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# Formation Flying: 2000-2004

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A Custom Bibliography From the
NASA Scientific and Technical Information Program

October 2004

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OCTOBER 2004

**20040084078** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Relative Navigation Algorithms for Phase 1 of the MMS Formation**
Kelbel, David; Lee, Taesul; Long, Anne; Carpenter, Russell; Gramling, Cheryl; [2003]; In English, 25-30 Oct. 2003, Greenbelt, MD, USA; No Copyright; Avail: CASI; A03, Hardcopy

This paper evaluates several navigation approaches for the first phase of the Magnetospheric Multiscale (MMS) mission, which consists of a tetrahedral formation of four satellites in highly eccentric Earth orbits of approximately 1.2 by 12 Earth radii at an inclination of 10 degrees. The inter-satellite separation is approximately 10 kilometers near apogees. Navigation approaches were studied using ground station m g e =d two-way Doppler measurements, Global Positioning System (GPS) pseudorange measurements, crosslink range measurements among the members flying in formation, and various combinations of these measurement types. An absolute position accuracy of 10 kilometers or better can be achieved with most of the approaches studied and a relative position accuracy of 100 meters or better can be achieved at apogee in some cases. Among the various approaches studied, the approaches that use a combination of GPS and crosslink measurements were found to be more reliable in terms of absolute and relative navigation accuracies and operational flexibility.
Author
*Algorithms; Space Missions; Formation Flying; Satellite Navigation Systems; Magnetospheres*

**20040082188** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Development of a Crosslink Channel Simulator**
Hunt, Chris; Smith, Carl; Burns, Rich; January 2004; In English, Mar. 2004, Big Sky, MT, USA
Contract(s)/Grant(s): GS-35F-0060N
Report No.(s): IEEEAC Paper 1376; Copyright; Avail: CASI; A02, Hardcopy

Distributed Spacecraft missions are an integral part of current and future plans for NASA and other space agencies. Many of these multi-vehicle missions involve utilizing the array of spacecraft as a single, instrument requiring communication via crosslinks to achieve mission goals. NASA s Goddard Space Flight Center (GSFC) is developing the Formation Flying Test Bed (FFTB) to provide a hardware-in-the-loop simulation environment to support mission concept development and system trades with a primary focus on Guidance, Navigation, and Control (GN&C) challenges associated with spacecraft flying. The goal of the FFTB is to reduce mission risk by assisting in mission planning and analysis, provide a technology development platform that allows algorithms to be developed for mission functions such as precision formation navigation and control and time synchronization. The FFTB will provide a medium in which the various crosslink transponders being used in multi-vehicle missions can be integrated for development and test; an integral part of the FFTB is the Crosslink Channel Simulator (CCS). The CCS is placed into the communications channel between the crosslinks under test, and is used to simulate on-mission effects to the communications channel such as vehicle maneuvers, relative vehicle motion, or antenna misalignment. The CCS is based on the Starlight software programmable platform developed at General Dynamics Decision Systems and provides the CCS with the ability to be modified on the fly to adapt to new crosslink formats or mission parameters. This paper briefly describes the Formation Flying Test Bed and its potential uses. It then provides details on the current and future development of the Crosslink Channel Simulator and its capabilities.
Derived from text
*Hardware-in-the-Loop Simulation; Crosslinking; Time Synchronization; Simulators*

**20040081408** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Formation Control for the Maxim Mission.**
Luquette, Richard J.; Leitner, Jesse; Gendreau, Keith; Sanner, Robert M.; January 2004; In English, 14-16 Sep. 2004, Washington, DC, USA; Copyright; Avail: CASI; A01, Hardcopy

Over the next twenty years, a wave of change is occurring in the spacebased scientific remote sensing community. While the fundamental limits in the spatial and angular resolution achievable in spacecraft have been reached, based on today's technology, an expansive new technology base has appeared over the past decade in the area of Distributed Space Systems (DSS). A key subset of the DSS technology area is that which covers precision formation flying of space vehicles. Through precision formation flying, the baselines, previously defined by the largest monolithic structure which could fit in the largest launch vehicle fairing, are now virtually unlimited. Several missions including the Micro-Arcsecond X-ray Imaging Mission (MAXIM), and the Stellar Imager will drive the formation flying challenges to achieve unprecedented baselines for high resolution, extended-scene, interferometry in the ultraviolet and X-ray regimes. This paper focuses on establishing the feasibility for the formation control of the MAXIM mission. The Stellar Imager mission requirements are on the same order of those for MAXIM. This paper specifically addresses: (1) high-level science requirements for these missions and how they evolve into engineering requirements; (2) the formation control architecture devised for such missions; (3) the design of the formation control laws to maintain very high precision relative positions; and (4) the levels of fuel usage required in the duration of these missions. Specific preliminary results are presented for two spacecraft within the MAXIM mission.
Author
*Formation Flying; Space Missions; X Ray Imagery; Control Systems Design; Remote Sensing*

**20040081269** AI Solutions, Inc., Lanham, MD, USA
**Tetrahedron Formation Control**
Guzman, Jose J.; 2003; In English, 28-30 Oct. 2003, Greenbelt, MD, USA
Contract(s)/Grant(s): NAS5-01090; No Copyright; Avail: CASI; A03, Hardcopy

Spacecraft flying in tetrahedron formations are excellent instrument platforms for electromagnetic and plasma studies. A minimum of four spacecraft - to establish a volume - is required to study some of the key regions of a planetary magnetic field. The usefulness of the measurements recorded is strongly affected by the tetrahedron orbital evolution. This paper considers the preliminary development of a general optimization procedure for tetrahedron formation control. The maneuvers are assumed to be impulsive and a multi-stage optimization method is employed. The stages include targeting to a fixed tetrahedron orientation, rotating and translating the tetrahedron and/or varying the initial and final times. The number of impulsive maneuvers citn also be varied. As the impulse locations and times change, new arcs are computed using a differential corrections scheme that varies the impulse magnitudes and directions. The result is a continuous trajectory with velocity discontinuities. The velocity discontinuities are then used to formulate the cost function. Direct optimization techniques are employed. The procedure is applied to the Magnetospheric Multiscale Mission (MMS) to compute preliminary formation control fuel requirements.
Author
*Tetrahedrons; Formation Flying; Spacecraft Control; Spacecraft Configurations; Optimization*

**20040081137** AI Solutions, Inc., Lanham, MD, USA
**Calipso's Mission Design: Sun-Glint Avoidance Strategies**
Mailhe, Laurie M.; Schiff, Conrad; Stadler, John H.; [2004]; In English, 8-12 Feb. 2004, Maui, HI, USA
Contract(s)/Grant(s): NAS5-01090
Report No.(s): AAS-04-114; No Copyright; Avail: CASI; A03, Hardcopy

CALIPSO will fly in formation with the Aqua spacecraft to obtain a coincident image of a portion of the Aqua/MODIS swath. Since MODIS pixels suffering sun-glint degradation are not processed, it is essential that CALIPSO only co- image the glint h e portion of the MODIS instrument swath. This paper presents sun-glint avoidance strategies for the CALIPSO mission. First, we introduce the Aqua sun-glint geometry and its relation to the CALIPSO-Aqua formation flying parameters. Then, we detail our implementation of the computation and perform a cross-track trade-space analysis. Finally, we analyze the impact of the sun-glint avoidance strategy on the spacecraft power and delta-V budget over the mission lifetime.
Author
*Glint; Sun; Satellite Observation; Aerosols; Clouds (Meteorology); Optical Radar; Space Missions; Spacecraft Design*

**20040079838** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**An Environment for Hardware-in-the-Loop Formation Navigation and Control Simulation**
Burns, Rich; January 30, 2004; In English, Aug. 2004, Providence, RI, USA
Contract(s)/Grant(s): GS-35F-0060N; No Copyright; Avail: Other Sources; Abstract Only

Recent interest in formation flying satellite systems has spurred a considerable amount of research in the relative

navigation and control of satellites. Development in this area has included new estimation and control algorithms as well as sensor and actuator development specifically geared toward the relative control problem. This paper describes a simulation facility, the Formation Flying Testbed (FFTB) at NASA's Goddard Space Flight Center, which allows engineers to test new algorithms for the formation flying problem with relevant GN&C hardware in a closed loop simulation. The FFTB currently supports the injection of GPS receiver hardware into the simulation loop, and support for satellite crosslink ranging technology is at a prototype stage. This closed-loop, hardware inclusive simulation capability permits testing of navigation and control software in the presence of the actual hardware with which the algorithms must interact. This capability provides the navigation or control developer with a perspective on how the algorithms perform as part of the closed-loop system. In this paper, the overall design and evolution of the FFTB are presented. Each component of the FFTB is then described in detail. Interfaces between the components of the FFTB are shown and the interfaces to and between navigation and control software are described in detail. Finally, an example of closed-loop formation control with GPS receivers in the loop is presented and results are analyzed.
Author
*Computerized Simulation; Control Simulation; Formation Flying; Guidance (Motion); Navigation; Feedback Control; Actuators*

