Enabling Spacecraft Formation Flying through Spaceborne GPS and Enhanced Automation Technologies[†]

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Abstract

Formation Flying is quickly revolutionizing the way the space community conducts autonomous science missions around the Earth and in space. This technological revolution will provide new, innovative ways for this community to gather scientific information, share this information between space vehicles and the ground, and expedite the Human exploration of space. Once fully matured, this technology will result in swarms of space vehicles flying as a virtual platform and gathering significantly more and better science data than is possible today. Formation flying will be enabled through the development and deployment of spaceborne differential Global Positioning System (GPS) technology and through innovative spacecraft autonomy techniques. This paper provides an overview of the current status of NASA/DoD/Industry/University partnership to bring Formation Flying technology to the forefront as quickly as possible, the hurdles that need to be overcome to achieve the formation flying vision, and the team's approach to transfer this technology to space. It will also describe some of the formation flying testbeds, such as Orion, that are being developed to demonstrate and validate these innovative GPS sensing and formation control technologies.

Introduction

Earth and Space scientists are just beginning to understand the full potential of space vehicle formation flying. In a few short years, this technology has gone from something that the space community considered an oddity and a very high risk to one that has been fully embraced by Earth and space scientists around the world. Just prior to the selection of the New Millennium Program Earth Orbiter-1 (EO-1) mission in 1996~~the~~ first

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autonomous formation flying Earth science mission—there were only one or two formation flying concepts being considered by NASA. This has changed dramatically. Table 1 depicts the Earth and space mission sets currently being considered by NASA and the Air Force Research Laboratory (AFRL). Clearly, the substantial benefits gleaned from obtaining simultaneous measurements from numerous formation flying vehicles has resulted in a virtual explosion of future Earth and space science mission sets.

A simple analogy can be used to illustrate the fundamental change that occurs in Earth and space science when formation flying is employed. The analogy used is the observation of a football game from two different perspectives. The Earth and space science measurements performed today are comparable to viewing a football game through the perspective provided by still images taken at a very slow rate. Using formation flying technology, the visual perspective and understanding will be radically changed. In the football example, this would be analogous to watching a video of the game using many fixed and/or movable cameras. For the scientists, this new perspective should provide a unique “birds eye view” of the Earth and universe.

For example, the current complement of Earth Science missions perform somewhat infrequent measurements of targeted areas of the Earth using very large, expensive spacecraft platforms (e.g. Landsat-7 which takes 16 days to retrace its ground swath). In the future, swarms of inexpensive miniature space vehicles, flying in formation, will replace these expensive spacecraft platforms. These spacecraft formations will provide continuous measurements of the processes and events effecting the Earth. Space science will also be significantly impacted by formation flying technology. For example, the space science community's ability to understand the events and processes that occur between the Sun and the Earth (the so called Sun-Earth connection) is limited to a just a few spacecraft in various Earth and Heliocentric orbits. A significant improvement in the understanding of the dynamics of the magnetosphere can be accomplished if these spacecraft were replaced by an armada of miniature science probes flying around the Earth and Sun in a loose formation. Significant improvements in space-based interferometery can be accomplished by flying several spacecraft in formation, increasing the number of instruments comprising the system & eliminating the restrictions imposed by the use of physical structures to establish maintain, and control instrument separation and stability. As shown, the benefits of formation flying propagate throughout the entire Space Science Enterprise—Origins, Sun-Earth Connection, Structure and Evolution of the Universe, and Solar System Exploration.

Formation flying will also change the way NASA and the space community conducts the Human Exploration and Development of Space. In the future, autonomous Space Shuttle and Space Station rendezvous and docking using GPS-based formation flying will become commonplace. Very low cost scientific payloads, such as Spartan, will be deployed from Space Station, fly in formation, and autonomously return for eventual retrieval. In the future, aerobots, autonomous balloon systems flying in formation using GPS-like navigation sensing will be conducting scientific investigations around the planet Mars (figure 1).

It is clear that formation flying will result in a fundamental change in the way science measurements will be conducted from space. The mission sets already on the drawing boards at NASA and the DoD span the whole spectrum of formation flying performance requirements, from 2-3 spacecraft in a loose formation to tens or hundreds of tightly controlled spacecraft flying in an armada. Some missions, such as the Mag Constellation mission, figure 2, will require very loose (1-100 km) formation knowledge and control. On the other end of the spectrum, space science interferometry missions, planet finders (figure 3) and relativity missions will require micro-meter and, in some cases, pico-meter knowledge and control. These differing mission sets require an entire spectrum of sensing, controlling and actuation capabilities to satisfy these varied requirements challenges.

Figure 1: Mars Aerobots

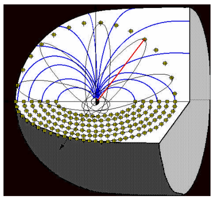


Fig. 2: Mag Constellation

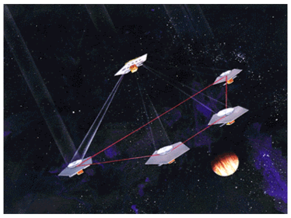


Fig. 3: Planet Finder

Developing the technology to produce virtual platforms will be a long-range challenge. Similar to GPS technology [1], there are several technological “stairsteps” that must be overcome to go from autonomous navigation and constellation control to one and two-way formation flying and finally to virtual platforms.

Table 1: Representative List of Satellite Missions Utilizing Formation Flying Techniques

Projected Launch Year	Mission Name	Mission Type
99	New Millennium Program (NMP) EO-1	Earth Science
01	University Nanosats/Air Force Research Laboratory	Technology Demonstrator
01	Gravity Recovery and Climate Recovery (GRACE)	Earth Science
01	MightySat/Orion/Orion Jr.	Technology Demonstrator
02	Auroral Multiscale Mission (AMM)/APL (MIDEX)	Space Science/SEC
02	Lightweight Synthetic Aperture Radar (LightSAR)	Earth Science
03	New Millennium Program (NMP) ST-3	Space Science/ASO
03	New Millennium Program (NMP) ST-5	Space Science
03	Techsat-21/AFRL	Technology Demo
05	Magnetospheric Multiscale (MMS)	Space Science/SEC
05	Space Interferometry Mission (SIM)	Space Science/ASO
07	Global Precipitation Mission (EOS-9)	Earth Science
07	Geospace Electrodynamic Connections (GEC)	Space Science/SEC
08	Constellation-X	Space Science/SEU
08	Magnetospheric Constellation (MC)	Space Science/SEC
08	Laser Interferometric Space Antenna (LISA)	Space Science/SEU
09	DARWIN Space Infrared Interferometer/European Space Agency	Space Science
11	Terrestrial Planet Finder	Space Science/ASO
	Astronomical Low Frequency Array (ALFA)/Explorers	Space Science
05+	Leonardo (GSFC)	Earth Science
05+	Soil Moisture and Ocean Salinity Observing Mission (EX-4)	Earth Science
05+	Time-Dependent Gravity Field Mapping Mission (EX-5)	Earth Science
05+	Vegetation Recovery Mission (EX-6)	Earth Science
05+	Cold Land Processes Research Mission (EX-7)	Earth Science
05++	Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)	Space Science/SEU
15+	MAXIM X-ray Interferometry Mission	Space Science/SEU
15+	Solar Flotilla, IHC, OHRM, OHRI, ITM, IMC, DSB Con	Space Science/SEC
15+	NASA Goddard Space Flight Center Earth Sciences Vision	Earth Science
15+	NASA Institute of Advanced Concepts/Very Large Optics for the Study	Space Science
15+	NASA Institute of Advanced Concepts /Ultra-high Throughput X-Ray	Space Science
15+	NASA Institute of Advanced Concepts /Structureless Extremely Large Yet Very Lightweight Swarm Array Space Telescope	Space Science

