation use relative states with respect to the Master and the Reference. A particular mechanization of information exchange will directly impact the quality of the formation estimate and therefore the quality of formation control.

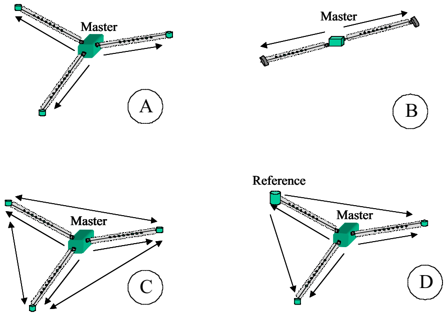


Figure 8. Four Possibilities of Making Relative State Measurements

4.3 Commander/Controller

The observation cycle is at least of two types: Stop and Stare observing mode (in which the configuration is brought to a halt with zero relative velocity between spacecraft before any observations are attempted), and Observe on the Fly mode (in which fringe measurements on astronomical targets can be made while the spacecraft are moving). There are at least four internal dynamics control modes in the system when working as an interferometer [4]:

- **Attitude Rigidity Control Mode**. This mode is used for fine pointing and stabilization only.
- **Spin/Despin Control Mode**. This mode is used to modulate the rotational spin rate of the system about its center of mass.
- **Tether Deployment/Retrieval Control Mode**. This mode is used to change the baseline of the interferometer or to control the baseline finely for corrections at the centimeter level or less.
- **Retargeting Mode**. This mode is used when the tethers are retracted into the collector spacecraft, and the whole system is repointed to a different target before the whole sequence of u-v plane coverage begins for the new target, and involves a precession maneuver.

4.4 Sensing/control authority levels for interferometry

Figure 9 depicts a block diagram of sensor and control levels for a tethered interferometer spacecraft with similar goals to the Terrestrial Planet Finder (imaging, nulling, planet finding). We may identify four levels of control and sensing authority with different bandwidths and precision:

1. Level 1: is the formation global control residing on the light-combining spacecraft. Ground communication links, inertial pointing, and inertial guidance for the formation are commanded from this location (0.1Hz, meters, arc-sec).
2. Level 2: refers to the control/sensing by each collector spacecraft for purposes of baseline stabilization (0.01-0.1 Hz, sub-cm and arc minute).
3. Level 3 refers to control authority enabled by RF and optical links to stabilize the metrology loop (KHz, micrometer, sub arc-sec).
4. Level 4 refers to tracking/nulling operations involving the maximum precision level of the interferometer during observation (KHz, nm and sub arc-sec).

The focus of the technology to be demonstrated in a potential LEO flight is on Level 1 and 2, although a demonstrator in deep space would be able to demonstrate Level 3 control and estimation technology.

<u>5. TECHNOLOGY IN NEED OF DEVELOPMENT FOR FUTURE PRECISION TETHER APPLICATIONS</u>

Several important technologies have already been demonstrated in-orbit during at least 16 tethered spacecraft flights:

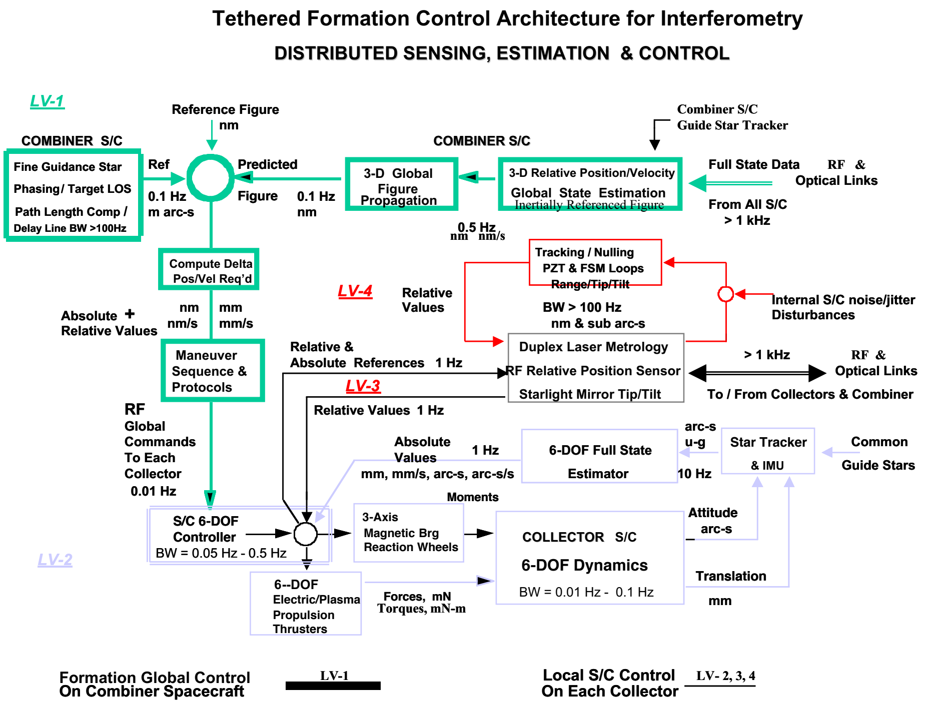


Figure 9. Sensing/Control authority for TPF class tethered interferometer spacecraft.

1. Controlled deployment, with accurate control along local vertical: +/- 4 degrees (this was achieved with a simple spool-out-only deployer; a much higher accuracy can be achieved with a reel-in and out deployer).
2. Controlled stationkeeping , allowing for long term orbit and attitude dynamic prediction.
3. Long-term (>5 years) survival and dynamic stability of a 4-km tether in LEO at a 1000km-altitude, high-inclination orbit (i.e., the dirtiest region in LEO).
4. Sizeable current flow in both directions (for boost and deboost applications) of conductive tethers.

Several technologies need further development before autonomous and reliable precision applications of tethered spacecraft can be made.

1. Controlled tethered system retargeting strategies to different sources in the sky.
2. Precision stationkeeping.
3. Disturbance rejection and vibration abatement of tether dynamics caused by transient maneuvers.
4. Very smooth reeling in and out of tether suitable for precision baseline control.

These objectives can be accomplished with ground testing and in-orbit validation of the following key technologies:

1. Active/passive control of tether attachment point, via movable hinge or movable boom or via dissipative flexures or joints;
2. autonomous on-board control logic for reliable deployment and retrieval at specified tether length and tension profiles;
3. crawler technology, to enable distributed arrangements of tethered vehicles on a very long tether or multiple tethers;
4. accurate metrology between adjacent tethered vehicles which does not suffer from scattered illumination from the intervening tether.

6. CONCLUSIONS

In this paper, we have described the models currently being used at JPL for dynamics analysis, control, and estimation, of tethered formations in deep space and in LEO intended as precursor demonstrators of SPECS. We have identified the features needed by a tethered interferometer in space in order to qualify as a system capable of imaging, nulling, planet detection and general far-IR and sub-mm space science. The key technologies which need to be pursued and developed in order to achieve these goals have also been described.

Acknowledgments

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. E. C. Lorenzini was supported by JPL Contract 1215076. Thanks to Mr. C. Bombardelli of SAO for producing Figures 1-4.

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