FROM AFF TO CCNT: JPL'S EVOLVING FAMILY OF MULTI-FUNCTION CONSTELLATION TRANSCEIVERS

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1. ABSTRACT

JPL is developing novel RF tracking sensors for both of NASA's New Millennium Program constellation missions, ST-3/StarLight and ST-5. ST-3/StarLight, the Separated Spacecraft Interferometer, is a two-satellite formation in heliocentric orbit designed to demonstrate various technologies required for space interferometry. Scheduled for a 2006 launch, ST-3 will fly JPL's Autonomous Formation Flying (AFF) sensor for sub-cm inter-spacecraft ranging accuracy and 1 arcmin bearing accuracy. ST-5, the Nanosatellite Constellation Trailblazer, is a three-satellite constellation in geosynchronous transfer orbit designed to test and validate technologies in advance of MagCon, the large magnetospheric constellation scheduled to enter engineering development in 2006. Scheduled for launch in late 2003, each of the ST-5 spacecraft will carry JPL's Constellation Communications and Navigation Transceiver (CCNT), integrating inter-spacecraft ranging, communications, and GPS-based absolute positioning.

This paper describes the profiles and requirements of the ST-3 and ST-5 missions, and discusses the unique technological challenges each of them presents. Both the AFF and CCNT trace their heritage to GPS receivers, using measurements of both RF carrier phase and a ranging code. They will operate, however, at very different frequency bands: the AFF at Ka-band, and the CCNT at S-band.

2. INTRODUCTION

Separated spacecraft constellations (also known as distributed spacecraft, or formations) recently emerged as an efficient and an enabling tool in the study of our universe. Recognizing the exceptional value, new capabilities, and unique challenges that are offered by constellations of spacecraft for Earth science and for space science, NASA is funding an increasing number of constellation missions (e.g., GRACE, ST-3/StarLight, ST-5, LISA), and is investing heavily in the development of critical constellation technologies. The various funded and proposed constellations vary greatly in size, from a pair of spacecraft (e.g. GRACE, ST-3), to a trio (LISA, ST-5), to swarms of spacecraft (e.g., the Magnetospheric Constellation, or MagCon). The relative positioning, orientation, and control requirements for these constellation missions span the spectrum from picometer level (LISA) and 1 arcmin (ST-3) to meter level (Figure 1). Clearly, the constellations on the extreme edge of the requirement spectrum will require very specialized metrology systems, probably outside the RF band. However, the majority of the proposed and planned constellations require relative positioning accuracy that could be provided by a RF metrology system. JPL is currently building RF metrology systems for three very demanding constellations, namely, GRACE, ST-3/StarLight, and ST-5. These instruments could be used for other constellations, with some minor or, perhaps, major modifications.

The separated spacecraft metrology instruments that JPL is developing have a strong GPS heritage. This is of particular value for near Earth constellations where a hybrid GPS/inter-spacecraft metrology system is a viable option. Such a system is being implemented for GRACE and, to some extent, for ST-5. However, in its purest form, the system, known as the

Autonomous Formation Flying (AFF) sensor, is completely independent of GPS and can be applied in deep space.

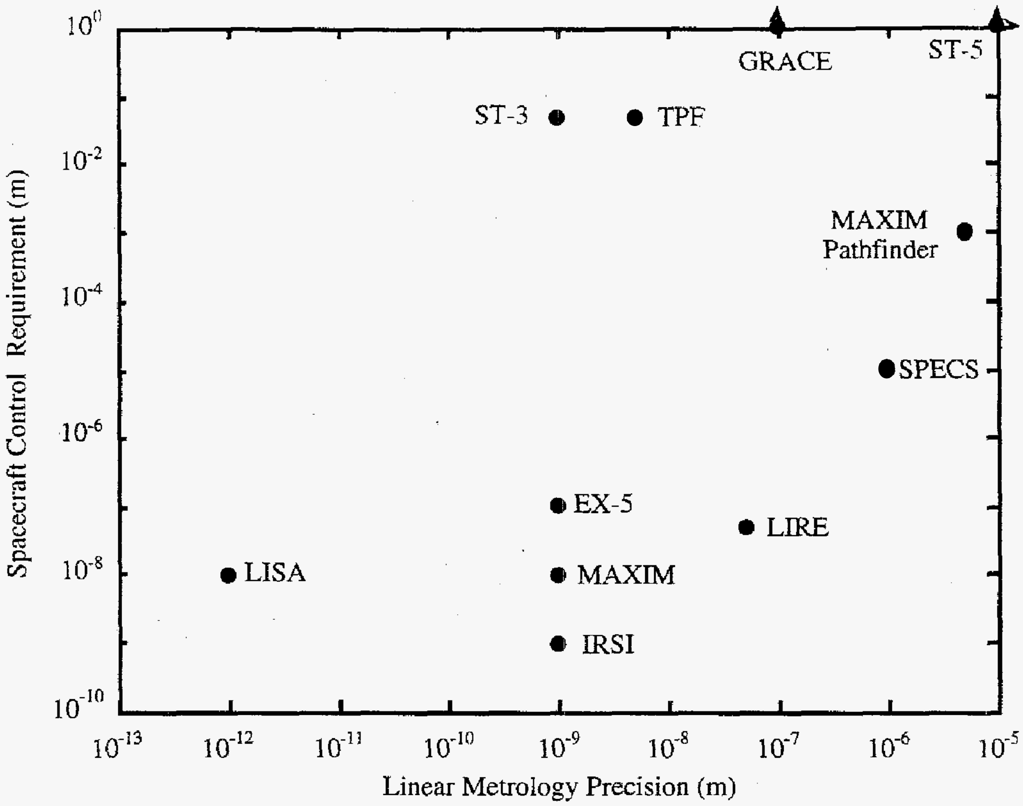


Fig. 1. Ranging knowledge requirements vs. range control requirements for a variety of current and future constellation missions.

3. THE AUTONOMOUS FORMATION FLYING (AFF) SENSOR

The AFF sensor is based on the TurboRogue GPS receiver that was originally developed at JPL for precise positioning and timing applications [1,2]. The TurboRogue space receiver was modified so that its internally-generated GPS models are used for a beacon transmission as well as for processing of the received data. Instead of tracking GPS satellites, the AFF *transceivers* track one another from within the spacecraft ensemble. Each spacecraft carries such transceiver for two-way tracking. It may be useful to use higher than L-band frequency to enable more precise tracking and to avoid any possible conflicts with the operational GPS constellation if AFF is used in Earth orbit. The AFF transceivers include appropriate new software and hardware to enable the ensemble of spacecraft to autonomously determine a self-consistent real-time solution for the relative position and orientation (bearing) of each spacecraft. 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 2).

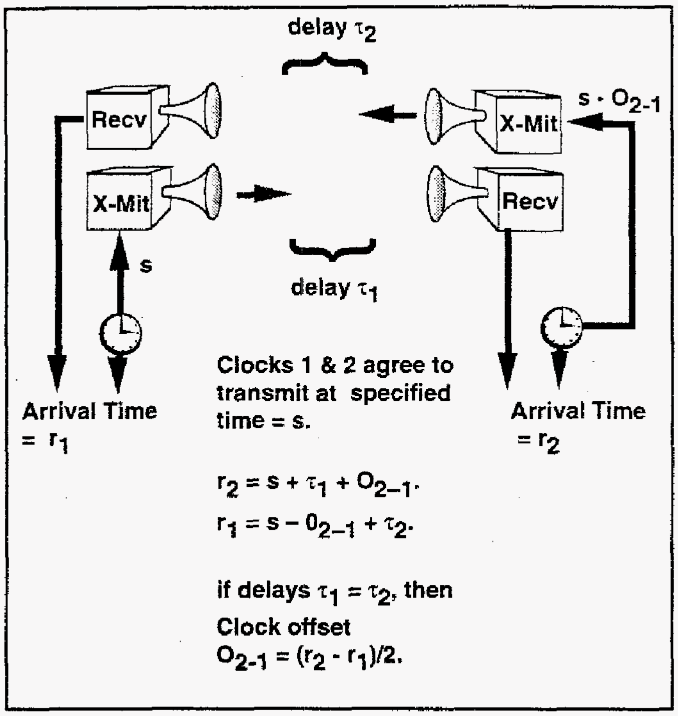


Fig. 2. Clock offset determination between 2 AFF sensors.