**20040074336** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**The Stellar Imager (SI)'Vision Mission'**
Carpenter, Ken; Danchi, W.; Leitner, J.; Liu, A.; Lyon, R.; Mazzuca, L.; Moe, R.; Chenette, D.; Karovska, M.; Allen, R., et al.; [2004]; In English; 204th Meeting fo the American Astronomical Society, 30 May - 3 Jun. 2004, Denver, CO, USA; Copyright; Avail: Other Sources; Abstract Only

The Stellar Imager (SI) is a 'Vision' mission in the Sun-Earth Connection (SEC) Roadmap, conceived for the purpose of understanding the effects of stellar magnetic fields, the dynamos that generate them, and the internal structure and dynamics of the stars in which they exist. The ultimate goal is to achieve the best possible forecasting of solar/stellar magnetic activity and its impact on life in the Universe. The science goals of SI require an ultra-high angular resolution, at ultraviolet wavelengths, on the order of 100 micro-arcsec and thus baselines on the order of 0.5 km. These requirements call for a large, multi-spacecraft (less than 20) imaging interferometer, utilizing precision formation flying in a stable environment, such as in a Lissajous orbit around the Sun-Earth L2 point. SI's resolution will make it an invaluable resource for many other areas of astrophysics, including studies of AGN s, supernovae, cataclysmic variables, young stellar objects, QSO's, and stellar black holes. ongoing mission concept and technology development studies for SI. These studies are designed to refine the mission requirements for the science goals, define a Design Reference Mission, perform trade studies of selected major technical and architectural issues, improve the existing technology roadmap, and explore the details of deployment and operations, as well as the possible roles of astronauts and/or robots in construction and servicing of the facility.
Author
*Angular Resolution; Cataclysmic Variables; Formation Flying; Imaging Techniques; Interferometers; Magnetic Effects; Stellar Magnetic Fields; Ultraviolet Radiation*

**20040074300** Jet Propulsion Lab., California Inst. of Tech., Pasadena, CA, USA
**An Overview of the StarLight Mission**
Lay, Oliver; Blackwood, Gary; Dubovitsky, Serge; Duren, Riley; New Concepts for Far-Infrared and Submillimeter Space Astronomy; April 2004, 224-234; In English; No Copyright; Avail: CASI; A03, Hardcopy

An overview of the Starlight Mission is presented. Mission summary: June 2006 launch to heliocentric orbit; Nominal 6 month mission with option of additional 6 month extension; Validate autonomous formation flying system: range control to 10 cm bearing, control to 4 arcmin; Demonstrate formation flying optical interferometry.The original 3 spacecraft design did not fit the budget. 2 spacecraft concept demonstrates all key areas of formation flying interferometry. Collector flown on the surface of a virtual paraboloid, with combiner at the focus. It Gives a baseline of 125 m with a fixed delay of only 14 m.
Derived from text
*Spacecraft Design; Trajectory Control; Astronomical Interferometry*

**20040074266** Jet Propulsion Lab., California Inst. of Tech., Pasadena, CA, USA
**Formations of Tethered Spacecraft as Stable Platforms for Far IR and Sub-mm Astronomy**
Quadrelli, Marco B.; Hadaegh, Fred Y.; Shao, Michael; Lorenzini, Enrico C.; New Concepts for Far-Infrared and Submillimeter Space Astronomy; April 2004, 472-482; In English
Contract(s)/Grant(s): JPL-1215076; No Copyright; Avail: CASI; A03, Hardcopy

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

**20040074265** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Tethered Formation Configurations: Meeting the Scientific Objectives of Large Aperture and Interferometric Science**
Farley, Rodger E.; Quinn, David A.; New Concepts for Far-Infrared and Submillimeter Space Astronomy; April 2004, 463-471; In English; No Copyright; Avail: CASI; A02, Hardcopy

With the success of the Hubble Space Telescope, it has become apparent that new frontiers of science and discovery are made every time an improvement in imaging resolution is made. For the HST working primarily in the visible and near-visible spectrum, this meant designing, building and launching a primary mirror approximately three meters in diameter. Conventional thinking tells us that accomplishing a comparable improvement in resolution at longer wavelengths for Earth and Space Science applications requires a corresponding increase in the size of the primary mirror. For wavelengths in the sub-millimeter range, a very large telescope with an effective aperture in excess of one kilometer in diameter would be needed to obtain high quality angular resolution. Realistically a single aperture this large is practically impossible. Fortunately such large apertures can be constructed synthetically. Possibly as few as three 3 - 4 meter diameter mirrors flying in precision formation could be used to collect light at these longer wavelengths permitting not only very large virtual aperture science to be carried out, but high-resolution interferometry as well. To ensure the longest possible mission duration, a system of tethered spacecraft will be needed to mitigate the need for a great deal of propellant. A spin-stabilized, tethered formation will likely meet these requirements. Several configurations have been proposed which possibly meet the needs of the Space Science community. This paper discusses two of them, weighing the relative pros and cons of each concept. The ultimate goal being to settle on a configuration which combines the best features of structure, tethers and formation flying to meet the ambitious requirements necessary to make future large synthetic aperture and interferometric science missions successful.
Author
*Tethered Satellites; Astronomical Satellites; Formation Flying; Astronomical Interferometry; Synthetic Apertures*

**20040074179** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Estimation of Aperture Errors with Direct Interferometer-Output Feedback for Spacecraft Formation Control**
Lu, Hui-Ling; Cheng, Victor H. L.; Leitner, Jesse A.; Carpenter, Kenneth G.; [2004]; In English, 30 Jun. - 2 Jul. 2004, Boston, MA, USA; No Copyright; Avail: CASI; A02, Hardcopy

Long-baseline space interferometers involving formation flying of multiple spacecraft hold great promise as future space missions for high-resolution imagery. The major challenge of obtaining high-quality interferometric synthesized images from long-baseline space interferometers is to control these spacecraft and their optics payloads in the specified configuration accurately. In this paper, we describe our effort toward fine control of long-baseline space interferometers without resorting to additional sensing equipment. We present an estimation procedure that effectively extracts relative x/y translational exit

pupil aperture deviations from the raw interferometric image with small estimation errors.
Author
*Apertures; Error Analysis; Interferometers; Feedback Control*

**20040070757** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Flying the Earth Observing Constellations**
Kelly, Angelita C.; Case, Warren F.; [2004]; In English, 17-21 May 2004, Montreal, Canada; No Copyright; Avail: Other Sources; Abstract Only

Prior to the launch of the Earth Observing System (EOS) Terra and Landsat-7 satellites in 1999, the Project Scientists for the two missions and the Earth Science Data and Information System (ESDIS) Project at the Goddard Space Flight Center signed an inter-project agreement document describing their plan to fly in loose formation, approximately 20 minutes within each other. In November 2000, a technology demonstration satellite, Earth Observer-1 (EO-1), was launched into the same orbit as that of Landsat-7 and Terra, with a goal of flying within a minute from Landsat-7. The SAC-C satellite, developed and operated by the government of Argentina, was launched along with EO-1, with a goal of flying near both Terra and Landsat-7. This formation enables the scientists to make use of the scientific synergy among the instruments on the different spacecraft. This group of satellites constitutes the morning constellation, which is led by the Landsat-7, which has a mean local time (MLT) at 10:00 a.m. In May 2002, the EOS Aqua satellite was launched into an orbit with an altitude of 705 km. and a 1:30 p.m. MLT. Two smaller satellites, CALIPSO (a joint U.S./French mission), and CloudSat (a joint NASA/Colorado State University/Air Force mission), plan to fly in tight formation, within 15 seconds of each other. In addition, CALIPSO and CloudSat also plan to be within 30 to 60 seconds of the Aqua satellite. A third satellite, PARASOL, managed by the French Space Agency, CNES, will be placed within a minute of the CALIPSO satellite. In 2004, the Aura satellite will be launched and phased in relation to the Aqua satellite, such that the instruments on Aura will be able to view the same mass of air no later than 8 minutes after the instruments on Aqua have observed it. Representatives from each mission are currently documenting a plan on how they will coordinate on-orbit operations. Why are all these satellites planning to fly as a constellation? The answer is that as a constellation. the scientists will be able to acquire science data not only from their specific instruments on a single satellite, but science data from the other satellites which will have been taken at approximately the same time, thus resulting in coordinated science observation data. This leads to better quality science. This paper describes how the mission design has been driven by the science requirements. The morning and the afternoon constellations present operational challenges, which had not previously been encountered. Operations planning must address not only how the satellites of each constellation operate safely together, but also, how the two constellations fly on the same orbits without interfering with each other as they downlink data to their respective ground stations. This paper describes the operations experience gained from the morning constellation and the planning for the afternoon constellation.
Author
*Earth Observing System (EOS); Spacecraft Launching; Formation Flying; Earth Sciences*

