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AN INNOVATIVE DEEP SPACE APPLICATION OF GPS TECHNOLOGY FOR FORMATION FLYING SPACECRAFT

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ABSTRACT

This paper describes the Autonomous Formation Flying Sensor (AFF) concept for extremely precise autonomous relative position and attitude determination for formations of satellites or spacecraft where real-time or near-real-time knowledge of relative position and attitude are required. Its technology is built around commercially available receivers widely used in Global Positioning System (GPS) ground applications and recently flight-tested in space. This sensor, however, does not actually require any observations of GPS satellite data for precise spacecraft-to-spacecraft position and attitude measurements. Thus, the AFF could be used in deep space or in Earth orbit, with or without GPS satellite data. Studies indicated that the AFF can provide a relative range measurement accuracy of 1 cm, along with a relative attitude measurement accuracy of 1 arcminute over formation distances of 1 m to 1300 km.

INTRODUCTION

Applications of Global Positioning System (GPS) receivers have proliferated well beyond the original vision of its system architects. Receivers are now being built which can provide absolute measurements such as translational position, velocity, time, as well as attitude and attitude rate. Moreover, technology is emerging which will make GPS receivers capable of routinely delivering highly accurate measurements for most of these states. Thus GPS receivers hold the promise of satisfying nearly all the guidance, navigation and control (GN&C) sensing requirements for Earth orbiting spacecraft in a single integrated, reliable, low mass, low volume, and low power package.

Because the NAVSTAR GPS system was originally designed for Earth applications, usage in deep space was nonexistent. This paper presents a sensor concept that awakens a fundamental new area of GPS technology that can be applied in deep space or in Earth orbit.

The Autonomous Formation Flying GN&C Sensor (AFF) is the new sensor concept which address some key challenges presented by the Deep Space Mission 3 (DS-3) under the NASA (National Aeronautic and Space Administration) New Millennium Program (NMP). One of the challenges is to devise a sensor which could enable an ensemble of three spacecraft in deep space to autonomously maintain a precise relative formation in both position and attitude. The sensor should be low-power, low mass, and low cost. Furthermore, it should have a general architecture which would enable it to be used on a variety of different missions without significant re-engineering.

<u>New Millennium DS-3 Separated Spacecraft Interferometer</u>

As imaging science inquiries demand better and better resolution, the concept of optical interferometry emerges as a very attractive alternative to the large aperture telescopes. There are several advantages to this approach. Interferometers can coherently combine the light from several small separated apertures to yield the equivalent angular resolution of a telescope as large as their separations. In doing so, interferometers weigh less and cost significantly less than an equivalent filled-aperture telescope. Furthermore, they can decouple sensitivity (collecting area) from angular resolution (baseline), thus providing higher angular resolution than is possible with a telescope with the same sensitivity.

NASA is currently placing heavy emphasis on the concept of separated spacecraft interferometry (SSI). SSI in free space, with its extremely long baselines, allows measurements unachievable with other techniques, such as single aperture telescopes and single structure interferometers. Unlike ground interferometers, these long baselines are not subjected to the Earth's curvature. Nor are the observations corrupted by Earth's atmospheric effects. Furthermore, SSI allows baseline lengths and orientations to change easily. It also permits incremental array expansions and replenishment.

The new challenge to the SSI concept is to provide a "virtual" structure in order to maintain the necessary structural rigidity. The solutions can be provided by three parts: active optics are used to control at high frequencies, and at small scales; laser metrology system is used to provide the measurements for the active optics; and Formation Flying is performed to do low frequency, large scale controls.

DS-3 is such a concept for a separated-spacecraft optical interferometer (Figure 1). The interferometer instrument would be distributed over three small spacecraft: two spacecraft would serve as collectors, directing starlight toward a third spacecraft, which in turn would combine the light and perform the interferometric detection. The mission would nominally be deployed in a low-disturbance heliocentric orbit, to minimize stationkeeping fuel burden. The interferometer baselines would be variable from 100 m to 1 km. Low-bandwidth corrections for 1 centimeter and 1 arcminute stationkeeping and relative attitude errors would be accomplished by spacecraft control with electric-propulsion or a cold-gas system; high-bandwidth corrections for 10 nanometer and 0.05 arcsecond stationkeeping and relative attitude errors would be accomplished by active optical controls.