4. THE ST-3/STARLIGHT DEEP SPACE INTERFEROMETRY MISSION

As part of NASA's Origin Program the ST-3/StarLight mission (StarLight is the new name of the mission, which was previously known as the New Millennium Program's Space Technology-3) will send two spacecraft to a heliocentric orbit in 2006. The spacecraft will fly in formation for a period of 3 months to demonstrate various elements of technology required for space interferometry. One of the mission goals is to validate the AFF technology to a level that enables future separated spacecraft missions, such as Terrestrial Planet Finder (TPF). The two spacecraft, to be labeled "Collector" and "Combiner", will make simultaneous observations of galactic optical sources with varying baseline length and orientation. The signals collected at the Collector will be mirror reflected to the Combiner where interferometric fringes will be detected and tracked, and interferometric delay derived. The fringe amplitudes will in turn yield the structure and size of the source being observed. Interferometric fringes are detected when the total signals observed at the Collector and the Combiner have identical total delays as they are compared at the Combiner. Fixed and variable delay lines over a finite range will be used to maintain the zero differential delay. To minimize the differential delay variation, the two spacecraft will fly in controlled formation. The Collector will move along a parabola whose axis is along the line-of-sight of the optical source to be observed, while the Combiner will stay at the focus, as shown in Figure 3. The inter-spacecraft distance will be configured so that the baseline will vary between 40 and 200 m in length. The formation will also rotate with respect to the parabola axis to vary the baseline orientation, thus mapping out a 2-dimensional U-V plane coverage. Both spacecraft will maintain the same orientation (attitude) while making interferometric observations.

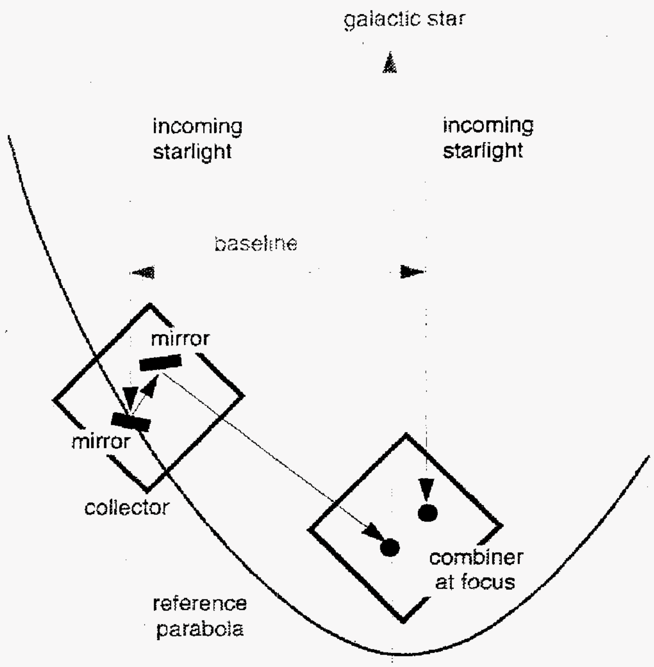


Fig. 3. ST-3 Formation

The separation between StarLight's two spacecraft will vary from 50 to 1010 meters. Three receiving antennas and one transmitting antenna will be installed at the four corners on one side of the nearly cubical body of each ST-3 spacecraft. In addition, a receiving and a transmitting antennas will be installed on the opposite side of the cube to assure contact between the two spacecraft regardless of each spacecraft's individual orientation. Under the normal observing condition, the sides with multiple receiving antennas will be facing each other, although at a slant angle in general. At any epoch, six pairs of pseudorange and carrier phase measurements can be acquired, as depicted in Figure 4, for the determination of the inter- spacecraft distance and their relative bearing angles [3]. The clock offset can also be determined from the dual one-way pseudorange measurements and isolated from the distance and angle determination. At the Ka-band frequency, the expected data qualities are 1 cm for pseudorange and 10 μm for carrier phase measurements at 1-sec interval.

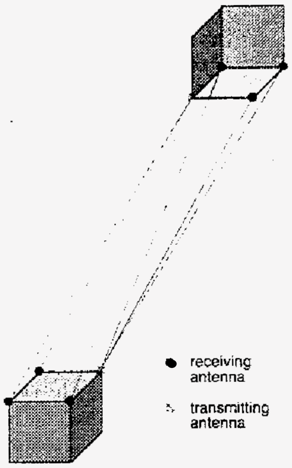
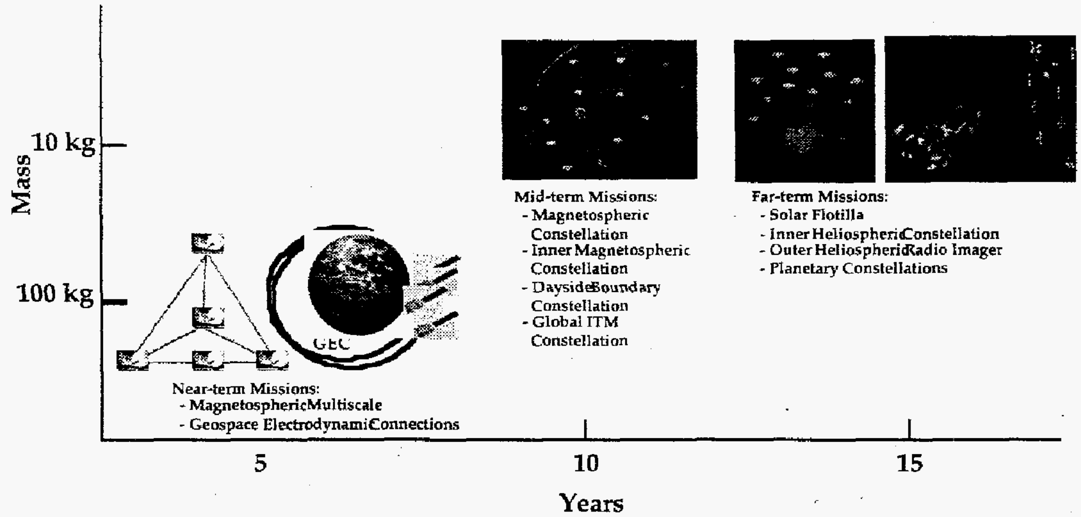


Fig. 4. ST-3 AFF radiometric measurements

5. THE ST-5 NANOSATELLITE CONSTELLATION TRAILBLAZER MISSION

NASA New Millennium Program's ST-5 Nanosatellite Constellation Trailblazer mission is a three-satellite constellation, slated for launch into a GTO in late 2003. ST-5 is a technology validation mission intended to validate breakthrough nanosatellite and constellation technologies that are needed for future missions in the NASA's Sun-Earth Connection (SEC) science theme. To characterize the dynamic solar electromagnetic fields and particle environment, simultaneous in-situ measurements are necessary. The current SEC science roadmap lists several "constellation class" missions either in development or envisioned for the future. The earliest of these, Magnetosphere Multi-Scale (MMS) will deploy five spacecraft weighing about 100-kg each into a highly elliptical Earth orbit (HEO). The development cost per spacecraft for MMS is about $16 million. Future constellation missions would involve many more spacecraft as shown in figure 5. For example, the planned Magentosphere Constellation (MagCon) mission would involve about 100 nanospacecraft weighing about 10-kg each and deployed in several HEO orbits. A significant reduction in both development and operations cost over MMS will be needed. For future constellation missions like MagCon to be economically affordable, the per spacecraft cost must be on the order of $0.5 million. NCT will validate spacecraft and constellation technologies to enable future missions involving large numbers of very small spacecraft.