**20040064944**
**System design and technology development for the Terrestrial Planet Finder infrared interferometer**
Blackwood, Gary; Serabyn, Eugene; Dubovitsky, Serge; Aung, MiMi; Gunter, Steven M.; Henry, Curt; Proceedings of SPIE - The International Society for Optical Engineering. Techniques and Instrumentation for Detection of Exoplanets; 2003; ISSN 0277-786X; Volume 5170, p. 129-143; In English; Techniques and Instrumentation for Detection of Exoplants, Aug. 5-7, 2003, San Diego, CA, USA; Copyright; Avail: Other Sources

This paper describes the technical program that will demonstrate the viability of two mid-infrared nulling interferometer architectures for the Terrestrial Planet Finder (TPF) to support a mission concept downselect in 2006 between a nulling interferometer and a visible coronagraph. The TPF science objectives are to survey a statistically significant number of nearby solar-type stars for radiation from terrestrial planets, to characterize these planets and to perform spectroscopy for detection of biomarkers. A 4-telescope, 36-m Structurally-Connected Interferometer using a dual-chopped Bracewell nuller will meet the minimum science requirement to completely survey at least 30 nearby stars and partially survey 120 others. A Formation-Flying Interferometer is being designed to meet the full science requirement to completely survey at least 150 stars, and involves a trade between dual-chopped Bracewell, degenerate Angel Cross, and the Darwin bow-tie configuration. The system engineering trades for the connected structure and formation-flying architectures are described. The top technical concerns for these architectures are mapped to technology developments that will retire these concerns prior to the project downselect.
EI
*Earth (Planet); Infrared Radiation; Interferometers; Light Transmission; Spacecraft; Systems Analysis*

**20040034068** NASA Goddard Space Flight Center, Greenbelt, MD, USA

**Nonlinear Observers for Gyro Calibration**

Thienel, Julie; Sanner, Robert M.; [2003]; In English, February 2004, Breckenridge, CO, USA; No Copyright; Avail: Other Sources; Abstract Only

High precision estimation and control algorithms, to achieve unprecedented levels of pointing accuracy, will be required to support future formation flying missions such as interferometry missions. Achieving high pointing accuracy requires precise knowledge of the spacecraft rotation rate. Typically, the rotation rate is measured by a gyro. The measured rates can be corrupted by errors in alignment and scale factor, gyro biases, and noise. In this work, we present nonlinear observers for gyro calibration. Nonlinear observers are superior to extended or pseudo-linear Kalman filter type approaches for large errors and global stability. Three nonlinear gyro calibration observers are developed. The first observer estimates a constant gyro bias. The second observer estimates scale factor errors. The third observer estimates the gyro alignment for three orthogonal gyros. The convergence properties of all three observers are discussed. Additionally, all three observers are coupled with a nonlinear control algorithm. The stability of each of the resulting closed loop systems is analyzed. The observers are then combined, and the gyro calibration parameters are estimated simultaneously. The stability of the combined observers is addressed, as well as the stability of the resulting closed loop systems. Simulated test results are presented for each scenario. Finally, the nonlinear observers are compared to a pseudo-linear Kalman filter.
Author

*Gyroscopes; Calibrating; Nonlinearity; Formation Flying*

**20040031734** NASA Goddard Space Flight Center, Greenbelt, MD, USA

**Flight Test Results from the Low Power Transceiver Communications and Navigation Demonstration on Shuttle (CANDOS)**

Rush, John; Israel, David; Harlacher, Marc; Haas, Lin; September 23, 2003; In English, 23 Sep. 2003, Long Beach, CA, USA
Report No.(s): AIAA Paper 2003-6337; No Copyright; Avail: CASI; A03, Hardcopy

The Low Power Transceiver (LPT) is an advanced signal processing platform that offers a configurable and reprogrammable capability for supporting communications, navigation and sensor functions for mission applications ranging from spacecraft TT&C and autonomous orbit determination to sophisticated networks that use crosslinks to support communications and real-time relative navigation for formation flying. The LPT is the result of extensive collaborative research under NASNGSFC s Advanced Technology Program and ITT Industries internal research and development efforts. Its modular, multi-channel design currently enables transmitting and receiving communication signals on L- or S-band frequencies and processing GPS L-band signals for precision navigation. The LPT flew as a part of the GSFC Hitchhiker payload named Fast Reaction Experiments Enabling Science Technology And Research (FREESTAR) on-board Space Shuttle Columbia s final mission. The experiment demonstrated functionality in GPS-based navigation and orbit determination, NASA STDN Ground Network communications, space relay communications via the NASA TDRSS, on-orbit reconfiguration of the software radio, the use of the Internet Protocol (IP) for TT&C, and communication concepts for space based range safety. All data from the experiment was recovered and, as a result, all primary and secondary objectives of the experiment were successful. This paper presents the results of the LPTs maiden space flight as a part of STS- 107.
Author

*Flight Tests; Transmitter Receivers; Navigation Instruments; Signal Processing; Platforms; Space Communication*

**20040031678** Swedish Defence Research Establishment, Stockholm, Sweden

**Space Activities at the Swedish Defence Research Agency**

Lindstroem, S.; May 2003; In Swedish
Report No.(s): PB2004-101822; FOI-R-0867-SE; No Copyright; Avail: National Technical Information Service (NTIS)

This report is a summary of an inventory of space activities at the Swedish Defense Research Agency (FOI). The objective of this review is to show FOI's employers in what areas FOI has knowledge and capabilities within the concept of space. Another reason is to inform co-workers at FOI about the present projects to avoid duplication of work and hopefully also to strengthen the cooperation within the area of space research at FOI. The questionnaire concerning the present space activities (1995-2003) that was sent to all departments at FOI addressed anybody who has worked or are working with space related issues as space physics, satellite data, the satellite structure, telemetry or command, the ground station and so on. The survey showed that present space related activities cover the development of propulsion systems and propellant, research about laser ignition systems, laser communication, accident investigation of the launch rocket Ariane-5, studies for the Swedish Armed

Forces related to the use of satellite systems in the Network Based Defense, analysis of interference in navigation systems and study of formation flying satellites.
NTIS
*Inventories; Atmospheric Physics; Network Analysis; Propulsion System Configurations; Propulsion System Performance*

**20040030567** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Relative Motion of Two Spacecraft Near the Sun-Earth L2 Point**
Collange, Guillaume; Leitner, Jesse; December 23, 2003; In English, 1 Aug. 2004, Providence, RI, USA; No Copyright; Avail: Other Sources; Abstract Only

Over the next two decades international space agencies including the National Aeronautics and Space Administration and the European Space Agency are proposing space missions which employ distributed spacecraft technologies to enable vast improvements in remote sensing performance as compared to fundamental performance limitations associated with fairing sizes of even the largest launch vehicles. These missions will require numerous advanced technologies to enable some extreme scientific goals. However, on the critical path to developing many of those technologies, understanding realistic achievable performance, and formulating such missions involving formation flying spacecraft, is the detailed understanding of the vehicle relative motion in the appropriate dynamic environment. Due to the appealing gravitational and thermal environment, the Sun-Earth L(sub 2) point is a strong candidate for placement of many of these missions. Henceforth, this paper begins to unravel the dynamics of relative motion near L(sub 2), with particular consideration given to the ultimate requirements for flying space- craft in precise formation. This work is meant to be a predecessor to detailed formation flying mission analysis efforts in the areas of formation design, formation control, and relative navigation.
Author
*Formation Flying; NASA Programs; Remote Sensing; Spacecraft Motion; Thermal Environments*

**20040027695** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Linear State-Space Representation of the Dynamics of Relative Motion, Based on Restricted Three Body Dynamics**
Luquette,Richard J.; Sanner, Robert M.; January 2004; In English, 16-19 Aug. 2004, Providence, RI, USA; Copyright; Avail: CASI; A03, Hardcopy

Precision Formation Flying is an enabling technology for a variety of proposed space-based observatories, including the Micro-Arcsecond X-ray Imaging Mission (MAXIM) , the associated MAXIM pathfinder mission, Stellar Imager (SI) and the Terrestrial Planet Finder (TPF). An essential element of the technology is the control algorithm, requiring a clear understanding of the dynamics of relative motion. This paper examines the dynamics of relative motion in the context of the Restricted Three Body Problem (RTBP). The natural dynamics of relative motion are presented in their full nonlinear form. Motivated by the desire to apply linear control methods, the dynamics equations are linearized and presented in state-space form. The stability properties are explored for regions in proximity to each of the libration points in the Earth/Moon - Sun rotating frame. The dynamics of relative motion are presented in both the inertial and rotating coordinate frames.
Author
*Formation Flying; Three Body Problem; Algorithms; Nonlinearity; Stability*