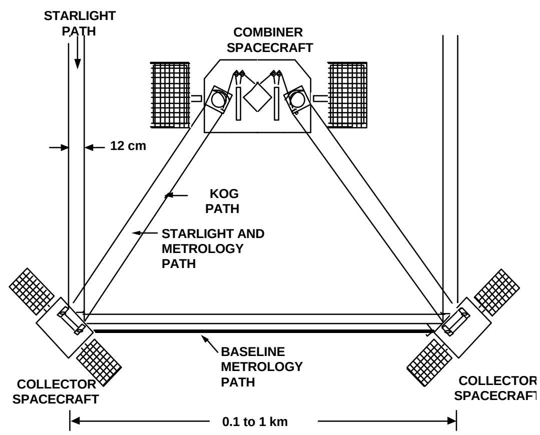

Figure 1. DS-3 Separated Spacecraft Interferometer

As DS-3 is planned for use in interplanetary space at a distance of 0.1 AU, well beyond the coverage of the NAVSTAR GPS constellation, deployment and coarse relative stationkeeping would be monitored with the AFF system. Laser metrology among the three spacecraft would be used to measure more precise relative motions of the three spacecraft. Determination of rotation of the constellation as a whole would use a kilometric optical gyro (KOG), which is a free space ring laser gyro that uses counterpropagating laser beams among the three spacecraft to measure rotation with high accuracy.

Applicability to DS-3 Objectives

The AFF could result in significant reduction in life-cycle costs and spacecraft mass and complexity for missions requiring precise relative positioning and orientation of multiple spacecraft. Once an AFF based spacecraft formation is launched, the operations costs on the ground are essentially zero for maintenance of the desired spacecraft formation configuration. This is indeed a revolutionary change from existing operations concepts, where major expenditures are currently required to acquire, process, and analyze data from any mission, and then to command the spacecraft to the desired positions and orientations. Those current traditional methods will not be feasible for ensembles of 2 to 16 (or more) spacecraft designed for very low-cost operations in the NMP. The AFF will enable multiple spacecraft missions to be operated at a small fraction of the current operations costs.

The original concept for constellation initialization consisted of three types of metrology systems used in successive field of view (FOV) versus accuracy levels. An radio-frequency (RF) ranging system would be used as a coarse acquisition sensor at an accuracy on the orders of meters. Even though this system may have a fairly large FOV, a sequence of search maneuvers may still be required. Then an optical beaconing system would be used as an intermediate acquisition sensor to increase the accuracy to centimeter levels and to provide relative orientation information. Finally a laser metrology system would be used to provide fine ranging information between spacecraft. However, the FOV of this system is very, very limited.

By using the AFF, the RF and the optical beaconing systems are now combined into one all-inclusive sensor. Other savings in cost and mass, at least for DS-3, will be realized from the potential elimination of star-tracking sensors from two of the three spacecraft for that mission (at least one star tracker is still required to calibrate the absolute, or inertial, orientation of the spacecraft) and reduction in fuel mass since the AFF would have 4p steradian coverage, thus eliminating search maneuvers. Additionally, other cost savings likely to be realized on DS-3 from the 1 cm level of positioning accuracy would be the elimination of at least one type of metrology system which would otherwise be required to reach the 1 cm accuracy level.

The AFF development will benefit from parallel efforts, some of which are supported by the NMP, to develop a “GPS-on-a-chip” receiver capability[1]. Such technology would be applicable to the AFF as well, thus further lowering the mass and power estimates given above.

A revolutionary improvement in accuracy and performance for relative positioning and attitude determination is anticipated from the AFF. Traditional ground-based systems are orders of magnitude too noisy and too expensive to provide the required information, at least for DS-3. Alternative methods using spaceborne laser tracking or star sensors are probably competitive in performance but will increase system complexity and cost. In addition, if the spacecraft are separated by more than a few kilometers, power requirements for an optical system would need to be large in order to provide light spreading over a large FOV.

Other Separated Spacecraft Missions

Many other NASA separated spacecraft missions could potentially benefit from the AFF technology being studied for missions such as DS-3. They include Earth orbiting imaging missions such as TOPSAT (Figure 2), and the New Millennium EO-1 (Earth orbiting mission 1) Landsat Co-flyer (Figure 3), gravity mapping missions such as GRACE (Figure 4), deep space sparse-aperture RF telescope such as ALPHA (Figure 5), and MUSIC (Figure 6), a moderately filled aperture interferometer constellation. All of which requires moderate to precision formation sensing capabilities.