SEC Roadmap Constellation Missions



- **Revolutionize the multi-point remote and in-situ scientific investigations of key physical processes in the SEC Theme by creating new generations of high performance, integrated spacecraft observatories which are dramatically lighter, compact, and cost-effective.**

Fig. 5. Sun-Earth Connection roadmap for constellation class missions

ST-5 will develop, deploy and operate three full function 20-kg class spacecraft with three principle goals:

1) The design development, integration, and operation of a full service 20-kg class spacecraft though the use of multiple new technologies.
2) The ability to achieve accurate research quality measurements using this class of spacecraft.
3) The design, development, and operation of multiple spacecraft to act as a single constellation rather than as individual elements.

The three spacecraft will be deployed into a geosynchronous transfer orbit with 200 km perigee (figure 6). After forming the initial configuration the spacecraft will be allowed to drift, resulting in inter-spacecraft ranges that vary from 100 km to 5000 km. These spacecraft will be spin stabilized and provide spacecraft functions of propulsion, navigation, attitude control, command and data handling, and high-rate communications (X-Band) to the ground typically found in much larger spacecraft. In addition, constellation management capabilities such as relative navigation, cross platform communications, and autonomy will enable affordable constellation operation.

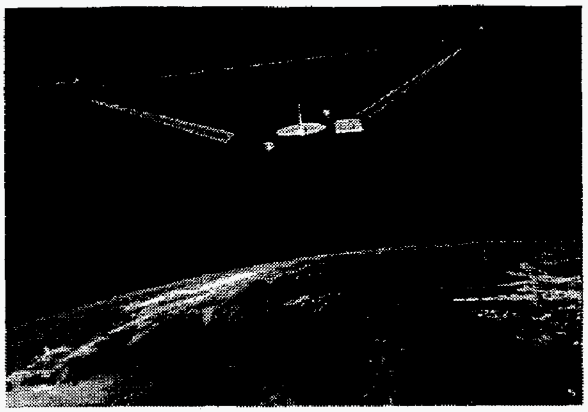


Fig. 6. Artist rendition of the ST-5 constellation.

Miniature instruments, nominally a vector magnetometer and an energetic particle detector, would serve to validate the platform and operational concept suitability for future science measurements. ST-5 will demonstrate the ability for one spacecraft to adjust the data acquisition strategy of its companion spacecraft. This will provide the foundation for multiple platforms to act as if it were a single instrument. The three spacecraft would be launched together as a secondary payload into a Geosynchronous Transfer Orbit. Each spacecraft will initially adjust their orbit using onboard miniature cold gas thrusters.

Each spacecraft will carry the JPL-provided Constellation Communications and Navigation Transceiver (CCNT). The CCNT is a multi-function payload that provides for inter-constellation ranging, communications, and GPS-based absolute positioning. The CCNT is based on the fundamental AFF architecture for inter-spacecraft ranging capability, but it also exploits the AFF's built-in ability for communications that stems from the need to generate and interpret the pseudo random noise (PRN) code. The CCNT also integrates a GPS receiver capability primarily for the purpose of validating the crosslink ranges, but also to provide for time synchronization and autonomous orbit determination. The CCNT will be capable of GPS-based autonomous orbit determination of each spacecraft, as well as of autonomous constellation state determination using a combination of GPS and crosslink measurements. The main challenges for the CCNT are to provide this multiple functionality under very tight mass, power and size constraints, compatible with nanosatellite technology. Specifically, the CCNT will have the following physical specifications:
Mass: 1.5 kg
Power: 1 W transmit, 12 W peak
Size: $18x8x16\ cm^3$

The CCNT is dissimilar to the ST-3 implementation of the AFF is several important areas. The CCNT is using a single S-band antenna (ST-3 is using Ka-band) to transmit and receive, and hence it is not required to perform differential phase measurements and to provide bearing angles. ST-5's radio metric measurements include 1-way and 2-way Doppler, as well as 1-way and 2-way phase and range. The accuracy requirements for the CCNT are much looser than those for ST-3: only 1 m ranging. But the transmit power limitation coupled with the long inter-constellation ranges make it a challenging requirement nonetheless. On the other hand, CCNT has additional requirements stemming from it communications function. For example, it is required to transfer certain messages between spacecraft (science event alerts) with less than 1 second latency, and data rate is specified at 1Kb/sec at 1000 km range.

Another unique challenge for the CCNT is posed by the three spacecraft configuration, and the need to provide for three-way communications and ranging without self jamming. Our solution is to use a two-frequency scheme coupled with a "star" architechture. In this scheme the spacecraft at the center of the star (the Master spacecraft) transmits on f_t and receives on f_r. The other spacecrarft (the Slaves) transmit on f_r and receive on f_t (Figure 7). This architechture does not allow for simultaneous links between all spacecraft, but the Master role can rotate among all spacecraft, eventually providing for crosslinks between all pairs of spacecraft. Simplicity and scalability to arbitrary size constellations are the main advantages of this architechture.

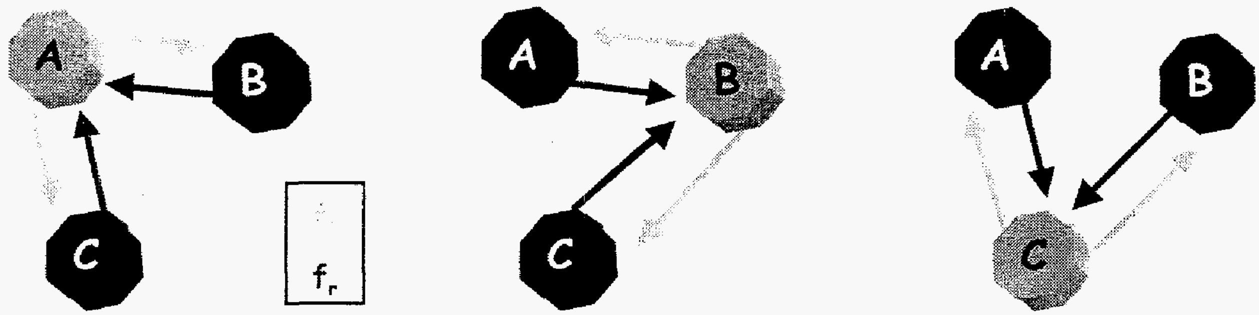


Fig. 7. The revolving master-slave architecture for ST-5 inter-constellation crosslinks.

6. REFERENCES

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2. Thomas, J. B., "Signal-Processing Theory for the TurboRogue Receiver", JPL Publication 95-6.

3. Wu, S-C, and Kuang, D.X., "Positioning with Autonomous Formation Flyer (AFF) on Space Technology 3", Proc of the Institute of Navigation International Technical Meeting, Nashville, TN, Sept. 1999.