Notes: ASO-Astronomical Search for Origins, SEC-Sun Earth Connections, SSE-Solar System Exploration, SEU- structure and Evolution of the Universe

Figure 4 depicts the planned evolution of formation flying technology from its current state to the achievement of virtual platforms. Precisely, a virtual platform is defined as the collective, coordinated operation of multiple spacecraft that are oriented and positioned to achieve pre-defined mission objectives.

A distinction must be made between formation flying and constellation control. NASA is focusing on the control of multiple, cooperating satellites in autonomous formations that operate together to accomplish a variety of science objectives. Therefore, formation flying typically involves active, real-time, closed-loop control of these satellites in the formation. Formation flying can also be characterized as a combination of multiple assets, that is, space vehicles, sub-orbital balloons and surface robots, all operating autonomously together. Constellation control typically does not require this level of autonomy or real-time coordination. However, several subsystems, such as the satellite cross-link communications and data transfer are critical to both constellations and formations.

Formation Flying: From a Dream to Reality

Converting this formation flying vision into a real product is a formidable task, and both NASA and the Air Force Research Laboratory (AFRL) are leading several

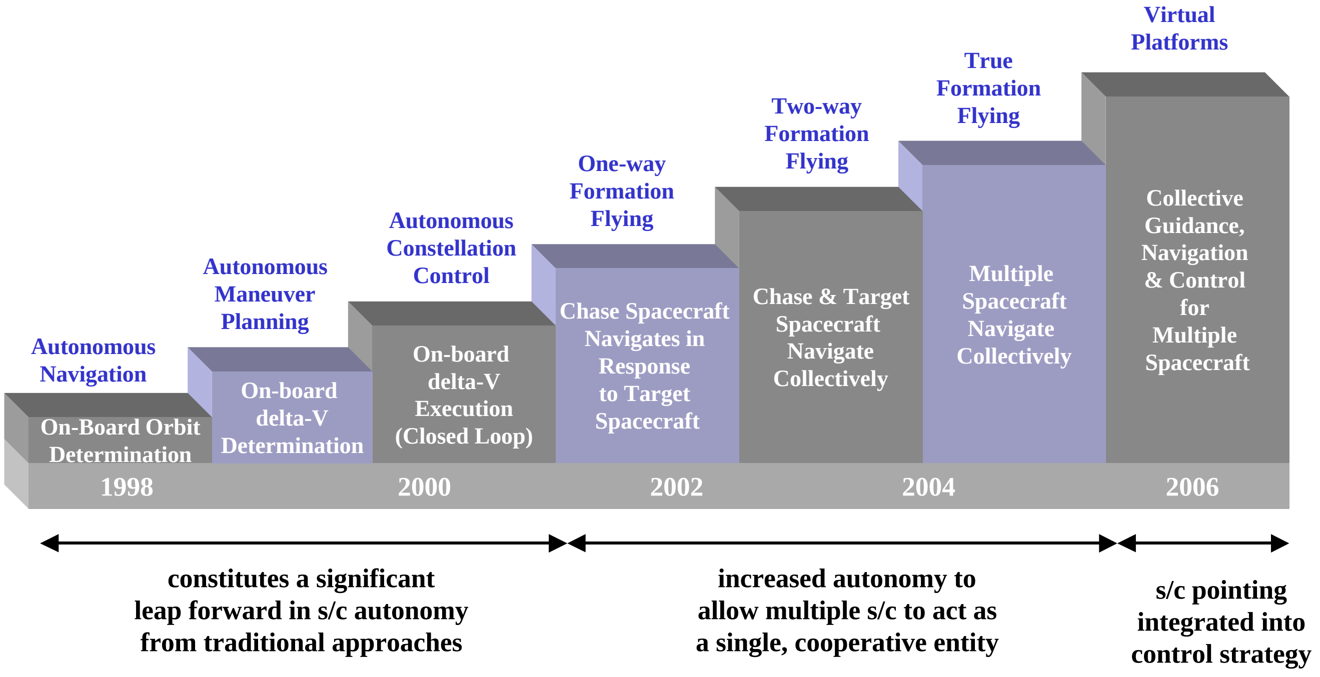


Table 4: Formation Flying & Virtual Platforms Technology “

government-university-contractor teams to make this happen. Some of the leading researchers that comprise this team are from the Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), AFRL, the Naval Research Laboratory (NRL), the Johns Hopkins University Applied Physics Laboratory (APL), Stanford University, Massachusetts Institute of Technology, University of California Los Angeles, and Space Products and Applications (SPA), Incorporated.

NASA’s primary focus for formation flying technology is through the “Distributed Spacecraft” thrust area of the Cross Enterprise Technology Development Program (CETDP). The research within this thrust area is focused on the collaborative behavior of multiple space vehicles that form a distributed network of individual vehicles acting as a single functional unit while exhibiting a common system-wide capability to accomplish various mission goals. A combined Government-University-Industry team has identified 6 formation flying technology focus areas that require further research to reach the goals of future missions. These technology focus areas, shown in figure 5, include:

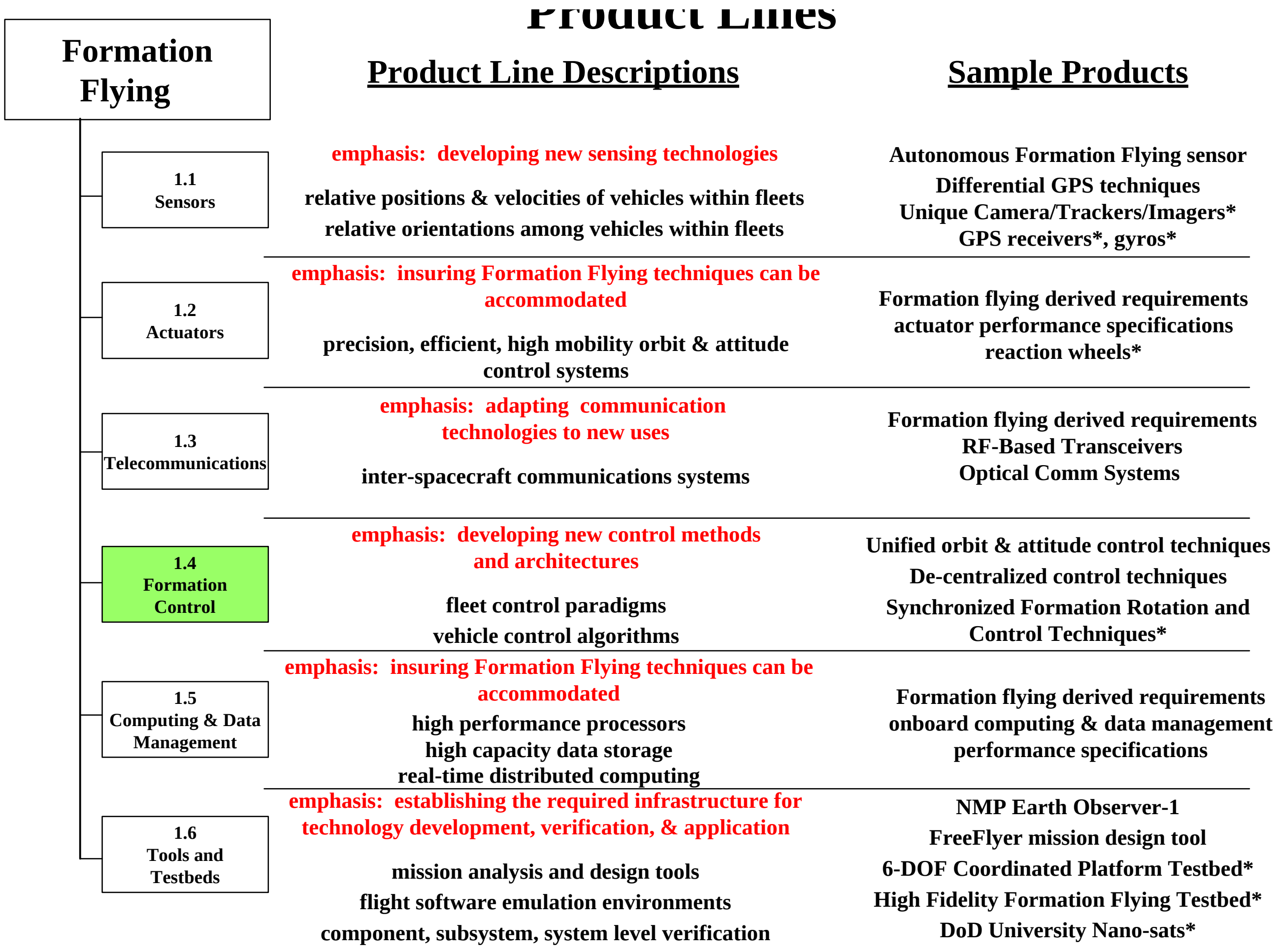
1) Sensor development
2) Actuator development
3) Telecommunications–inter-spacecraft communication
4) Formation Control Strategies
5) Computing and Data Management, and
6) Tools & Testbeds

As figure 5 depicts, the sensor development and telecommunications focus areas rely very heavily on GPS-based systems. The development and deployment of robust GPS systems (focus 1) to sense absolute and relative navigation is critical to enable autonomous formation flying to occur. These receiver systems are being modified to also transmit formation control data to the virtual platform–providing a telecommunications capability (focus 3) to the formation. Embedded in these transceivers and in the discrete formation space vehicles are the computers (focus 5) and the autonomous formation control algorithms (focus 4) that process the sensor data and issue formation control commands to the fleet. The vehicle actuators (focus 2) then reposition and reorient (attitude & navigation) the vehicles in the formation based on the above control commands to achieve the mission requirements.

Validating the performance and capabilities of these new formation flying technologies will be very challenging. Thus a complement of tools in concert with ground and on-orbit testbeds (focus 6) are being developed to minimize risk and reduce research costs. The rest of this paper describes these six focus areas in more detail, including the current status of each of these and the future directions.

Focus Area 1: Sensors

The ability to determine and control the relative positions, orientations, and their respective velocities for a vehicle



Product Lines

Formation Flying	Product Line Descriptions	Sample Products
1.1 Sensors	emphasis: developing new sensing technologies relative positions & velocities of vehicles within fleets relative orientations among vehicles within fleets	Autonomous Formation Flying sensor Differential GPS techniques Unique Camera/Trackers/Imagers* GPS receivers*, gyros*
1.2 Actuators	emphasis: insuring Formation Flying techniques can be accommodated precision, efficient, high mobility orbit & attitude control systems	Formation flying derived requirements actuator performance specifications reaction wheels*
1.3 Telecommunications	emphasis: adapting communication technologies to new uses inter-spacecraft communications systems	Formation flying derived requirements RF-Based Transceivers Optical Comm Systems
1.4 Formation Control	emphasis: developing new control methods and architectures fleet control paradigms vehicle control algorithms	Unified orbit & attitude control techniques De-centralized control techniques Synchronized Formation Rotation and Control Techniques*
1.5 Computing & Data Management	emphasis: insuring Formation Flying techniques can be accommodated high performance processors high capacity data storage real-time distributed computing	Formation flying derived requirements onboard computing & data management performance specifications
1.6 Tools and Testbeds	emphasis: establishing the required infrastructure for technology development, verification, & application mission analysis and design tools flight software emulation environments component, subsystem, system level verification	NMP Earth Observer-1 FreeFlyer mission design tool 6-DOF Coordinated Platform Testbed* High Fidelity Formation Flying Testbed* DoD University Nano-sats*

Figure 5: Formation Flying Focus Areas

or fleet of vehicles is only as effective as the sensors that are on-board these vehicles. To this end, the formation flying team is emphasizing the development of new relative and absolute sensing techniques.

Spaceborne GPS**—**For formation flying, the capstone position and timing sensor technology is spaceborne GPS. Several teams, including NASA GSFC, APL, and JPL, are working with university and industry partners to move this technology to the forefront [1]. As described in [1], it will take three generations of receiver developments to achieve the GPS (transmit/receive) space vehicle crosslink sensor that is needed for future formation flying missions. When this third generation GPS receiver is coupled with autonomous on-board maneuver planning and orbit control software, and formation control algorithms, formation flying becomes feasible.

In addition to relative and absolute positioning, GPS provides low cost, spacecraft timing systems, vehicle attitude determination and attitude control, and autonomous data transmissions over ground stations. Miniaturized copies of a GPS receiver can also serve as the heart of an autonomous formation flying micro-sciencecraft providing attitude and orbit sensing, attitude commanding, orbit control, command and data handling services, formation control transmission and reception and science instrument timing all in one package.

VISNAV**—**Many formation flying missions, in particular, interferometry missions, rely on high precision relative position and attitude knowledge. Although GPS can provide this capability near Earth, deep space missions must rely on other technologies. One of these alternative technologies is the vision-based navigation (VISNAV) system under development by Texas A&M University. VISNAV comprises an optical sensor of a new kind combined with specific light sources (beacons) in order to achieve a selective or “intelligent”vision. The sensor is made up of a Position Sensing Diode (PSD) placed in the focal plane of a wide-angle lens. When the rectangular silicon area of the PSD is illuminated by the energy from a beacon, it generates electrical currents that are processed to determine position coordinates. The concept of intelligent vision is that the PSD can be used to see only specific light sources or beacons. The light sources can be at the end of a deployed boom of a single spacecraft for determining alignment, or on other spacecraft in a formation to determine position and attitude.