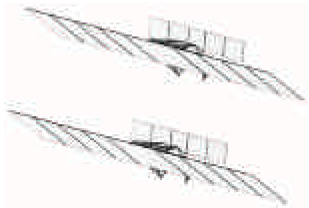

Figure 3. TOPSAT

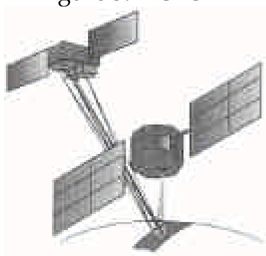

Figure 2. Landsat Co-flyer.

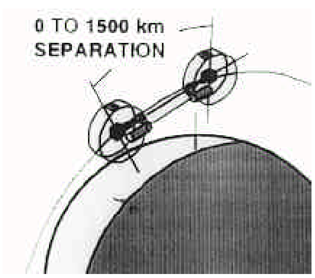

Figure 4. GRACE.

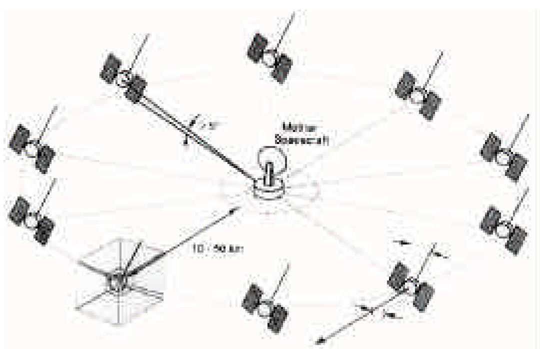

Figure 5. ALPHA.

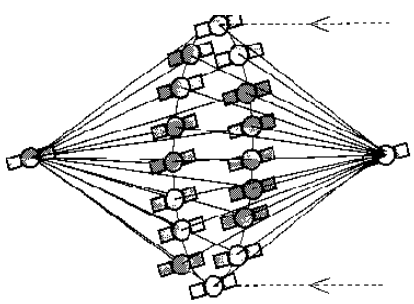

Figure 6. MUSIC.

Other Applications of the AFF

The AFF can also be used as a rendezvous and docking sensor.   Using the AFF capabilities, a sample-return spacecraft can rendezvous and dock with a "mother" spacecraft so that soil samples can be transferred and returned back to Earth.

Another rendezvous and docking application can be exemplified by the Space Shuttle docking with the Space Station. Because of the Station's large structural elements (solar arrays, strut structures, etc.), the Shuttle-to-GPS line-of-sight may be blocked. An AFF implemented in the existing Shuttle GPS receiver may be considered by some to be more capable and elegant than those provided by the currently planned optical based docking sensors .

The applications of the AFF for Earth based applications are limited only by imagination. The concept can also be extended underwater, providing the appropriate sonar frequencies are used.

THE AUTONOMOUS FORMATION FLYING GN&C SENSOR

While the Jet Propulsion Laboratory (JPL) has had an active role in developing and demonstrating GPS technology for Earth orbiter and ground-based tracking applications, the AFF represents a fundamental new area of application of GPS technology. It is based in part on several novel and innovative uses for the TurboRogue GPS receiver which do not actually involve the tracking of GPS satellites. The TurboRogue GPS receiver was originally developed at JPL[2,3] for precise positioning and timing applications, and is currently commercially available from Allen Osborne and Associates.

The TurboRogue GPS receiver has flexible software and hardware to generate models of GPS ranging codes and carrier phase. These models are correlated with incoming NAVSTAR GPS data and enable precise pseudorange and phase observables to be measured. The term “pseudorange” is used to indicate that the derived range includes an additional delay due to the offset of the transmitter and receiver clocks.

The innovative new approach provided by the AFF is to modify the commercially available TurboRogue space receiver so that its internally generated GPS models are used for a 1-way beacon transmission as well as for processing of the received data. Instead of tracking GPS satellites, the TurboRogue space receivers track one another from within a spacecraft formation. Each spacecraft would carry one such *transceiver* for dual one-way tracking. It may be useful to use a Ka-band frequency (instead of the usual GPS L-band) to enable more precise tracking and to avoid any possible conflicts with the operational GPS constellation if the AFF is used in Earth orbit.