ACKNOLEDGMENT

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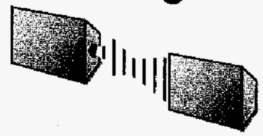
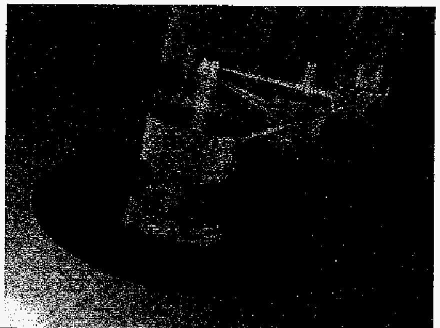
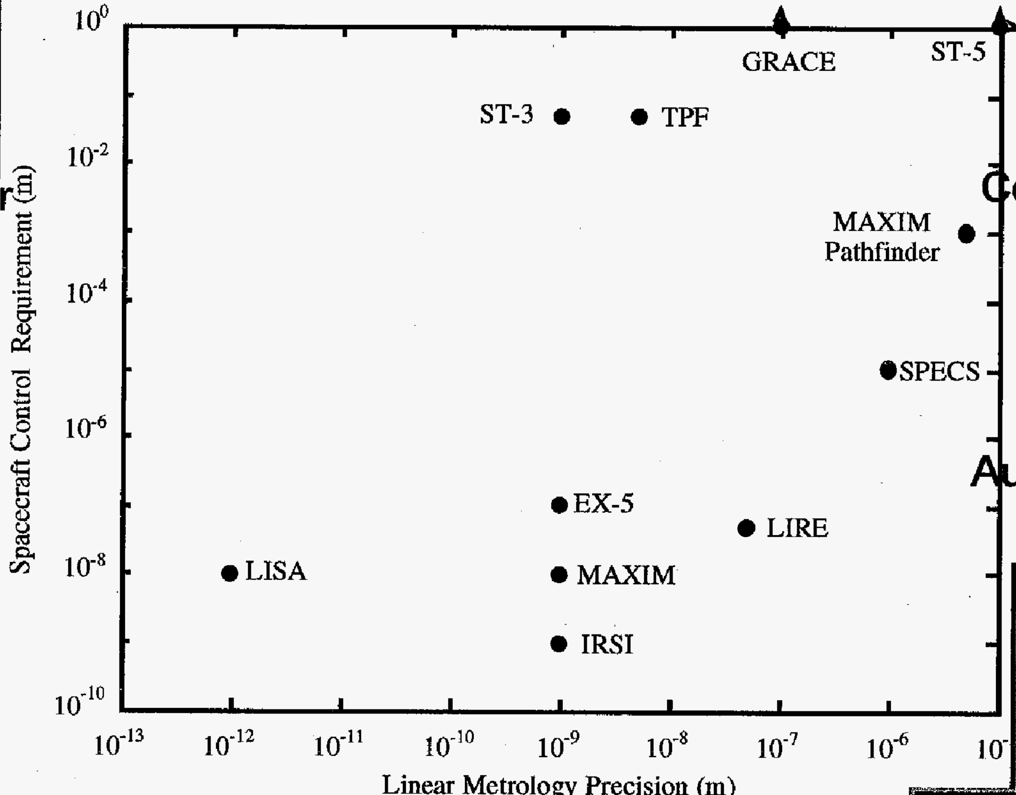
Formations Requirement Spectrum

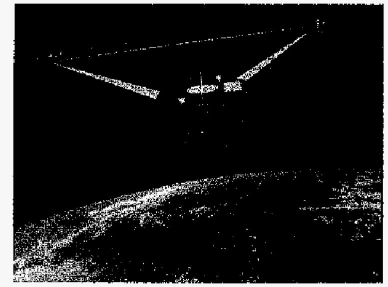
Gravity Recovery and Atmospheric Change Experiment (GRACE)





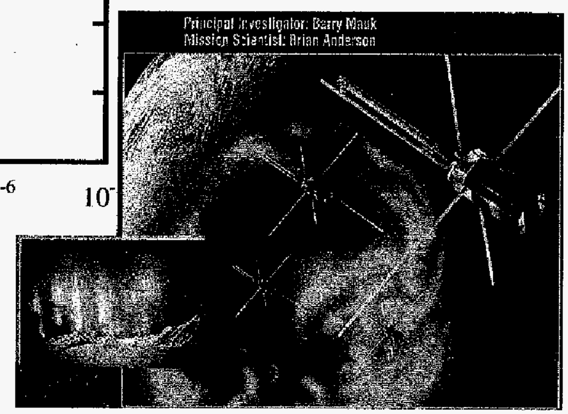
Terrestrial Planet Finder (TPF)

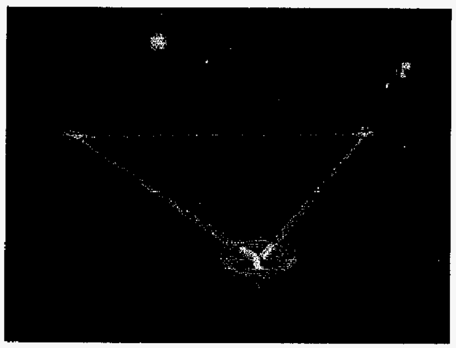




ST-5 Nanosatellite Constellation Trailblazer

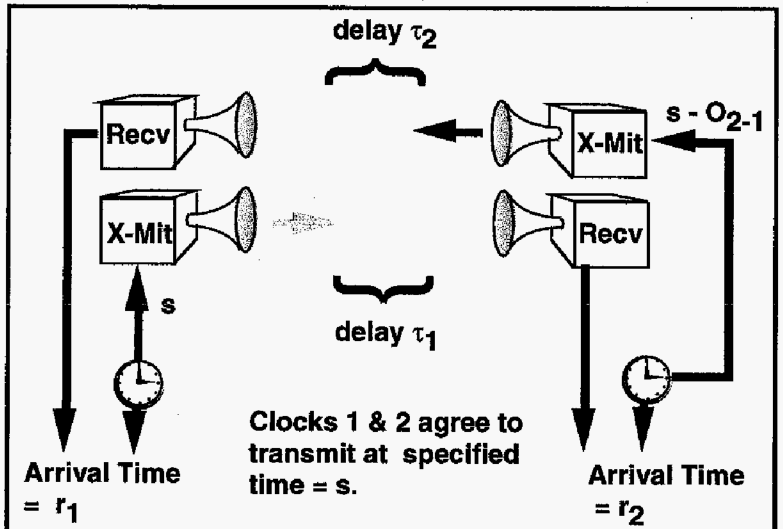
Auroral Multiscale Midex (AMM)





Laser Interferometer Space Antenna (LISA)