***Attitude Sensing*—**If formation flying technologists are going to achieve the concept of virtual platforms, as shown in figure 4, a set of absolute and relative attitude sensing devices are needed. Very precise, autonomous star tracking and gyro systems are needed to support the requirements demanded from formation flying missions such as the interferometry and relativity missions. In addition, developing fleets of very low cost spacecraft will require inexpensive, miniaturized attitude sensors such as microgyros, and low weight, low power attitude tracking devices. To this end, the CETDP Distributed Spacecraft thrust area is teaming up with the Nanosat thrust area to ensure these sensors are available for formation flying missions of the future.

Focus Area 2: Actuators

The ability to redirect specific spacecraft as well as the entire formation in translation and rotation is contingent upon the installation of adequately sized attitude and trajectory actuators. From an attitude perspective, these are usually reaction wheels and thrusters. From a trajectory perspective, this is primarily thrusters. Formation control puts high demands on these spacecraft actuators. New technologies are necessary to ensure sufficient resources are available onboard to maintain the formation. These technologies must support higher pointing constraints, provide greater precision thrust capability and significantly improve use of propellant expendables since a greater maneuvering frequency is expected to maintain precision relative positioning.

Several initiatives are underway to develop actuators to enable very low cost formation flying. This activity is being sponsored by both the Distributed Spacecraft Control and the Nanosat thrust areas in NASA and by AFRLš TechSat 21 program. Of particular interest are micro-reaction wheels and micro-thrusters. These are needed to support very small micro and nanosatellites as well the extremely fine pointing needed to achieve the requirements for formation flying missions such as planet finder, interferometry, synthetic aperture radar, and relativity. In NASA, micro-thruster research is being conducted at GSFC in the Guidance, Navigation and Control Center to support future formation flying testbeds such as ST-5 and Orion. At AFRL as at GSFC, a great deal of effort is being spent on Micro-Electro-Mechanical Systems (MEMS), pulse plasma and colloid thrusters.

NASA GSFC is sponsoring the development of a Pulse Plasma Thruster (PPT) as an experimental technology for the New Millennium Program (NMP) Earth Orbiter-1 (EO-1). The PPT uses solid Teflon propellant and is capable of delivering high specific impulse (900-1200 sec), very low impulse bits (10-1000uN-s) at low average power (<1 to 100W).

Colloid microthrusters (with thrust in the milli-Newton range) are a promising new technology in the field of small spacecraft propulsion. Because of their small size and low weight these devices are particularly interesting to missions incorporating formation flying and nanosatellites. Colloid thrusters work by accelerating charge particles using an electrostatic field. For propellant, the thrusters use a conductive liquid that is typically doped with salt to increase charge carrying capacity. The liquid is channeled through a tiny orifice. At the back opening of the orifice, a high electrostatic field is applied causing imbalance of surface forces that caused the liquid to breakdown to small charged droplets. The same electrostatic field then accelerates these droplets, thus creating thrust.

Current research, based at the Stanford Plasma Dynamics Laboratory (PDL), aims to better understand the working mechanism of colloid thrusters, and to develop an integrated, micro-electro-mechanically based colloid thruster for space propulsion. To enable small-scale position control, these thrusters can supply vectored thrust on the order of 0.11 milli-Newtons, and have a specific impulse of approximately 1000 seconds. The Stanford University thrusters are scheduled to fly on Stanford/Santa Clara Emerald formation under the AFRL University nanosatellite program.

Focus Area 3: Telecommunications

Formation Flying cannot be accomplished without an adequate inter-spacecraft communications medium. The specific medium used for formation flying spacecraft is primarily a function of the performance and science data gathering requirements for the mission. Missions requiring low to medium formation knowledge and control (km to cm-level) and nominal data requirements will use Radio Frequency (RF)-based telecommunications capabilities. Currently, researchers are investigating GPS-like transceivers as the primary RF-based formation flying communications medium. Missions requiring high performance formation knowledge and control (sub-cm to picometer) and/or very high data rates (>10 Mbps) will require optical communications methods to support the virtual platform. The current research thrusts in this focus area are described in the following paragraphs.

RF-Based Transceivers

***APL CLT*—**The Applied Physics Laboratory (APL) Cross Link Transceiver (CLT) represents an integrated crosslink communication and relative navigation system for multiple distributed spacecraft flying in formation. [2][3][4][5]. The CLT (figure 6) will support inter-spacecraft communications at a nominal rate of 5-20kbps focused primarily upon the distribution of command and control information. This includes the dissemination of directives for vehicle coordination and well as ancillary data exchange needed to support intelligent control strategies. The nature of the crosslink data is not limited to high-level control directives, indeed lower level control approaches (e.g., decentralized control methodologies that rely upon state vector sharing) are also supported. The data fields for inter-spacecraft communications are generic and protocol dependent, with a nominal, packetized approach that is CCSDS compliant.

A critical aspect of the CLT crosslink communications approach is that it is explicitly designed to support formation flying missions, which require capabilities such as dynamic adaptivity, scalability, and robustness. As such, the CLT is designed to simultaneously receive data from multiple spacecraft and the signal structure is such that it will support a variety of logical command and control architectures (e.g., centralized, hierarchical, fully distributed) by providing a flexible communications infrastructure.

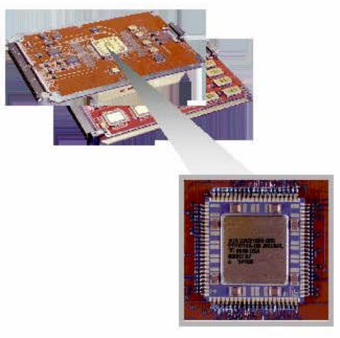


Figure 6: APL CLT

The CLT provides both an absolute and relative navigation solution (position and velocity) and provides precision time recovery and a steered one pulse-per-second output. Orbit determination is provided by reception of GPS signals and processing by an extended Kalman filter. In addition, crosslink signals support relative navigation, with the potential for both direct solutions as well as relative GPS solutions which rely upon the computation of double differences of GPS data in a pairwise manner among spacecraft. Ranging using crosslink pseudorandom noise codes can supplement the GPS measurements in the relative navigation solution to enable more rapid convergence of the solution for low Earth orbit missions. The crosslink ranging data could entirely replace the GPS measurements for highly elliptical or deep space missions. In this case the relative clock error and range can be solved on a per-link basis. The ranges establish the relative geometry of the constellation, subject to an indeterminate rigid-body rotation.

JPL AFF**—**The NASA New Millennium Program (NMP) Space Technology (ST)-3 mission is expected to demonstrate various elements of the technology required for space interferometry, including the Autonomous Formation Flying (AFF) sensor [6], and an autonomous reconfigurable formation control system [7,8].