In order for the formation to self-track autonomously from arbitrary initial orientations, each spacecraft would need to carry a total of 6 corner-located receive antennas and two transmit antennas mounted on opposing corners (Figures 7 & 8). This would provide full sky coverage in all directions (4p steradian), assuming hemispherical fields of view for each antenna. The AFF would provide true autonomy for the ensemble because changes in relative positions and orientations of the multiple spacecraft could be effected automatically by an intelligent onboard control system. This system would continuously compare the measured positions and orientations with the desired values and initiate corrective sequences or maneuvers to maintain the target ensemble configuration.

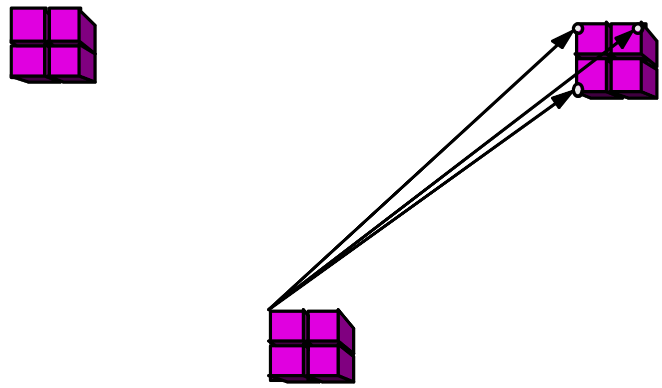

Fig. 7. Configuration with 3 Small Receive Antennas for Relative Attitude Determination and Position. (Spacecraft Represented as a Cube. Not Visible are 3 Additional Receive Antennas on Opposite Side.)

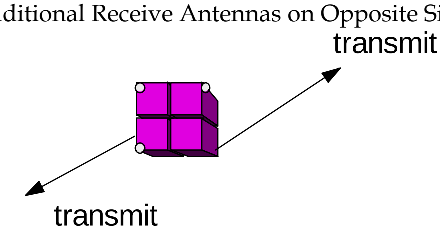

Fig. 8. 2 Transmit Antennas, Mounted on Diammetrically Opposed Corners.

The AFF would enable determination of precise relative attitude of the spacecraft in the formation by tracking the relative carrier phase received in each of three antennas mounted on a face of the spacecraft. The relative positions of each spacecraft in the ensemble can be precisely determined from the spacecraft-to-spacecraft phase and pseudorange data. Such antennas can be made quite small and inexpensive. For example, GPS “omni” patch antennas flown successfully in space have mass on the order of 100 grams and can be obtained commercially for several hundred dollars. Because the transmission and reception of the dual one-way range and phase observables are nearly simultaneous, there will not be a stringent onboard requirement for a stable clock.

Leveraging Previous Research

The GPS group at JPL has been studying a similar technique for sub-nanosecond dual one--way time transfer over intercontinental distances on Earth. This time transfer study, funded in the Deep Space Network (DSN) Advanced Technology Program, utilized pairs of TurboRogue receivers to transmit and receive to one another in a JPL testing facility. Prototype boards were built in the GPS receiver development lab and measurements were successfully made in 1993-1994 at the DSN Information Systems Engineering Laboratory (Figures 9 & 10). Figure 10 shows actual measurements of clock offsets from the demo. The RMS scatter about the mean is 0.02 nanosecond, which corresponds to 6 mm in range.

The AFF resembles the time transfer system in some respects, since in each case, no actual GPS satellites are tracked; instead, each TurboRogue "tracks" signals from other TurboRogue receivers, and the TurboRogue receiver is used as a transceiver. The setup for the time-transfer demo (Figure 9) was actually more complex in some ways than the TurboRogue-based AFF due to the presence of other components (two multiplexers and a simulated satellite). The AFF would operate with two TurboRogues transmitting and receiving each others' signals directly. With this configuration, measurements comparable in consistency to those shown in Figure 10 can be expected.