Two transceivers exchanging 1-way GPS-like signals

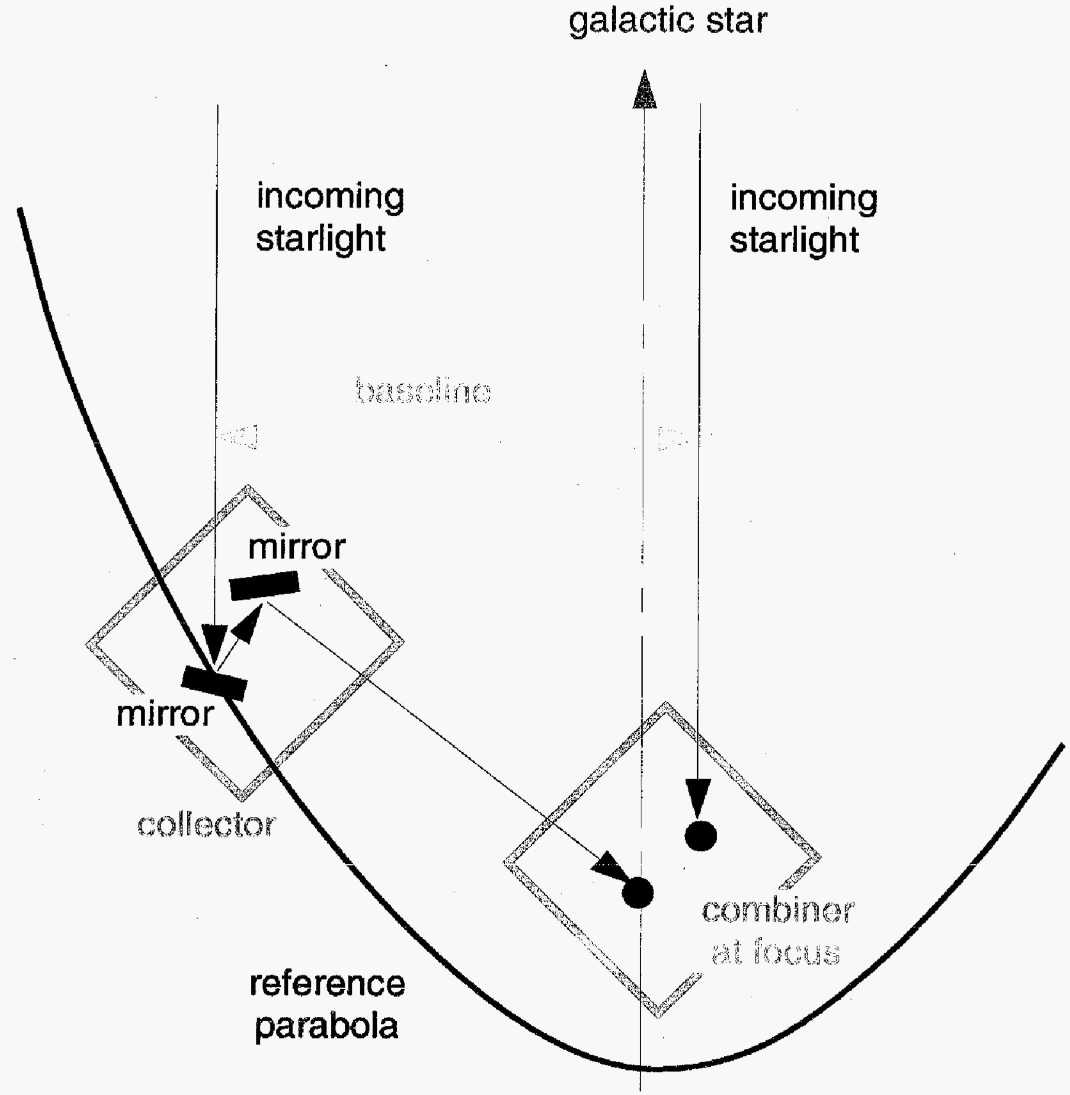


$r_2 = s + \tau_1 + O_{2-1}$.

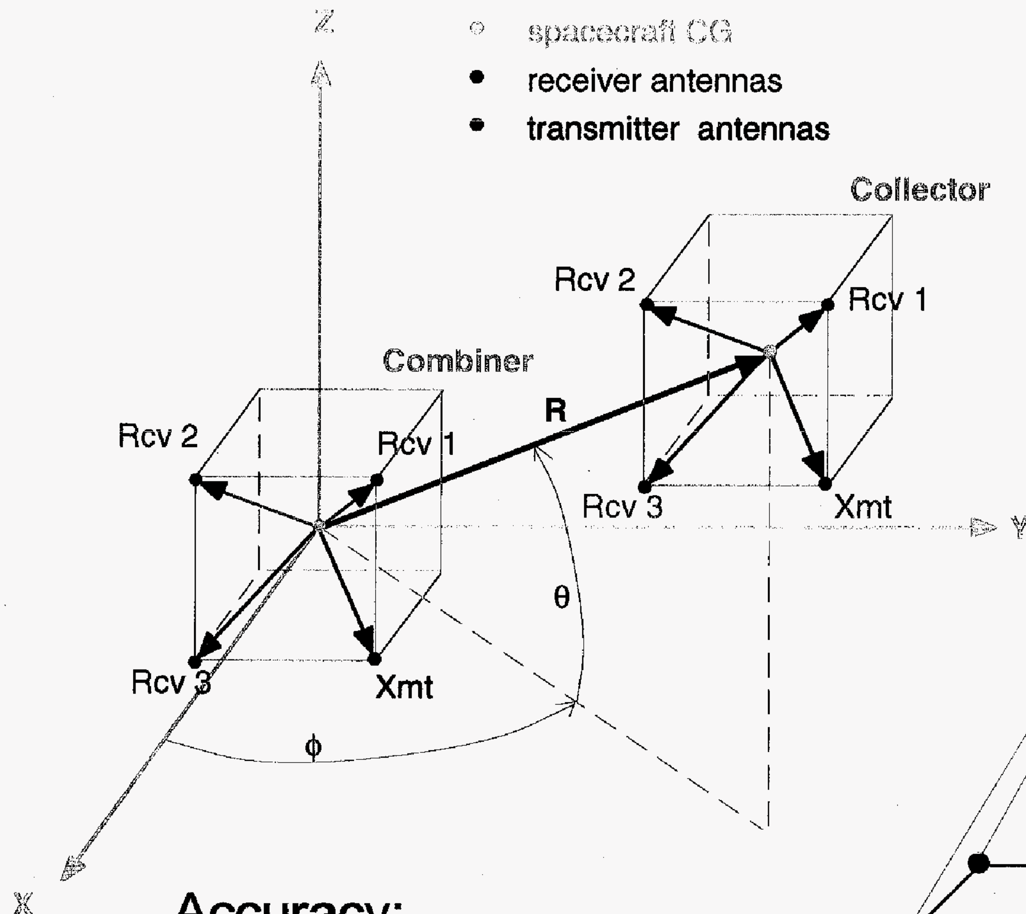
$r_1 = s - 0_{2-1} + \tau_2$.

if delays $\tau_1 = \tau_2$, then
Clock offset
$O_{2\text{-}1} = (r_2 - r_1)/2$.