SPTC**—**The Stanford Pseudolite Transceiver Crosslink (SPTC) is being developed at Stanford University as a relative navigation and communication crosslink system for formation flying spacecraft. The SPTC was designed using COTS devices (modems, L_1 pseudolites, and an attitude-capable GPS receiver). Carrier phase Differential GPS (CDGPS) measurements are used to achieve very precise relative positioning. Using GPS measurements, the SPTC is expected to provide relative position accuracies on the order of 2-5 cm, depending on GPS satellite geometry. Attitude determination to within 0.25 degrees and time transfer between separated vehicles to within 1 microsecond is also expected. The pseudolites within the SPTC are used to enhance the operating range (orbital altitude) of the CDGPS approach and to provide additional GPS measurements (improved geometry) at lower altitudes. For inter-vehicle relative positioning, the pseudolite within the SPTC can be used to obtain relative vehicle range measurements to within 0.5 cm. The onboard pseudolites will also enable the use of CDGPS relative navigation at Geostationary Earth Orbit using only 1-3 GPS satellites. The SPTC system has been tested extensively on the Formation Flying Testbed at Stanford University [9][10]

Stanford Telecom LPT**—**NASA/GSFC and Stanford Telecommunications, Inc. are jointly sponsoring the development of a Low Power Transceiver (LPT). The LPT integrates TDRSS S-band 2-way communications and GPS navigation in a compact flexible package. Once completed, the LPT will reflect substantial reductions in power, size, weight, and cost relative to current transceiver options, and is envisioned to serve as the communications/navigation subsystem for a wide range of space-based science missions. This technology is ideal for formation flying which requires crosslink communications and relative navigation often on small spacecraft with limited power.

Optical Communications & Metrology Systems

JPL Optical Communications**—**At NASA, the Jet Propulsion Laboratory is conducting research in optical communications systems. These systems will provide a significant crosslink and downlink conduit for scientific and formation control data. Moreover, these laser-based systems can also provide very precise information on the relative positioning and orientation of multiple spacecraft in a formation (micrometers and arc-seconds). Using these optical and metrology systems, a "virtual aperture" can be developed using several spacecraft in a tight formation. This technology is crucial for Earth and space science missions that have very precise formation control requirements. These mission sets will most likely use both the RF and optical systems together. The RF system will support coarse formation control. Once the formation is in place, the optical-based fine navigation/pointing system would take over to tighten the formation until it met the mission objectives.

Focus Area 4: Formation Control Strategies

Implementation of distributed coordinating satellite concepts will require tight maintenance and control of the relative distances and orientations of the participating satellites. Thus formation control poses very stringent challenges in the areas of:

1. Onboard sensing of relative and absolute vehicle positions/attitudes,
2. Maneuvering, retargeting, collision avoidance, and aperture optimization including resource/task allocation within the fleet,
3. Modeling the orbital mechanics and the impact of differential drag and solar disturbances,
4. Fleet and vehicle autonomy, including high-level fault detection and recovery to enhance the mission robustness,
5. Decentralized control & computation for a fleet of many (e.g. from 16 to hundreds) vehicles,
6. Testbeds and simulations to validate the various sensing and control concepts.

A ground-based command and control system for relative spacecraft positioning would be very complex, heavily over-burdened, and may not provide sufficiently rapid corrective control commands. Thus, the overall focus of this work is to significantly increase the onboard autonomy of the future spacecraft, thereby reducing the ground support required.

Conceptually, autonomous formation flying is a process in which an array of spacecraft makes continuous measurements of the "array configuration" and uses these measurements to maintain an existing configuration or to smoothly transition to a new one, all without external measurement or control. Generally speaking, the array configuration includes both the distances between all pairs of spacecraft in the array and the orientations of the spacecraft in a coordinate frame defined by the array's internal geometry. From initialization to targeting, then to maneuvering, the formation will experience significant changes in the control requirements. A completely autonomous, configurable control system must be implemented to switch between the various system models and controllers.

Cooperative formation control can take several forms. Typically, for a small number of spacecraft (e.g. less than 16) operating as a formation, a master/slave or a hierarchical control structure could be used. In the master/slave scenario, a single spacecraft acts as a leader and issues commands to the fleet or the fleet reacts to the actions of the leader according to a planned behavior. The hierarchical control divides the formation into subsets. Each subset has its own leader and a small number of "followers." However, for large formations, these types of control carry too much overhead and are impractical. A distributed or decentralized approach is necessary.

Decentralized architectures are non-hierarchical and coordination by a central supervisor is not required. Detected failures would then tend to degrade the system performance gracefully. Each node in the decentralized network processes only it's own measurement data in parallel with all of the others.

One example of the decentralized approach being pursued by NASA/GSFC uses a stand-alone, standard GPS point solution to maintain the spacecraft formation [21]. In this approach, if each of the vehicles transmits and receives data to and from the other vehicles in the formation, relative states can be computed, without the need for direct measurements of the inter-satellite states. This would enhance the accuracy and allow coordination of the formation maneuvers. If sufficient onboard processor capacity is available, the GPS measurement data (*e.g.* pseudo-range, carrier) could be processed for improved accuracy. Ideally, if one or more of the vehicles had the capability to make relative measurements to the other formation members, all available data could be used to maximize the relative navigation accuracy.

The team at Stanford University has experimentally analyzed and demonstrated several estimation architectures (centralized and decentralized) that could be used to perform the differential carrier-phase GPS relative sensing for a large fleet of vehicles [32,33,34]. They have also demonstrated a multi-level fleet control system that includes a coordinator, a planner, and distributed regulators using a fully nonlinear orbital simulation. A linear programming approach is used to rapidly solve for the optimal formation maneuvers using the linearized group dynamics (both LEO and deep space) [30]. This same control architecture has been experimentally demonstrated on the Formation Flying Testbed at Stanford [31]. The team is also designing autonomous formation flying algorithms that will be demonstrated on Orion [29].

Several others groups are working on resolving the various technical issues listed above. The MIT Space Systems Lab is currently working on the aperture synthesis of a formation flying cluster of satellites [11], with a special emphasis on the optimal placement within the aperture for both distributed interferometry and SAR systems [12,13]. They have also analyzed the effects of the primary orbital perturbations on passive formations and analyzed the ΔV required to overcome these perturbations [14].

A group at the University of Texas A&M has developed an optimal relative orbit design for minimizing the effects of the dominant orbital perturbations (using the nonlinear orbital dynamics) [15,16]. They have also developed techniques to perform fuel optimal control of a two spacecraft rendezvous [17]. Honeywell is analyzing the distributed resource allocation and collective management of a large satellite cluster [18].

NASA GSFC have designed various control systems for the EO-1/Landsat-7 formation flying experiment (e.g. linear output feedback control, decentralized LQG) [19,20,21,22]. A team of researchers from the Virginia Polytechnic University & AFRL has developed LQR control of a two-satellite formation [23]. They have also developed linear output feedback based adaptive nonlinear control for a two-satellite formation (with a detailed nonlinear stability analysis) [24].