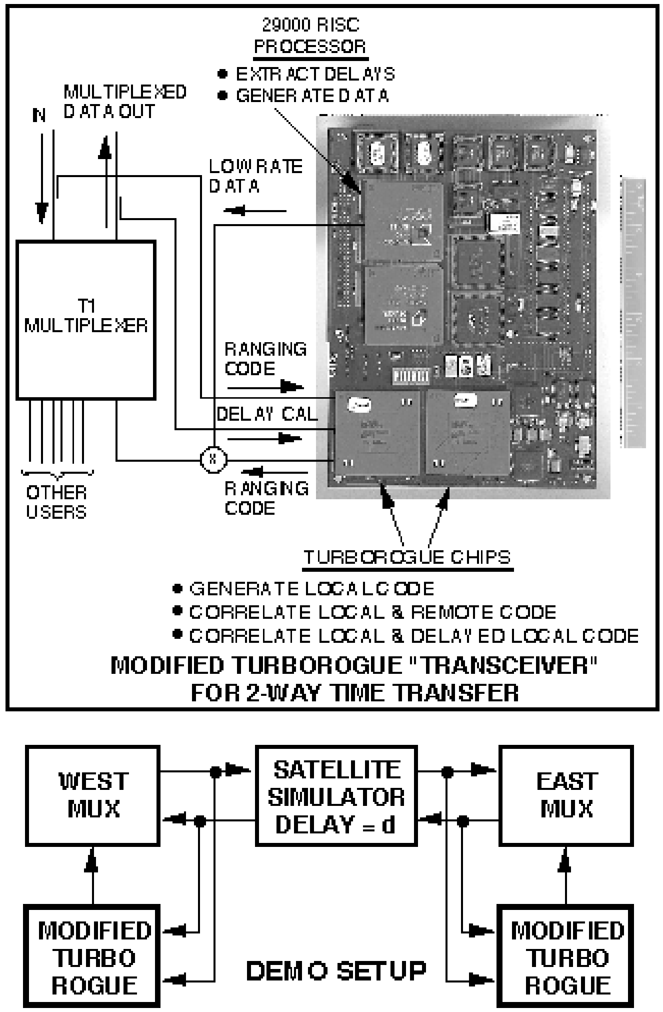

Fig. 9. TurboRogue GPS Receiver Components Used for the AFF.

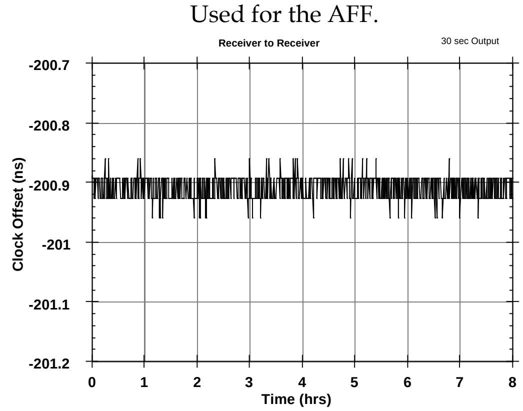

Fig. 10. Measurements of 2 Modified TurboRogue "Transceivers" in 1994 Demonstration.

Clock Calibration

When two AFF sensors are used to self-track, each sends out a 1-way signal and each receives a 1 way signal from the other simultaneously. The combination of these two 1-way signals enables the clock offset and distance between the two AFF sensors to be uniquely determined (Figure 11

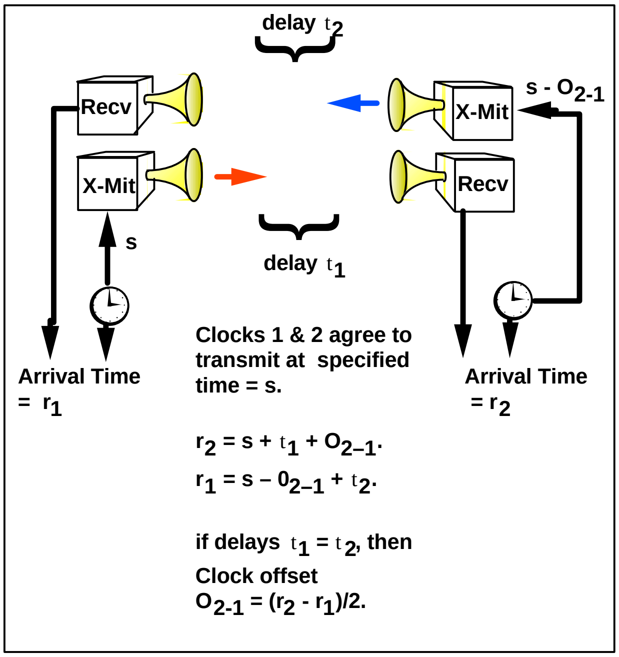

Fig. 11. Clock Offset Determination Between 2 AFF.