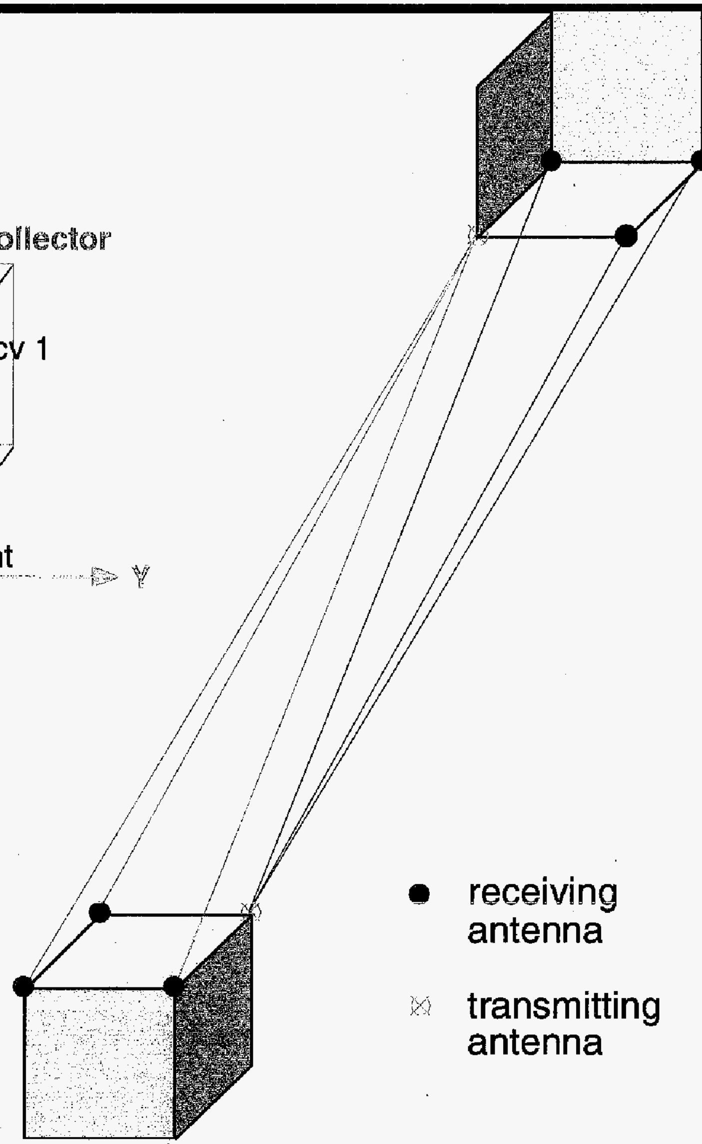
The ST-3/StarLight Space Interferometer Mission



AFF Implementation of ST-3/StarLight



Accuracy:
1 μm range
1 arcsec bearing



The ST-5 Nanosatellite Constellation Trailblazer Mission

Miniature Spacecraft

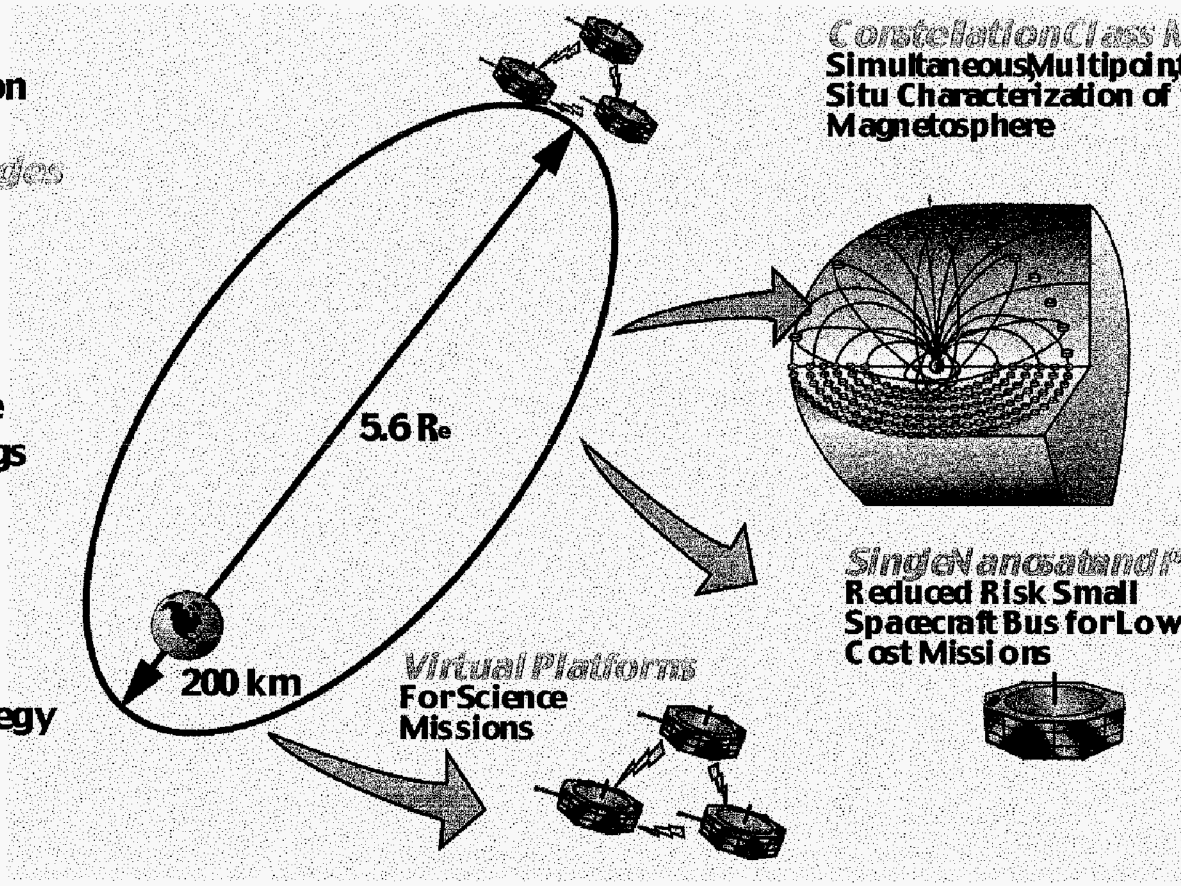
- Systems Design Integration and Test Technologies

Candidate Spacecraft Technologies

- 5V – 1/4V logic
- Li-Ion batteries
- Miniature transponder
- Miniature Thrusters
- Multi-functional structure
- Variable emittance coatings

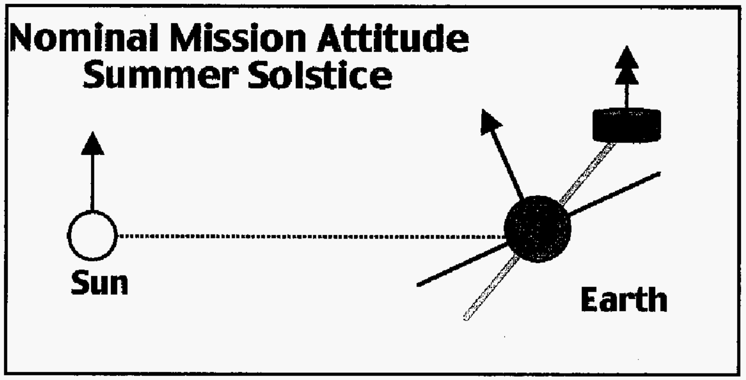
Constellation Control, Coordination, and Operations Architecture

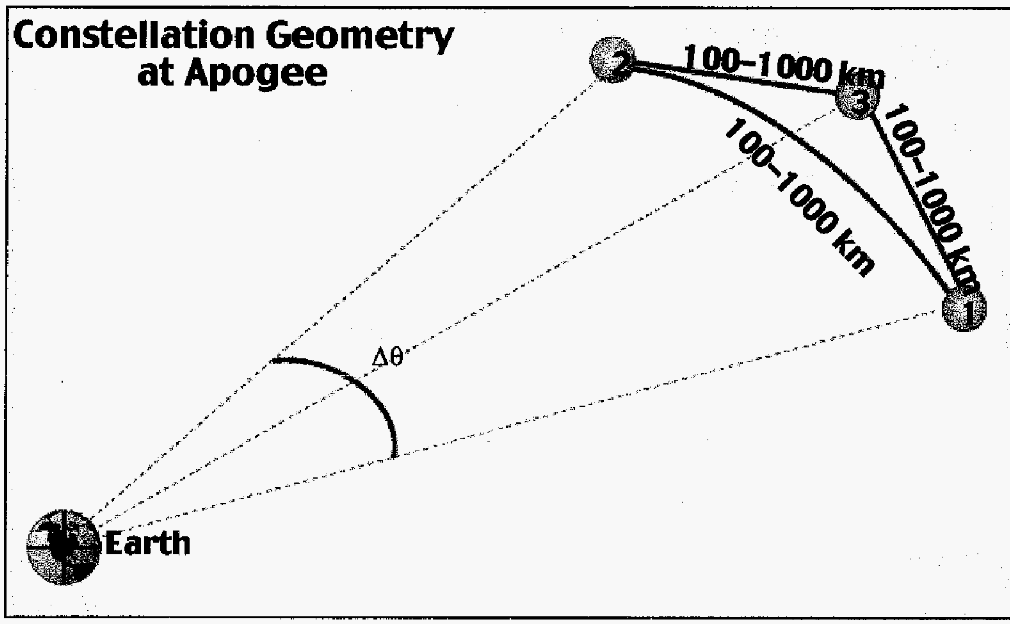
- Ground system autonomy
- Relative ranging
- Telecommunications strategy