**20040013411** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Development of a Crosslink Channel Simulator for Simulation of Formation Flying Satellite Systems**
Hart, Roger; Hunt, Chris; Burns, Rich D.; [2003]; In English, Mar. 2004, Big Sky, MT, USA
Contract(s)/Grant(s): GS-35F-0060N; Copyright; Avail: Other Sources; Abstract Only

Multi-vehicle missions are an integral part of NASA s and other space agencies current and future business. These multi-vehicle missions generally involve collectively utilizing the array of instrumentation dispersed throughout the system of space vehicles, and communicating via crosslinks to achieve mission goals such as formation flying, autonomous operation, and collective data gathering. NASA s Goddard Space Flight Center (GSFC) is developing the Formation Flying Test Bed (FFTB) to provide hardware-in- the-loop simulation of these crosslink-based systems. The goal of the FFTB is to reduce mission risk, assist in mission planning and analysis, and provide a technology development platform that allows algorithms to be developed for mission hctions such as precision formation flying, synchronization, and inter-vehicle data synthesis. The FFTB will provide a medium in which the various crosslink transponders being used in multi-vehicle missions can be plugged in for development and test. An integral part of the FFTB is the Crosslink Channel Simulator (CCS),which is placed into the communications channel between the crosslinks under test, and is used to simulate on-orbit effects to the communications channel due to relative vehicle motion or antenna misalignment. The CCS is based on the Starlight software programmable

platform developed at General Dynamics Decision Systems which provides the CCS with the ability to be modified on the fly to adapt to new crosslink formats or mission parameters.
Author
*Formation Flying; Artificial Satellites*

**20040013326** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Formation Flying and the Stellar Imager Mission Concept**
Carpenter, Kenneth G.; [2003]; In English, 5-7 Feb. 2003, Washington, DC, USA; No Copyright; Avail: Other Sources; Abstract Only

The Stellar Imager (SI) is envisioned as a space-based, W-optical interferometer composed of 10 or more one-meter class elements distributed with a maximum baseline of 0.5 km. image stars and binaries with sufficient resolution to enable long-term studies of stellar magnetic activity patterns, for comparison with those on the sun. It will also support asteroseismology (acoustic imaging) to probe stellar internal structure, differential rotation, and large-scale circulations. SI will enable us to understand the various effects of the magnetic fields of stars, the dynamos that generate these fields, and the internal structure and dynamics of the stars. The ultimate goal of the mission is to achieve the best-possible forecasting of solar activity as a driver of climate and space weather on time scales ranging from months up to decades, and an understanding of the impact of stellar magnetic activity on life in the Universe. In this paper we briefly describe the scientific goals of the mission, the performance requirements needed to address these goals, and the 'enabling technology' development efforts required, with specific attention for this meeting to the formation-flying aspects. It is designed to
Author
*Acoustic Imaging; Stellar Magnetic Fields; Interferometers; Stellar Structure; Magnetic Effects; Asteroseismology*

**20040012862** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**ST7-DRS: A Step Towards Drag-free and High-precision Formation Control**
Houghton, M.; Folkner, W.; Hanson, J.; Hruby, V.; [2003]; In English, 6-13 Mar. 2004, Big Sky, MT, USA; Copyright; Avail: Other Sources; Abstract Only

The Space Technology 7 Disturbance Reduction System (ST7-DRS) is an in-space technology demonstration within NASA's New Millennium Program. ST7-DRS is designed to validate system-level technologies that are required for future gravity missions (including the planned LISA gravitational-wave observatory) and for future formation-flying interferometer missions (including the planned MAXIM black-hole imager). ST7-DRS is based around a freely-floating test mass contained within a spacecraft structure that will shield this test mass from all external forces (aside from gravity). The spacecraft position will be continuously controlled, such that the spacecraft, itself, will remain centered about this test mass, essentially flying in formation with it. Colloidal micro-thrusters will be used to control the spacecraft s position to within a few nanometers, over time scales of tens to thousands of seconds. In order to detect the residual acceleration noise on the main test mass, a second test mass will be flown alongside the first, within the same physical spacecraft structure. This test mass will serve as a cross-reference for the first, and will also be used as a reference for the spacecraft's attitude control. The spacecraft's attitude will be controlled to an accuracy of a few milli-arc-seconds, also utilizing the colloidal micro-thrusters. ST7-DRS will consist of an instrument package (containing the test masses) and a set of micro-thrusters, which will be attached to the European Space Agency s SMART-2 spacecraft, set to launch in November 2007.
Author
*Aerospace Technology Transfer; NASA Programs; Gravitation; Space Missions; Drag Reduction; Formation Flying; Satellite Attitude Control*

**20030106025** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**An IP-Based Software System for Real-time, Closed Loop, Multi-Spacecraft Mission Simulations**
Cary, Everett; Davis, George; Higinbotham, John; Burns, Richard; Hogie, Keith; Hallahan, Francis; [2003]; In English, 4 Jun. 2003, Cleveland, OH, USA; No Copyright; Avail: CASI; A02, Hardcopy

This viewgraph presentation provides information on the architecture of a computerized testbest for simulating Distributed Space Systems (DSS) for controlling spacecraft flying in formation. The presentation also discusses and diagrams the Distributed Synthesis Environment (DSE) for simulating and planning DSS missions.
CASI
*Architecture (Computers); Spacecraft Control; Feedback Control; Formation Flying; Space Navigation; Satellite Constellations*

**20030105750** Jet Propulsion Lab., California Inst. of Tech., Pasadena, CA, USA
**The TechSat-21 Autonomous Sciencecraft Experiment**
Chien, Steve; Sherwood, Rob; Doyle, Richard; Intelligent Systems for Aeronautics; June 2003, 7-1 - 7-10; In English; Original contains color illustrations; Copyright; Avail: CASI; A02, Hardcopy; Available from CASI on CD-ROM only as part of the entire parent document

The Autonomous Sciencecraft Experiment flight demonstration (ASE) will fly onboard the US Air Force's TechSat-21 constellation, an unclassified mission scheduled for launch in 2004. ASE will use onboard science analysis, replanning, robust execution, and formation flying to radically increase science return by enabling intelligent downlink selection and autonomous retargeting. Demonstration of these capabilities in a flight environment will open up tremendous new opportunities in planetary science, space physics, and earth science that would be unreachable without this technology.
Author
*Autonomy; Microsatellites; Airborne/Spaceborne Computers; Aerospace Sciences; Flight Tests; NASA Space Programs*

**20030105593** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**Investigation of Space Interferometer Control Using Imaging Sensor Output Feedback**
Leitner, Jesse A.; Cheng, Victor H. L.; April 28, 2003; In English, 11-13 Aug. 2003, Austin, TX, USA
Contract(s)/Grant(s): NAS5-01184; No Copyright; Avail: CASI; A03, Hardcopy

Numerous space interferometry missions are planned for the next decade to verify different enabling technologies towards very-long-baseline interferometry to achieve high-resolution imaging and high-precision measurements. These objectives will require coordinated formations of spacecraft separately carrying optical elements comprising the interferometer. High-precision sensing and control of the spacecraft and the interferometer-component payloads are necessary to deliver sub-wavelength accuracy to achieve the scientific objectives. For these missions, the primary scientific product of interferometer measurements may be the only source of data available at the precision required to maintain the spacecraft and interferometer-component formation. A concept is studied for detecting the interferometer's optical configuration errors based on information extracted from the interferometer sensor output. It enables precision control of the optical components, and, in cases of space interferometers requiring formation flight of spacecraft that comprise the elements of a distributed instrument, it enables the control of the formation-flying vehicles because independent navigation or ranging sensors cannot deliver the high-precision metrology over the entire required geometry. Since the concept can act on the quality of the interferometer output directly, it can detect errors outside the capability of traditional metrology instruments, and provide the means needed to augment the traditional instrumentation to enable enhanced performance. Specific analyses performed in this study include the application of signal-processing and image-processing techniques to solve the problems of interferometer aperture baseline control, interferometer pointing, and orientation of multiple interferometer aperture pairs.
Author
*Feedback; Imaging Techniques; Interferometers; Detection; Telescopes; Spacecraft Control; Apertures*