Autonomous Formation Flying Determination and Control

The determination of precise relative orientation (attitude) of a platform with GPS receivers and multiple antennas has been thoroughly studied at JPL and elsewhere[4,5,6,7,8,9,10]. Based on preliminary studies which assume 2 m diameter spacecraft and transmitting at Ka band, it is expected that this system can provide relative attitude information with accuracy better than ±1 arcminute each second[11,12] using carrier phase data. It is also expected that the relative spacecraft positions accurate to 1-cm will be possible with this AFF[11,12].

The autonomous controls algorithm for constellation control and formation flying is currently under development at JPL under a 1994 Director Discretionary Fund Award. Based on the exploratory work, two types of control architecture can be developed: a master-slave control configuration and equal authority (decentralized) control configuration. The complete development of at least one of these two configurations is necessary in order to implement the AFF into a constellation spacecraft avionic system. The master-slave control configuration simply assumes that a given (slave) spacecraft will perform formation adjustment with respect to a second one (master). This control architecture works best when there are a small number of spacecraft in a formation. The decentralized control configuration assumes that all spacecraft will perform formation adjustment to maintain the constellation. However, the control laws will be much more complex in order to maintain formation stability and to avoid conditions such as duplicate spacecraft firings.

Maturity of Technology

The JPL GPS group has considerable experience in determination of precise relative positions with GPS and GPS-like observables over distances ranging from a few meters to thousands of kilometers[13,14]. Furthermore, the ability to use GPS technology to measure distances to the cm-level has been convincingly and uniquely demonstrated by the group, both in ground and space-based experiments.

The TurboRogue receiver, which was originally developed by JPL, has been used in a variety of innovative applications, including: tracking satellites from a low-Earth platform[15]; autonomous experiment schedule and control from a low-Earth platform; tracking geostationary (non-GPS) satellites[16]; and even tracking of spacecraft in interplanetary space. The TurboRogue receiver has also been adapted to track various spacecraft signals at S-, X-, and K-band.

SUMMARY OF THE AFF CHARACTERISTICS

The AFF is envisioned to have the following characteristics:

- Self-orienting from any starting configuration, due to full-sky coverage of receive and transmit antennas on each spacecraft (4p steradian field-of-view). Position and attitude solutions for spacecraft will be exchanged through the same radio links established for tracking, so that constellation internal geometry, relative orientation, and integrity can be autonomously monitored and maneuvers can be automatically sequenced and executed. No ground commands are needed for system operation.

- Solutions will be rapidly generated onboard one or more spacecraft using a continuously running factorized Kalman-type filter within a second or two of real-time, enabling real-time knowledge to be inferred from propagated spacecraft states. The JPL GPS group has studied the design and use of such continuously running filters in other GPS application contexts. The solutions will be incorporated into the spacecraft G&C attitude filter so that it can be folded with other attitude sensors for individual spacecraft attitude control and constellation control.

- Low cost for hardware previously flown in space will result from the exploitation of existing TurboRogue receiver technology at JPL. These receivers are inexpensive and are available commercially. If ordered in quantity, we anticipate that recurring hardware cost per flight unit will fall below $100K. Non-recurring engineering will be needed to add: transmit capability; software for dual one-way data processing; accommodations for multiple antennas; software for relative positioning and orientation; integrity monitoring; Ka-band capability (instead of L-band); interface for spacecraft control subsystem.

- Clock offsets between pairs of AFF can be uniquely determined when two AFF are used to self-track, each sending out a 1-way signal and each receiving a 1-way signal from the other With the clock corrections determined, the 1-way ranging data can be used to measure precisely the distance between the two AFF. In addition, precise carrier phase data can provide precise attitude measurements between the platforms on which the AFF is mounted on

- Provides relative position knowledge to ±1 cm, relative velocity to ±0.1 mm/s, and attitude knowledge to ±1 arcminute.

- Transmit power required could be less than 0.1 watt while still allowing for precise tracking up to separations of 1300 km. Total power required by the AFF is anticipated to be less than 1 Watt average, 5 Watts peak, with instrument mass < 2 kg.

- The AFF would be capable of carrying telemetry among spacecraft in the constellation.

CONCLUSION

This paper presents an innovative application of GPS technology for deep space formation flying missions using an AFF. This approach offers a new precision relative range and attitude sensor that offers unique advantages in deep space relative tracking accuracy and operability and which can also be applied toward Earth orbiting or Earth based formation flying missions, including rendezvous and docking missions.

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