The team from UCLA & JPL has investigated the navigation and control for multiple microspacecraft in formation (integrating the rotational dynamics into the control and coordination) [7,25]. They have also developed fuel equalization and adaptive control schemes [26,8], analyzed a formation flying control architecture based on a leader-follower framework, and presented a stability and convergence analysis of the controller modeled as a hybrid system [27,28].

Focus Area 5: Computing and Data Management

Computing and data management presents a number of challenges both in the hardware and algorithmic areas. Groups at GSFC, JPL, AMES, AFRL, university and industry are addressing many of these.

Very high performance, low-power, computing devices are critical for spaceborne GPS, formation flying and nanosatellites. The sophistication of the formation control algorithms and the need for sufficient floating point compute power for formation flying and GPS applications demand high performance microprocessors. These devices need to be radiation and single event effect tolerant since they are mission critical. Leveraging off the commercial sector, NASA, AFRL and the commercial space industry are working feverishly to bring these devices to flight-worthy status. Devices such as the StrongARM, Mongoose V, 603e and 720 Power PC and the RAD6000 represent the current generation of spaceflight processors.

A great deal of effort is being spent on spacecraft automation and autonomy. First, some definitions are necessary. Automation is focused on ground control while autonomy is on-board processing. Automation usually involves scripting product generation and creating a "lights-out" environment or situation where flight engineers are paged when necessary. The real focus of this work is to reduce mission cost. The goals of autonomy, on the other hand, are to create "thinking" spacecraft that can operate independent of ground support. Autonomy is truly critical in the realm of formation flying.

The introduction of autonomous systems, however, creates it own problems. The nondeterministic nature of autonomy greatly complicates testing. New techniques and tools are necessary to determine and fully understand system behavior. It is no longer possible to use structured testing and try to cover all the "expected" paths or outcomes.

Another area of study is fault detection and correction. This can be particularly critical in a distributed control environment. To ensure graceful degradation of the formation, failures must be detected and managed. For example, some of the distributed spacecraft control techniques at GSFC are looking at voting schemes to determine and remove failing spacecraft.

With large numbers of spacecraft collecting potentially huge amounts of data, serious research into data management and reduction is necessary. In some formations, the data must be shared between spacecraft, and allowances must be made for these large communication bandwidths. Also, the spacecraft will need to determine what data should be sent to the ground, what can be thrown away, and what needs to be kept on board in case the ground requests it. Aging of the data must also be managed. These are just a few of the problems that must be solved.

Focus Area 6: Tools & Testbeds

The challenge of deploying distributed spacecraft systems lies not only in controlling the vehicles to achieve and maintain a specified formation, but also in distributing information between the vehicles so that they act as a coordinated system. This requires the development of advanced distributed spacecraft control architectures and algorithms, absolute and relative navigation and attitude sensors, inter-spacecraft communication systems, and information management systems. To minimize mission risk associated when these new technologies are infused into formation flying missions, testbeds that will enable comprehensive simulation and experimentation, are required.

Thus, the NASA GSFC Guidance, Navigation and Control Center (GNCC) is developing a multi-pronged approach to testbed development. The first prong of this effort is a series of small testbeds based on specific technologies. For example, the team at GSFC has developed a GPS testbed that includes GPS constellation RF simulators and flight ready receivers. See figure 7. A second prong includes incorporating these smaller testbeds into a ground-based Formation Flying Testbed (FFTB). This testbed is built around a COTS product called VirtualSat Pro. VirtualSat, developed by the Hammers Co., is a real-time spacecraft dynamic simulator capable of simulating a formation of spacecraft. It was developed to facilitate flight software development and testing in parallel with hardware development. Since VirtualSat has a plug and play component structure, hardware can be plugged in place of software simulation modules as it is developed. These smaller hardware-based testbeds can, therefore, be plugged into the FFTB to create an extensive flight simulation environment.

Figure 7: GPS Test Facility

The third prong in the NASA testbed strategy is an extensive on-orbit campaign of demonstration missions. These on-orbit demonstrations will validate numerous formation flying technologies, including those mentioned in this paper, in various flight experiments.

NASA/GSFC is not the only group developing formation flying testbeds. The following paragraphs provide more details on some of the ground-based and on-orbit testbeds.

Ground-Based Testbeds

Stanford University Formation Flying Testbed (FFTB)~~A~~ formation flying testbed has been created at Stanford University to investigate the guidance, navigation, and control issues associated with precise formation flying [33,34]. See figure 8. The testbed consists of 3 active free-flying vehicles that move on a 12 ft x 9 ft granite table. Compressed air thrusters propel the vehicles. Each vehicle has onboard computing and batteries, and communicates with the other vehicles via a wireless ethernet (or modem), making them self-contained and autonomous. These air cushion vehicles are used to simulate the zero-g dynamics of a spacecraft formation in a horizontal plane. Pseudolites are used in this room to enable the use of CDGPS relative navigation for this formation. Recent results have demonstrated the feasibility of using a CDGPS based sensing system (with pseudolites) to achieve relative navigation accuracies on the order of 2 cm (relative position) and 0.5^0 (relative accuracy) on this formation of prototype space vehicles.

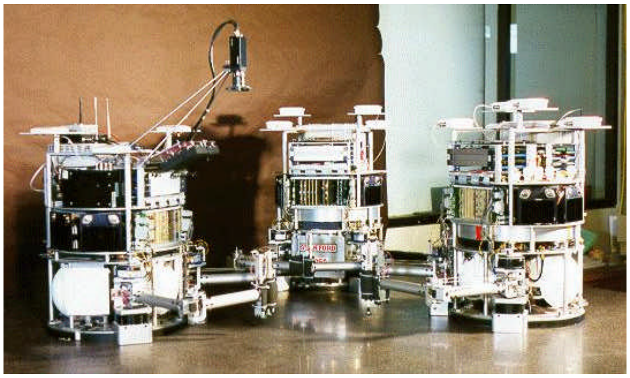


Figure 8: Stanford University Formation Flying Testbed

3D Formation Flying~~A~~ second testbed has been developed to demonstrate formation flight in three dimensions with larger separations between the vehicles [38]. See figure 9. This testbed consists of two blimps that fly inside a large highbay (200 ft x 65 ft x 95 ft). These vehicles also have onboard GPS sensors, 5 drive electronics/motors and 2 communication systems. The blimp testbed has been used to demonstrate that various GPS errors, such as the circular polarization effect, can be modeled and eliminated from the measurement equations. A new, low-cost GPS receiver was developed for these vehicles, and this will be used for the upcoming Orion space mission. Results on the blimps have shown very robust CDGPS sensing for the formation. The blimp formation has also been tested outside using the NAVSTAR constellation. Basic formation control strategies have also been investigated on this blimp testbed.