**20030105437**
**A nonlinear, six-degree of freedom, precision formation control algorithm, based on restricted three body dynamics**
Luquette, Richard J.; Sanner, Robert M.; Advances in the Astronautical Sciences; 2003; ISSN 0065-3438; Volume 113, p. 105-114; In English; Guidance and Control 2003: Advances in the Astronautical Sciences, Feb. 5-9, 2003, Breckenridge, CO, USA; Copyright; Avail: Other Sources

Precision Formation Flying is an enabling technology for a variety of proposed space-based observatories, including the Micro-Arcsecond X-ray Imaging Mission (MAXIM), the associated MAXIM pathfinder mission, Stellar Imager and the Terrestrial Planet Finder (TPF). An essential element of the technology is the control algorithm. This paper discusses the development of a nonlinear, six-degree of freedom (6DOF) control algorithm for maintaining the relative position and attitude of a spacecraft within a formation. The translation dynamics are based on the equations of motion for the general restricted three body problem. The control law guarantees the tracking error convergences to zero, based on a Lyapunov analysis. The simulation, modelled after the MAXIM Pathfinder mission, maintains the relative position and attitude of a Follower spacecraft with respect to a Leader spacecraft, stationed near the L2 libration point in the Sun-Earth system.
EI
*Algorithms; Computerized Simulation; Degrees of Freedom; Liapunov Functions; Observatories; Space Probes*

**20030093749** Naval Research Lab., USA
**Pulsed Thrust Method for Hover Formation Flying**
Hope, Alan; Trask, Aaron; April 15, 2003; In English, 3-7 Aug. 2003, Big Sky, MT, USA
Contract(s)/Grant(s): NDPR-S-65018-Y; No Copyright; Avail: Other Sources; Abstract Only

A non-continuous thrust method for hover type formation flying has been developed. This method differs from a true hover which requires constant range and bearing from a reference vehicle. The new method uses a pulsed loop, or pogo, maneuver sequence that keeps the follower spacecraft within a defined box in a near hover situation. Equations are developed for the hover maintenance maneuvers. The constraints on the hover location, pulse interval, and maximum/minimum ranges are discussed.
Author
*Formation Flying; Hovering; Thrust; Delta Launch Vehicle; Spacecraft Maneuvers; Pulse Amplitude*

**20030089587**
**Disturbance reduction system: Testing technology for precision formation control**
Folkner, W. M.; Buchman, S.; Byer, R. L.; DeBra, D.; Dennehy, C. J.; Gamero-Castano, M.; Hanson, J.; Hruby, V.; Keiser, G. M.; Kuhnert, A.; Markley, F. L.; Houghton, M.; Maghami, P.; Miller, D.; Prakash, S.; Spero, R.; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4860, p. 221-228; In English; High-Contrast Imaging for Exo-Planet Detection, Aug. 23-26, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

The Disturbance Reduction System (DRS) is a space technology demonstration within NASA's New Millennium Program. DRS is designed to validate system-level technology required for future gravity missions, including the planned LISA gravitational-wave observatory, and for formation-flying interferometers. DRS is based on a freely-floating test mass contained within a spacecraft that shields the test mass from external forces. The spacecraft position will be continuously adjusted to stay centered about the test mass, essentially flying in formation with the test mass. Colloidal microthrusters will be used to control the spacecraft position within a few nanometers, over time scales of tens to thousands of seconds. For testing the level of acceleration noise on the test mass, a second test mass will be used as a reference. The second test mass will also be used as a reference for spacecraft attitude. The spacecraft attitude will be controlled to an accuracy of a few milliarcseconds using the colloidal microthrusters. DRS will consist of an instrument package and a set of microthrusters, which will be attached to the European Space Agency's SMART-2 spacecraft with launch scheduled for August 2006.
EI
*Gravity Waves; Interferometers; Microrocket Engines; Positioning; Spacecraft; Spacecraft Propulsion*

**20030089549**
**Fringe tracking in the StarLight formation interferometer testbed**
Wehmeier, Udo J.; Liewer, Kurt M.; Shields, Joel; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4852, Issue no. 2, p. 818-826; In English; Interferometry in Space, Aug. 26-28, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

StarLight, a NASA/JPL mission originally scheduled for launch in 2006, proposed to fly a two spacecraft visible light stellar interferometer. The Formation Interferometer Testbed (FIT) is a ground laboratory at JPL dedicated to validating technologies for Starlight and future formation flying spacecraft such as Terrestrial Planet Finder. The FIT interferometer achieved first fringes in February 2002. In this paper we present our status and review progress towards fringe tracking on a moving collector target.
EI
*Interferometers; Interferometry; Interplanetary Flight; Interplanetary Spacecraft; Laboratories; Research Facilities*

**20030089537**
**Requirements and options for a stable inertial reference frame for a 100 mu arcsecond imaging telescope**
Gendreau, K. C.; Leitner, J.; Markley, L.; Cash, W. C.; Shipley, A. F.; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4852, Issue no. 2, p. 685-694; In English; Interferometry in Space, Aug. 26-28, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

The MAXIM Pathfinder (MP) and Stellar Imager (SI) missions are under study to do 100 microarcsecond resolution imaging for a number of different targets using interferometers divided over formation flying spacecrafts. One of the most challenging technical hurdles for these missions is to have an independent directional reference in the sky to use for target acquisition and tracking. This directional reference will guide the placement of separate free flying elements of the interferometers to have [similar to] less than 30 microarcseconds of alignment with the target. This paper will discuss some of the specific challenges as well as some possible options to explore for achieving this alignment.
EI
*Image Resolution; Imagery; Imaging Techniques; Interferometers; Measuring Instruments; Spacecraft*

**20030089520**

**The StarLight space interferometer: Optical design and performance modeling**

Martin, S. R.; Morgan, R.; Gunter, S. M.; Bartos, R.; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4852, Issue no. 2, p. 500-511; In English; Interferometry in Space, Aug. 26-28, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

The StarLight mission aimed to place the first formation flying optical interferometer into space in year 2006. Utilizing two spacecraft to form a long baseline Michelson interferometer, it would measure white light fringes on a number of partially resolved stars of magnitudes greater than 5 in the wavelength range 600 to 1000 nm. The interferometer baseline is variable between 30 and 125 m, and also has a fixed 1.3 m mode. The spacecraft are flown in a parabolic geometry which requires an optical delay line to build up more than 14 m of delay on one arm of the interferometer. To obtain high fringe visibility, starlight wavefront, pointing and intensity must be preserved through 22 reflections from mirrors and beamsplitters. The alignment of a total of 27 optics is maintained through careful thermal design and the use of two actuated mirrors on each arm. This paper describes the optical layout, including the beam combiner design which allows star tracking, optical system alignment and fringe formation on a single CCD. The effects of diffraction of the starlight transferred from a distant spacecraft and from optical surface imperfections are modeled. Other contributors to the visibility budget and the resulting variation of fringe visibility across the focal plane are discussed.

EI

*Aerospace Sciences; Charge Coupled Devices; Interferometers; Optics; Wave Fronts*

**20030089518**

**Formation-flying interferometry**

Lay, Oliver P.; Blackwood, Gary H.; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4852, Issue no. 2, p. 481-491; In English; Interferometry in Space, Aug. 26-28, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

There are many advantages to space-based interferometry, but monolithic, single-spacecraft platforms set limits on the collecting area and baseline length. These constraints can be overcome by distributing the optical elements of the interferometer over a system of multiple spacecraft flying in precise formation, opening up new realms of angular resolution and sensitivity. This paper discusses some of the key differences between formation-flying and structurally-connected interferometers, including formation configurations, controlling beam shear, station-keeping, and the importance of delay and delay rate estimation in determining the instrument sensitivity.

EI

*Aerospace Sciences; Imaging Techniques; Interferometers; Interferometry; Planets; Spacecraft; Submillimeter Waves; X Rays*

**20030089517**

**The StarLight mission: A formation-flying stellar interferometer**

Blackwood, Gary; Lay, Oliver; Deininger, William; Ahmed, Asif; Duren, Riley; Noecker, Charley; Barden, Brian; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4852, Issue no. 2, p. 463-480; In English; Interferometry in Space, Aug. 26-28, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

The StarLight mission is designed to validate the technologies of formation flying and stellar interferometry in space. The mission consists of two spacecraft in an earth-trailing orbit that formation-fly over relative ranges of 40 m to 600 m to an accuracy of 10 cm. The relative range and bearing of the spacecraft are sensed by a novel RF sensor, the Autonomous Formation Flyer sensor, which provides 2 cm and 1 mrad range and bearing knowledge between the spacecraft. Each spacecraft hosts an instrument payload for a Michelson interferometer that exploit the moving spacecraft to generate variable observing baselines between 30 m and 125 m. The StarLight preliminary design has shown that a formation-flying interferometer involves significant coupling between the major system elements-spacecraft, formation-flying control, formation-flying sensor, and the interferometer instrument. Mission requirements drive innovative approaches for long-range heterodyne metrology, optical design, glint suppression, formation estimation and control, spacecraft design, and mission operation. Experimental results are summarized for new technology development areas.