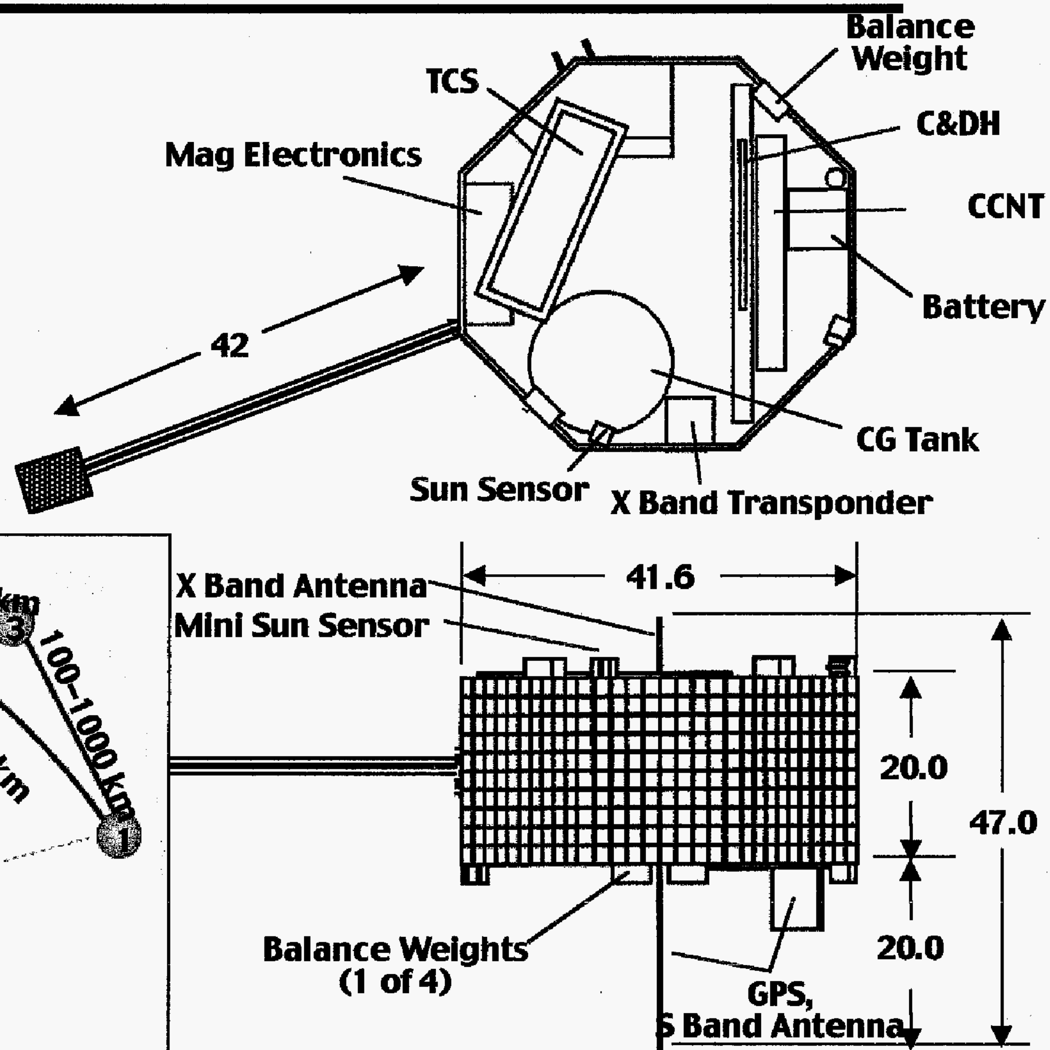


TECHNOLOGY **VALIDATION** **INFUSION**

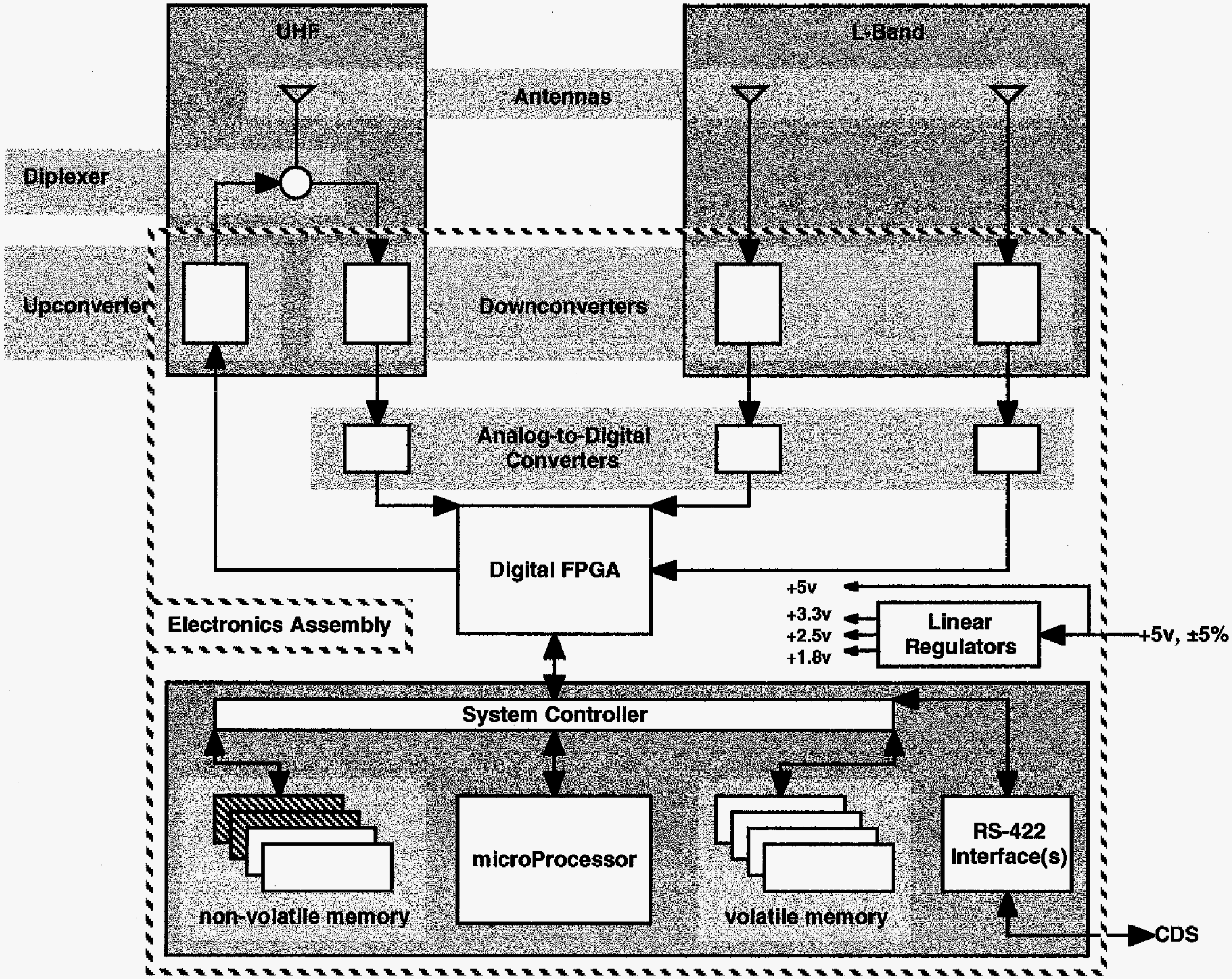
The ST-5 Nanosatellite Constellation Trailblazer Mission