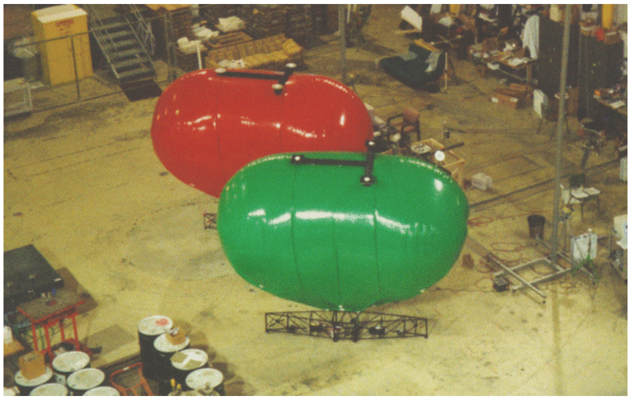


Figure 9: Stanford University Blimp Formation Flying Testbed

On-Orbit Testbeds

EO-1 Enhanced Formation Flying Experiment~~The~~ primary objective of the enhanced formation flying experiment on the EO-1 mission is to demonstrate onboard autonomous navigation and formation flying control between the EO-1 and Landsat-7 spacecraft. See figure 10. An automated mission design and automated maneuver planning tool, AutoCon [19], which was developed by AI Solutions under direction of the Goddard GN&C team, has been used for operational mission design. AutoCon is being modified to operate onboard the spacecraft to support autonomous formation flying. This will be accomplished by having the flight control system plan a maneuver that places EO-1 within 1 minute of separation from Landsat-7 and then maintain that separation to a tight tolerance of 6 seconds for an extended period of time. Flight validation is scheduled for December 1999.

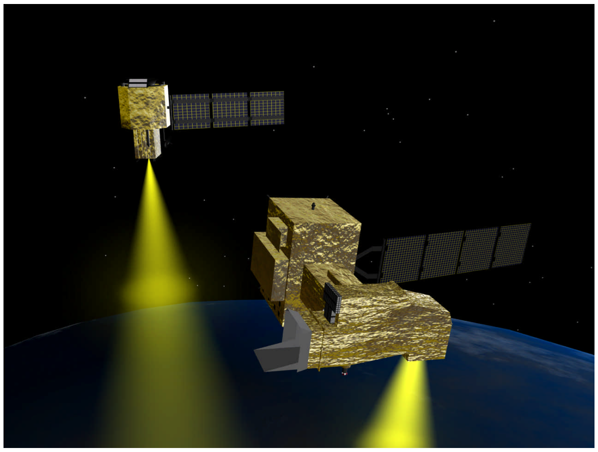


Figure 10: EO-1 & Landsat-7 Co-Observing Program

The GSFC-developed algorithms and software tools for this demonstration use a modular approach so they can easily be incorporated onboard future Earth orbiting missions. These algorithms [19,20,35] will be implemented using fuzzy logic engines for constraint checking and control of the formation flying algorithms. JPL and the Air Force Research Laboratory are supplying additional formation flying algorithms.

The key benefits of this enhanced formation flying technology are to eliminate routine ground maneuver planning and commanding requirements, reduce costs, enhance future science investigations, and to advance the technology for complete lights-out application for the New Millennium Program. The system will provide real-time low-cost formation flying control with the flexibility to meet a broad range of mission requirements including ground track, inclination, and altitude control as individual or multiple spacecraft requirements.

Orion~~The~~ Orion mission was developed to demonstrate true formation flying in low earth orbit using very low cost microsatellites designed and built at Stanford University. See figure 11. This mission will validate several key sensing and control issues associated with formation flying, and it represents an important step towards the virtual platforms envisioned for future Earth Sciences Enterprise missions.

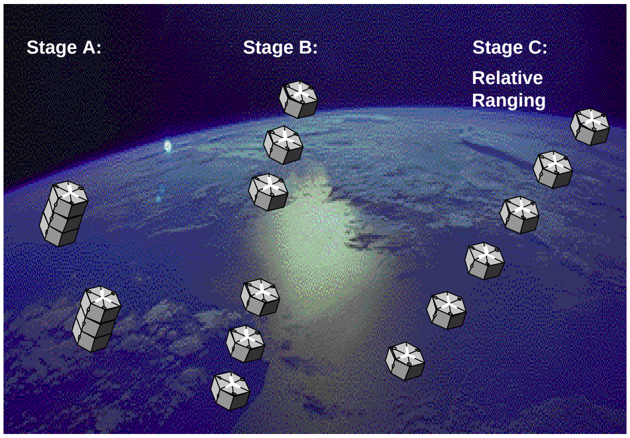


Figure 11: Orion—True Formation Flying

The microsatellite design for this mission is based on a modified version of the low-cost low-weight spacecraft bus developed at Stanford University called SQUIRT. Apart from being an excellent testbed for demonstrating the overall design of an active microsatellite, there are four important technical objectives of this program:

- On-orbit demonstration of formation control for a cluster of micro-satellites using real-time autonomous control software.
- Demonstration of a low-cost, low-power GPS receiver for real-time attitude & relative navigation and control. The particular emphasis of the program is on using carrier-differential GPS (CDGPS) for very precise relative navigation.
- Demonstration of a real-time inter-vehicle communication link to support the CDGPS and control data. Perform closed-loop control of the formation using various control architectures (e.g. centralized or leader-follower).
- Investigate several configurations of the fleet to demonstrate the formation flying in fuel-optimized relative orientations. Both coarse and precise formation flying will be demonstrated.

The current Orion vehicle hardware design is as follows:

1. Cold-gas thrusters for attitude and station-keeping maneuvers. There are 4 clusters of 3 nozzles to provide 6 DOF control. Four Nitroduck tanks carrying a total of 2.5 kg of nitrogen should deliver about 25 m/s of ΔV.
2. Torquer coils and magnetometers will be used as an auxiliary ACS for de-tumbling the satellite during the start-up mode, thereby allowing the GPS system to reliably obtain its initial signal lock.
3. The communications subsystem provides reliable inter-satellite and ground links. The current design includes the Hamtronics Transmitter (437.475 MHz carrier, 2.5 W output power), Hamtronics R451 Receiver (437.475 MHz), SpaceQuest MOD-96 Modem
4. The SpaceQuest space-rated CPU and BekTek OS will be used for the command and data handling.
5. The basic structure is a modular construction with1/2" aluminum honeycomb trays and panels. The C-channel tray frames have been designed to help with the heat conduction. There are 2 strings of 12 Sanyo CADNICA NiCd batteries and 11000 cm^2 of solar panels.
6. A Stanford modified Mitel chipset design for the attitude-capable GPS receiver. The receiver supports 6 antennas and requires 8 W peak power and 2 W in rest mode. The receiver uses a StrongArm CPU for processing of the relative navigation data and control algorithms. Current simulations of a two vehicle fleet in LEO indicate that, with this receiver, the relative position can be estimated at 1 Hz to 2-5 cm (depending on GPS geometry), and the CDGPS biases can be reliably resolved in under 15 minutes.