EI

*Aerospace Sciences; Interferometers; Interferometry; Sensors; Spacecraft*

**20030089516**

**The StarLight interferometer architecture and operational concepts**

Duren, Riley; Lay, Oliver; Wette, Matt; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4852, Issue no. 2, p. 451-462; In English; Interferometry in Space, Aug. 26-28, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

The StarLight flight project was designed to demonstrate the key technologies of spaceborne long-baseline stellar interferometry and precision formation flying for potential use on the Terrestrial Planet Finder (TPF) and other future astrophysics missions. Interferometer performance validation could be achieved over a 6-12 month period by obtaining several hundred fringe visibility amplitude measurements for stars in the band 600-1000 nm for a variety of stellar visibilities (0.2-1.0), magnitudes (Mv = 2-5), and baselines (B = 30-125 meters). Interferometry could be performed both in a 1 meter fixed-baseline combiner-only mode and in a two-spacecraft formation mode. In formation mode, the combiner spacecraft would remain at the focus of a virtual parabola, while the collector spacecraft assumed various positions along the parabola such that the two arms of the interferometer remained equal over a variety of separations and bearing angles. Challenges to be encountered in flight include high-bandwidth inter-spacecraft stellar and metrology pointing control, alignment and shear correction, delay and delay-rate estimation, visibility calibration, and robust fringe tracking in the presence of local and inter-spacecraft dynamics. This paper is based on the StarLight project design-capture of March 2002 and will describe the StarLight Interferometer System architecture and selected operational concepts (both of which have relevance to the on-going TPF Technology Program).

EI

*Aerospace Sciences; Astrophysics; Interferometers; Interferometry; Spacecraft*

**20030087975**

**The MAXIM pathfinder X-ray interferometry mission**

Gendreau, K. C.; Cash, W. C.; Shipley, A. F.; White, N.; Proceedings of SPIE - The International Society for Optical Engineering; 2002; ISSN 0277-786X; Volume 4851, Issue no. 1, p. 353-364; In English; X-ray and Gamma-Ray telescopes and Instruments for Astronomy, Aug. 24-28, 2002, Waikoloa, HI, USA; Copyright; Avail: Other Sources

The MAXIM Pathfinder (MP) mission is under study as a scientific and technical stepping stone for the full MAXIM X-ray interferometry mission. While full MAXIM will resolve the event horizons of black holes with 0.1 microarcsecond imaging, MP will address scientific and technical issues as a 100 microarcsecond imager with some capabilities to resolve microarcsecond structure. We will present the primary science goals of MP. These include resolving stellar coronae, distinguishing between jets and accretion disks in AGN. This paper will also present the baseline design of MP. We will overview the challenging technical requirements and solutions for formation flying, target acquisition, and metrology.

EI

*Aerospace Sciences; Astronomy; Imagery; Interferometry; Measuring Instruments; X Rays*

**20030071202** Air Force Research Lab., Edwards AFB, CA, USA

**Propulsion Technologies for Microsatellite Missions**

Bromaghim, Daron; Singleton, James; Bushman, Stewart; Spores, Ron; Johnson, Lee; Apr. 11, 2003; In English

Contract(s)/Grant(s): Proj-6340

Report No.(s): AD-A415035; AFRL-PR-ED-AB-2003-089; No Copyright; Avail: CASI; A01, Hardcopy

Many near, to mid-term satellite missions have been identified for 200 kg class spacecraft. For many of these applications, significant delta-v capability is desired in order to perform orbit transfer, on-orbit repositioning and formation flying. Several of these systems are in advanced engineering development and could be ready to support flight opportunities as early as summer 2004. A 200 W Hall Effect Thruster (RET) system is being developed to satisfy traditional high specific impulse (Isp) missions such as stationkeeping and orbit transfer, and has demonstrated Isp of 1,370 sec, thrust of 12.2 mN and 35% total efficiency. This system, however, has also demonstrated the ability to produce very small impulse bits, as low as 1.5 mN-sec, for formations flying applications that require precise maneuvers. To complement this system, a suite of miniaturized sensors is also in development that will enable a full description of the integration impacts of METs on Department of Defense (DoD), National Aeronautic and Space Administration (NASA), and commercial satellites. This instrumentation package consists of a xenon ion energy analyzer, electron (Langmuir) probes, radiometric and photometric sensors, and a solar array experiment. The combined package, including the instruments, electronics, harness, chassis, etc., is less than 2 kg total mass - representing a significant improvement in capability vs. mass and cost. The third system in advanced development is a micro pulsed plasma thruster (MPPT) for applications in propulsive attitude control, which can reduce a l50-kg class microsatellite's attitude control system mass by 90%. This thruster, based on traditional pulsed plasma thrusters, weighs approximately 1.5 kg, and

has three orthogonal thrust axes, each of which can be fired to produce impulse about any spacecraft axis. MPPT performance is now being optimized, but is expected to be from 25-100 microN, with an estimated Isp of 500-800 sec.
DTIC
*Microsatellites; Artificial Satellites; Space Missions; Spacecraft Propulsion; Thrust*

**20030067199** Virginia Polytechnic Inst. and State Univ., Blacksburg, VA
**Experimental Investigation of Distributed Attitude Control for Spacecraft Formation Flying**
Hall, Christopher; Jan. 20, 2003; In English
Contract(s)/Grant(s): F49620-01-1-0209
Report No.(s): AD-A413460; AFRL-SR-AR-TR-03-0148; No Copyright; Avail: CASI; A02, Hardcopy

Formation flying missions are continually growing in size and complexity, and the requirement for ground-based demonstration of distributed systems grows with them. However, simulating the on-orbit environment shared by a group of satellites is a difficult task. The primary purpose of this DURIP project was established a Distributed Attitude Control Systems Simulator (DSACSS) in the Space Systems Simulation Laboratory (SSSL) at Virginia Tech. The DSACSS comprises two spherical air bearing spacecraft simulators manufactured by Space Electronics, Inc. in Berlin, CT. One of these simulators was purchases with internal VT funding and the second was purchased as part of this DURIP project. This report describes the state of the art of existing spacecraft simulators, the Distributed Spacecraft Attitude Control System Simulator, as well as several projects that we are undertaking with this unique new facility.
DTIC
*Spacecraft; Attitude Control; Spacecraft Control; Systems Simulation; Active Control*

**20030062052** CU Aerospace, LLC, Urbana, IL, USA
**Ultrasail**
Burton, R.; Benavides, G.; Coverston, V.; Hartmann, W.; Hargens, J.; Westerhoff, J.; Jones, Jonathan, Technical Monitor; [2003]; In English; Advance Space Propulsion Workshop, 15-17 Apr. 2003, Huntsville, AL, USA; Copyright; Avail: Other Sources

Ultrasail is a complete sail system for the launch, deployment, stabilization and control of very large solar sails enabling reduced mission times for interplanetary and deep space spacecraft. Ultrasail is an innovative, non-traditional approach to propulsion technology achieved by combining propulsion and control systems developed for formation-flying microsatellites with an innovative solar sail architecture to achieve sq km-class controllable sail areas, sail subsystem area densities of 1 gm per sq m, and thrust levels equivalent to 400 kW ion thruster systems used for comparable deep space missions. Ultrasail can conceivably even achieve outer planetary rendezvous, a deep space capability now reserved for high-mass nuclear and chemical systems. Ultrasail is a Delta IV-launched multi-blade spin-stabilized system with blade lengths as long as 50 km, reminiscent of the MacNeal Heliogyro. The primary innovation is the near-elimination of sail supporting structures by attaching the sail tip to a rigid formation-flying microsatellite truss which deploys the sail blade, and which then articulates the blade to provide attitude control, including spin stabilization and precession of the spin axis. These tip microsatellites are controlled by a solar-powered 3-axis microthruster system (electric or cold gas) to maintain proper sail film tension during deployment and spin-up. The satellite mass also provides a stabilizing centrifugal force on the blade while in rotation. Understanding the dynamics of individual blades is key to the overall dynamics of Ultrasail. Forces and torques that must be modeled include those due to solar pressure, those generated by the microsatellite at the blade tip and by torques applied at the blade root. Centrifugal forces also play a significant role in the deployment and maintenance of the sail configuration. To capture the dynamics of the overall system, the equations of motion for the blades have been derived. Using these differential equations, a control law will be derived to maneuver Ultrasail. This law involves the pitching of the individual blades thereby moving the distribution of the radiation pressure on each individual blade and inducing a resultant torque on the system. The direction of the angular momentum vector and its rate of precession can be controlled through the pitch angle of the blades. The Ultrasail trajectory is also being studied. Optimal or near-optimal trajectories are being generated to showcase Ultrasail performance. Various missions, e.g. outer planet and solar polar missions for observation of the Sun, are currently being investigated to demonstrate the performance enhancements generated by Ultrasail technology. Calculus-of-variations-based optimization software is used to produce optimal Ultrasail trajectories. The performance of these trajectories is being compared to optimal results generated with other propulsion models, including chemical propulsion, ion propulsion, and competing solar sail concepts. Results of these studies will quantify the performance of Ultrasail compared to existing solar sail concepts for high energy missions.
Author
*Solar Sails; Spacecraft Propulsion; Propulsion System Configurations; Microsatellites; Spacecraft Design; Trajectory Analysis; Loads (Forces)*