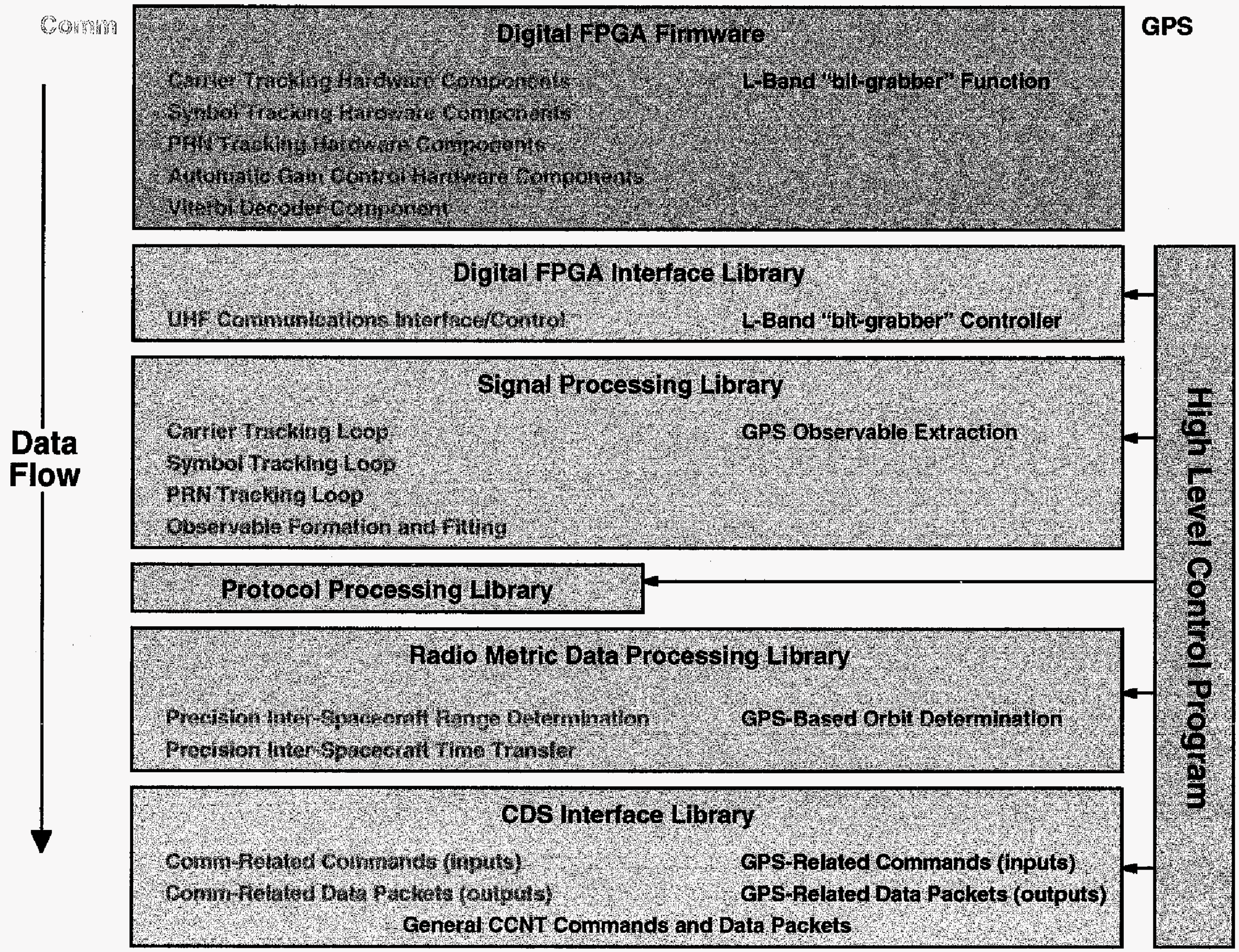




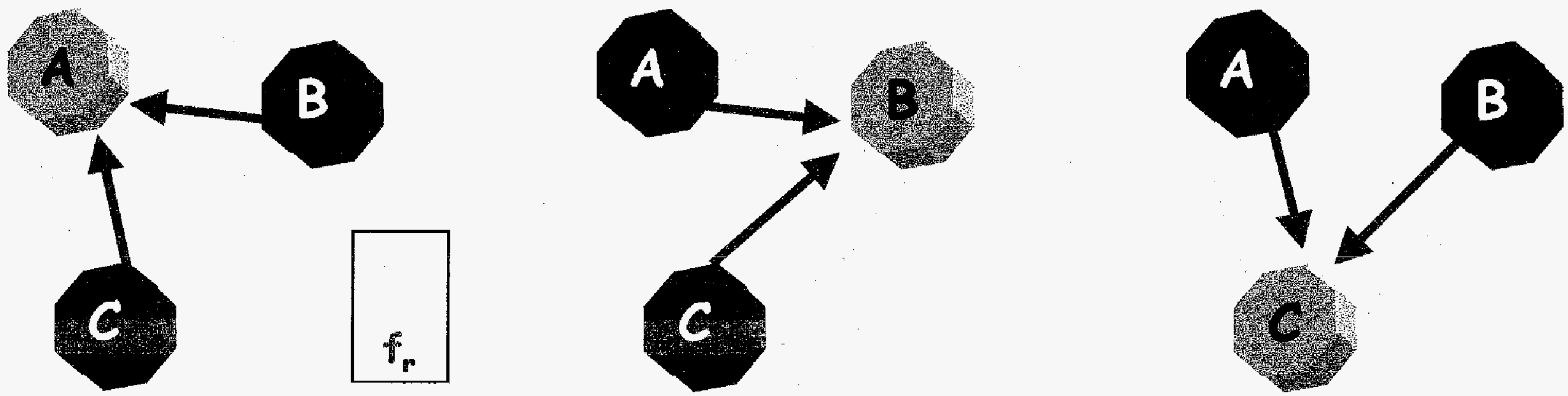
Constellation Communications and Navigation Transceiver (CCNT)



CCNT Software Functional Block Diagram



Fully Redundant Ranging Pass



Range Pass 1:
$R1_{AB}$, $R1_{BA}$, $R1_{AC}$, $R1_{CA}$

Range Pass 2:
$R2_{AB}$, $R2_{BA}$, $R2_{BC}$, $R2_{CB}$

Range Pass 3:
$R3_{AC}$, $R3_{CA}$, $R3_{BC}$, $R3_{CB}$

- Each Pass Simultaneously Produces Four Range Observables
- After 3 Passes, Two Complete Sets Of Observables Are Available