The original mission plan had 3 Orion vehicles that would be launched together, initialized, and then perform a sequence of coarse and precise formation flying. This has recently been changed so that a single Orion vehicle would fly in formation with two Emerald vehicles that are being developed at Stanford and Santa Clara Universities as part of the AFRL Nanosat program. While the Emerald vehicles are less capable than the current Orion spacecraft design (they have no significant thrust actuation and have significantly reduced onboard computing) this fleet of three vehicles should be able to meet all of the original Orion formation flying sensing and control objectives.

The Orion team is also exploring the possibility of flying an Orion vehicle in formation with MightySatII.2 as a combined NASA/AFRL program. This configuration will allow substantially more complex station-keeping operations to be validated on-orbit. A further option would be to perform joint scientific experiments using the TRAM radar system under development for the TechSat21 program. In either mission scenario, Orion will demonstrate and validate many key technologies for future formation flying missions.

ST-3~~S~~pace Technology-3 (ST-3, previously known as DS-3) is being developed by JPL and Ball Aerospace to demonstrate spaceborne optical interferometry with very large baselines (100m-10km). This can be accomplished using multiple spacecraft flying in precise formation. While the optical pathlengths over these distances must be controlled to nanometers, the vehicle accuracies are 1 cm and 1 arcmin in relative range and attitude, respectively. The mission will also be used to test the new relative ranging technology (Autonomous Formation Flyer) and various formation flying control algorithms.

ST-3 will consist of two spacecraft, each having a degree of autonomy, but both comprising a single instrument and constrained to move together in a relative distance of 50-1000 meters. In order to meet the mission goals, the control system must maintain the distances between spacecraft to within 1-2 cm, and the relative orientations of the spacecraft within 1 arcminute per axis. The sensing for ST-3 will be performed using the AFF described previously. The AFF borrows technology from GPS, using measurements of both radio frequency (RF) carrier phase and a ranging code. Each spacecraft will have at least one transmitting antenna and two receiving antennas, operating at 30 GHz with a code rate of 100 Mchips per second. Both spacecraft will be collecting elements for the interferometer. The vehicles are roughly cubic in shape and have masses of about 150 kg. Each will use a mirror with a diameter of 12 cm to reflect the collected light (wavelengths 500-900 nanometers) to one of the spacecraft that will also serve as the combiner. Because of the modest collecting area, the faintest measurable sources will have visual magnitudes in the range 10 to 12. The interferometric baselines will vary in length from perhaps 50-1000 m. During a planned lifetime of six months, the instrument will demonstrate its ability to point at specified targets, change baseline length, and maintain the formation at the required accuracy, as well as to find and track the interferometric fringes and report its measurements back to Earth. The need to maintain the array configuration without continual thruster firings mandates that the array operate in a solar orbit similar to the Earth's (trailing Earth by approximately 0.1 astronomical unit). Clearly, monitoring and controlling the array configuration will be a crucial element in the operation of the ST-3 interferometer.

ST-5~~V~~arious partners are developing ST-5, called the Nanosat Constellation Trailblazer mission [36]. This mission will use three very small satellites (approx 10kg). The mission objectives are to validate methods of operating several spacecraft as a system, and to test various technologies (e.g. GPS for relative ranging, low-power communication, Lithium Ion Power System) in the harsh space environment near the boundary of Earth's protective magnetic field, or magnetosphere. The launch is planned for in 2003.

TechSat-21—Air Force Research Laboratory (AFRL) is leading the development of microsatellites (10--100kg) to replace several complex, expensive Air Force satellites, such as MilStar, Defense Support Program, and Defense Meteorological Satellite Program. The key focus of this work is to develop new technologies, such as Micro-Electro-Mechanical Systems (MEMS), that will lead to lightweight, low-cost, and highly capable microsatellites. The AFRL is exploring this new paradigm for performing space missions in an effort called TechSat-21 (Technology Satellite of the 21st Century) [37]. See figure 12. A space-based radar mission for Ground Moving Target Indication was chosen as a stressing case and is the focus of the initial investigation. The program is focused on MEMS development, sparse aperture design, and formation control strategies.

Figure 12: TechSat 21

University Nanosats—The University Nanosat program serves as a technology host to test algorithms, software and hardware in the space environment. Since there are three formations of multiple Nanosats, various technologies can be tested and validated in parallel. The parallel development and deployment of these spacecraft, as well as Orion, provides opportunities for the formation flying community to “climb the technology stair steps” while minimizing mission risks through multiple on-orbit tests.

DoD, NASA, and Industry are also jointly sponsoring the development and launch of 10 university nanosatellites (approx 10 kg) to demonstrate miniature bus technologies, formation flying, and distributed satellite capabilities. The satellites are planned to launch from the Shuttle in late 2001. Three of the teams are focusing on technologies that are directly relevant to formation flying.

A team from Arizona State University, University of Colorado Boulder, and New Mexico State University is developing the Three Corner Sat Constellation. The primary science objective of the Three Corner Sat constellation is to perform stereo image small (< 100 meter), highly dynamic (< 1 minute) scenes including deep convective towers, atmospheric waves, and sand/dust storms. To accomplish the science objectives, the 3 satellites will form a “virtual formation” in which the satellites cooperate to perform targeting, data acquisition, and data downlinking. For the mission to be accomplished, the locations of the satellites will need to be “in range” and mutually known in order for each to support its portion of the mission, but physical proximity is not a requirement for the formation network. Stereo imaging only requires a nominal spacing of tens of kilometers, so these vehicles will not use a propulsion system.

A team from Utah State University, University of Washington, and Virginia Polytechnic Institute & State University are developing the Ionospheric Observation Nanosatellite Formation (ION-F) to demonstrate satellite coordination and management technologies. The primary objective of the mission is to investigate the ionosphere (Density Structure Sizes, Drifts, Decay Rates) using measurements from the distributed satellites. Various propulsion and formation control algorithms are currently being investigated for this mission.

A team from Stanford Space Systems Development Laboratory, Santa Clara Remote Extreme Environment Mechanisms Laboratory, and the Stanford Formation Flying Laboratory is developing Emerald. Emerald is being designed as a low-cost demonstration of the basic components of NASA's “virtual spacecraft bus” concept. In particular, it will demonstrate the use of Carrier-Phase Differential GPS (CDGPS) techniques to autonomously track the relative position and attitude between several spacecraft. This sensing technology, together with coarse position control devices (differential drag) and inter-satellite communication links will be used to develop a virtual spacecraft bus comprised of a distributed array of simple, low-cost, highly-coordinated vehicles such as a formation of small satellites.

Conclusions

Formation flying technology will make fundamental changes in the way the Civil and DoD space community conducts missions in space. These changes will revolutionize all space missions of the future: Earth Science, Space Science, Human Exploration and DoD and Commercial ventures. The NASA/AFRL Formation Flying team is on the forefront of the Formation Flying technology effort, providing hardware and software solutions to overcome the current technology hurdles. A series of collaborative on-orbit experiments and ground-based tools and testbeds will provide a low cost validation of the Formation Flying hardware and software algorithms. Future missions will rely heavily on spaceborne GPS technology as well as advanced space vehicle autonomy techniques to enable the construction of Virtual Platforms in space.

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