**20030032295** NASA Goddard Space Flight Center, Greenbelt, MD, USA

**Initialization of Formation Flying Using Primer Vector Theory**

Mailhe, Laurie; Schiff, Conrad; Folta, David; January 2002; In English, 29-31 Oct. 2002, Toulouse, France; Copyright; Avail: CASI; A02, Hardcopy

In this paper, we extend primer vector analysis to formation flying. Optimization of the classical rendezvous or free-time transfer problem between two orbits using primer vector theory has been extensively studied for one spacecraft. However, an increasing number of missions are now considering flying a set of spacecraft in close formation. Missions such as the Magnetospheric MultiScale (MMS) and Leonardo-BRDF (Bidirectional Reflectance Distribution Function) need to determine strategies to transfer each spacecraft from the common launch orbit to their respective operational orbit. In addition, all the spacecraft must synchronize their states so that they achieve the same desired formation geometry over each orbit. This periodicity requirement imposes constraints on the boundary conditions that can be used for the primer vector algorithm. In this work we explore the impact of the periodicity requirement in optimizing each spacecraft transfer trajectory using primer vector theory. We first present our adaptation of primer vector theory to formation flying. Using this method, we then compute the AV budget for each spacecraft subject to different formation endpoint constraints.

Author

*Formation Flying; Vectors (Mathematics); Trajectory Optimization; Spacecraft Trajectories; Transfer Orbits*

**20030031373** NASA Goddard Space Flight Center, Greenbelt, MD, USA

**Integrated Orbit and Attitude Control for a Nanosatellite with Power Constraints**

Berry, Matthew M.; Naasz, Bo J.; Kim, Hye-Young; Hall, Christopher D.; [2002]; In English, 9-12 Feb. 2003, Ponce, Puerto Rico; Original contains black and white illustrations; Copyright; Avail: CASI; A01, Hardcopy

HokieSat is a NASA Goddard sponsored spacecraft currently being built by students at Virginia Tech. HokieSat is part of the Ionospheric Observation Nanosatellite Formation (ION-F) project. The project involves spacecraft built by three schools: Virginia Tech (VT), Utah State University (USU), and University of Washington (UW). The three spacecraft are similar in design and will perform formation flying demonstrations, and make ionospheric measurements. HokieSat uses Pulsed Plasma Thrusters (PPTs) to maintain its position in the formation. There are two pairs of PPTs on HokieSat; their position on HokieSat's hexagonal cross-section is shown. Thrusters T(sub 2) and T(sub 3) provide translation control, and Thrusters TI and T4 can provide yaw steering. Any thruster can be fired individually. However because they share a capacitor, thrusters T(sub 1) and T(sub 2) or thrusters T(sub 3) and T(sub 4) cannot be fired simultaneously. Thrusters T(sub 2) T(sub 3) can be fired simultaneously, as well as thrusters T(sub 1) and T(sub 4). Each thruster provides an impulse-bit of 56 micronN-s and fires at a rate of 1 Hz. For translation control thrusters T2 and T3 are fired together providing an impulse-bit of 112 micronN-s. All four thrusters are positioned slightly above the center of mass, and therefore exert a torque on the spacecraft. Because there are no thrusters in the zenith-nadir directions, and the communication system requires that the spacecraft remain nadir-pointing, there is no way to thrust in the radial direction. The attitude of HokieSat is controlled by 3 orthogonal magnetic torque coils. Attitude control is achieved by forcing a current through the torque coils, which interacts with the Earth's magnetic field and creates a torque. Due to magnetic field interactions between the coils and PPTs, the two actuator systems cannot be used simultaneously, and any attitude or orbit control must be performed in a piecewise fashion. Power limitations place an additional constraint on the HokieSat control subsystem. When the spacecraft is in eclipse, the power subsystem can provide only enough power to operate vital spacecraft functions.

Author

*Nanosatellites; Satellite Design; Formation Flying; Attitude Control; Satellite Control; Orbital Maneuvers*

**20030025739** AI Solutions, Inc., USA

**Flying a Four-Spacecraft Formation by the Moon...Twice**

Guzman, Jose J.; Edery, Ariel; [2002]; In English, 9-12 Feb. 2003, Ponce, Puerto Rico; No Copyright; Avail: CASI; A01, Hardcopy

Spacecraft flying in tetrahedron formations are excellent for electromagnetic and plasma studies. To better understand the Earth s magnetosphere and its interaction with the solar wind, the NASA Goddard Magnetospheric Multiscale (MMS) mission will fly a tetrahedron formation through different regions of the magnetosphere close to the magnetic equatorial plane. However, to explore regions that are almost perpendicular to the ecliptic plane a dramatic plane change is needed. To minimize fuel, a double lunar swingby can be used to perform the plane change. This paper investigates the feasibility of flying a four-spacecraft formation through the required double lunar swingby.

Author

*Earth Magnetosphere; Formation Flying; Trajectory Planning; Mission Planning; Orbit Determination; Spacecraft Trajectories; Swingby Technique*

**20030025298** NASA Goddard Space Flight Center, Greenbelt, MD, USA

**Coupled Attitude and Orbit Dynamics and Control in Formation Flying Systems**

Xu, Yun-Jun; Fitz-Coy, Norman; Mason, Paul; [2003]; In English, 5-9 Feb. 2003; Original contains black and white illustrations; Copyright; Avail: CASI; A01, Hardcopy

Formation flying systems can range from global constellations offering extended service coverage to clusters of highly coordinated vehicles that perform distributed sensing. Recently, the use of groups of micro-satellites in the areas of near Earth explorations, deep space explorations, and military applications has received considerable attention by researchers and practitioners. To date, most proposed control strategies are based on linear models (e.g., Hill-Clohessy-Wiltshire equations) or nonlinear models that are restricted to circular reference orbits. Also, all models in the literature are uncoupled between relative position and relative attitude. In this paper, a generalized dynamic model is proposed. The reference orbit is not restricted to the circular case. In this formulation, the leader or follower satellite can be in either a circular or an elliptic orbit. In addition to maintaining a specified relative position, the satellites are also required to maintain specified relative attitudes. Thus the model presented couples vehicle attitude and orbit requirements. Orbit perturbations are also included. In particular, the J(sub 2) effects are accounted in the model. Finally, a sliding mode controller is developed and used to control the relative attitude of the formation and the simulation results are presented.

Author

*Formation Flying; Dynamic Control; Dynamic Models; Attitude (Inclination); Orbital Mechanics*

**20030025292** NASA Goddard Space Flight Center, Greenbelt, MD, USA

**A Nonlinear, Six-Degree of Freedom Precision Formation Control Algorithm, Based on Restricted Three Body Dynamics**

Bauer, Frank, Technical Monitor; Luquette, Richard J.; Sanner, Robert M.; [2003]; In English, 5-9 Feb. 2003, Breckenridge, CO, USA

Report No.(s): AAS 03-007; Copyright; Avail: CASI; A02, Hardcopy

Precision Formation Flying is an enabling technology for a variety of proposed space-based observatories, including the Micro-Arcsecond X-ray Imaging Mission (MAXIM), the associated MAXIM pathfinder mission, and the Stellar Imager. An essential element of the technology is the control algorithm. This paper discusses the development of a nonlinear, six-degree of freedom (6DOF) control algorithm for maintaining the relative position and attitude of a spacecraft within a formation. The translation dynamics are based on the equations of motion for the restricted three body problem. The control law guarantees the tracking error convergences to zero, based on a Lyapunov analysis. The simulation, modelled after the MAXIM Pathfinder mission, maintains the relative position and attitude of a Follower spacecraft with respect to a Leader spacecraft, stationed near the L2 libration point in the Sun-Earth system.

Author

*Algorithms; Formation Flying; Nonlinearity; Three Body Problem; Degrees of Freedom; Spacecraft Control*

**20030022777** NASA Goddard Space Flight Center, Greenbelt, MD, USA

**NASA's Autonomous Formation Flying Technology Demonstration, Earth Observing-1(EO-1)**

Folta, David; Bristow, John; Hawkins, Albin; Dell, Greg; [2002]; In English, 29-31 Oct. 2002, Toulouse, France; Copyright; Avail: CASI; A02, Hardcopy

NASA's first autonomous formation flying mission, the New Millennium Program's (NMP) Earth Observing-1 (EO-1) spacecraft, recently completed its principal goal of demonstrating advanced formation control technology. This paper provides an overview of the evolution of an onboard system that was developed originally as a ground mission planning and operations tool. We discuss the Goddard Space Flight Center s formation flying algorithm, the onboard flight design and its implementation, the interface and functionality of the onboard system, and the implementation of a Kalman filter based GPS data smoother. A number of safeguards that allow the incremental phasing in of autonomy and alleviate the potential for mission-impacting anomalies from the on- board autonomous system are discussed. A comparison of the maneuvers planned onboard using the EO-1 autonomous control system to those from the operational ground-based maneuver planning system is presented to quantify our success. The maneuvers discussed encompass reactionary and routine formation maintenance. Definitive orbital data is presented that verifies all formation flying requirements.

Author

*Formation Flying; Autonomy; Spacecraft Control*

**20030020714** NASA Goddard Space Flight Center, Greenbelt, MD, USA
**First Results from a Hardware-in-the-Loop Demonstration of Closed-Loop Autonomous Formation Flying**
Gill, E.; Naasz, Bo; Ebinuma, T.; [2003]; In English, 5-9 Feb. 2003, Breckenridge, CO, USA
Report No.(s): AAS-03-040; Copyright; Avail: CASI; A03, Hardcopy

A closed-loop system for the demonstration of autonomous satellite formation flying technologies using hardware-in-the-loop has been developed. Making use of a GPS signal simulator with a dual radio frequency outlet, the system includes two GPS space receivers as well as a powerful onboard navigation processor dedicated to the GPS-based guidance, navigation, and control of a satellite formation in real-time. The closed-loop system allows realistic simulations of autonomous formation flying scenarios, enabling research in the fields of tracking and orbit control strategies for a wide range of applications. The autonomous closed-loop formation acquisition and keeping strategy is based on Lyapunov's direct control method as applied to the standard set of Keplerian elements. This approach not only assures global and asymptotic stability of the control but also maintains valuable physical insight into the applied control vectors. Furthermore, the approach can account for system uncertainties and effectively avoids a computationally expensive solution of the two point boundary problem, which renders the concept particularly attractive for implementation in onboard processors. A guidance law has been developed which strictly separates the relative from the absolute motion, thus avoiding the numerical integration of a target trajectory in the onboard processor. Moreover, upon using precise kinematic relative GPS solutions, a dynamical modeling or filtering is avoided which provides for an efficient implementation of the process on an onboard processor. A sample formation flying scenario has been created aiming at the autonomous transition of a Low Earth Orbit satellite formation from an initial along-track separation of 800 m to a target distance of 100 m. Assuming a low-thrust actuator which may be accommodated on a small satellite, a typical control accuracy of less than 5 m has been achieved which proves the applicability of autonomous formation flying techniques to formations of satellites as close as 50 m.
Author
*Formation Flying; Feedback Control; Hardware-in-the-Loop Simulation; Satellite Control; Control Systems Design; Satellite Guidance; Autonomous Navigation; Liapunov Functions*

**20030018262** Massachusetts Inst. of Tech., Cambridge, MA USA
**Agent Based Software for the Autonomous Control of Formation Flying Spacecraft**
How, Jonathan P.; Campbell, Mark; Dennehy, Neil, Technical Monitor; [2003]; In English
Contract(s)/Grant(s): NAG5-10440
Report No.(s): MIT-OSP-6891850; No Copyright; Avail: CASI; A03, Hardcopy

Distributed satellite systems is an enabling technology for many future NASA/DoD earth and space science missions, such as MMS, MAXIM, Leonardo, and LISA [1, 2, 3]. While formation flying offers significant science benefits, to reduce the operating costs for these missions it will be essential that these multiple vehicles effectively act as a single spacecraft by performing coordinated observations. Autonomous guidance, navigation, and control as part of a coordinated fleet-autonomy is a key technology that will help accomplish this complex goal. This is no small task, as most current space missions require significant input from the ground for even relatively simple decisions such as thruster burns. Work for the NMP DS1 mission focused on the development of the New Millennium Remote Agent (NMRA) architecture for autonomous spacecraft control systems. NMRA integrates traditional real-time monitoring and control with components for constraint-based planning, robust multi-threaded execution, and model-based diagnosis and reconfiguration. The complexity of using an autonomous approach for space flight software was evident when most of its capabilities were stripped off prior to launch (although more capability was uplinked subsequently, and the resulting demonstration was very successful).
Derived from text
*Formation Flying; Autonomous Navigation; Automatic Control; Applications Programs (Computers); Spacecraft Control; Flight Control; Guidance (Motion)*

**20030014819** Missouri Univ., Rolla, MO USA
**Design and Test of a Tethered Pair of Satellites: Equipment Requirements**
Pernicka, Henry J.; Leitner, Jesse, Technical Monitor; [2003]; In English
Contract(s)/Grant(s): NAG5-12589; No Copyright; Avail: CASI; A02, Hardcopy

A recent development in spacecraft mission design involves the increasing use of Distributed Spacecraft Systems (DSS). Several key technologies must mature sufficiently to facilitate these missions, including the use of spacecraft flying in tightly controlled formations. Such formations may be controlled using 'free flying' navigation schemes, or alternatively may use tethers to constrain the formation geometry. An investigation has been initiated here to further develop this technology using two small spacecraft connected by a short tether. After insertion into orbit, the tether will be extended and various data

collected on the performance of the dual-spacecraft 'formation.' At some later time, the tether will be cut, and the spacecraft pair will be navigated in a manner to maintain a geometry as closely as possible to that of the tethered configuration. Comparisons and evaluations of the two modes of operation can then be made so that the merits of both approaches are available to mission designers.
Derived from text
*Equipment Specifications; Spacecraft Design; Tethering; Artificial Satellites*

**20030001956** Air Force Research Lab., Kirkland AFB, NM USA
**A Backroom Mission Operations Center for TechSat 21**
Zetocha, Paul; Jan. 2002; In English
Contract(s)/Grant(s): Proj-8809
Report No.(s): AD-A407954; No Copyright; Avail: CASI; A02, Hardcopy

The TechSat 21 satellite program is an Air Force Research Laboratory (AFRL) technology initiative which has an objective to demonstrate and validate microsatellite cluster system concepts and enabling technologies. The primary experimental objectives are to demonstrate formation flying algorithms and technologies for clustered satellites, and to demonstrate autonomous cluster and spacecraft operations. TechSat 21 consists of three satellites which will fly in various configurations with variable separation distances. Command and control of a cluster of satellites with multiple heterogeneous experimental objectives poses several challenges from a ground perspective. To assist in operating TechSat 21, AFRL is developing a backroom Mission Operations Center (MOC) which will be capable of performing, among other tasks: planning and scheduling; command generation; state-of-health (SOH) monitoring; telemetry playbacks; fault detection, isolation, and resolution (FDIR); data storage; and payload data analysis. The objective of this paper is to describe the MOC architecture, highlight the key components, and outline its planned operational use.
DTIC
*Command and Control; Satellite Constellations; Microsatellites*

**20020089856** Stanford Univ., Stanford, CA USA
**Coordination and Control of Multiple Spacecraft using Convex Optimization Techniques**
How, Jonathan P.; Jun. 2002; In English
Contract(s)/Grant(s): F49620-99-1-0095
Report No.(s): AD-A406790; AFRL-SR-AR-TR-02-034; No Copyright; Avail: CASI; A08, Hardcopy

Formation flying of multiple spacecraft is an enabling technology for many future space science missions. These future missions will, for example, use the highly coordinated, distributed array of vehicles for earth mapping interferometers and synthetic aperture radar. This thesis presents coordination and control algorithms designed for a fleet of spacecraft. These algorithms are embedded in a hierarchical fleet archi- tecture that includes a high-level coordinator for the fleet maneuvers used to form, re-size, or re-target the formation configuration and low-level controllers to generate and implement the individual control inputs for each vehicle. The trajectory and control problems are posed as linear programming (LP) optimizations to solve for the minimum fuel maneuvers. The combined result of the high-level coordination and low-level controllers is a very flexible optimization framework that can be used off-line to analyze aspects of a mission design and in real-time as part of an on-board autonomous formation flying control system. This thesis also investigates several crit- ical issues associated with the implementation of this formation flying approach. In particular, modifications to the LP algorithms are presented to: include robustness to sensor noise, include actuator constraints, ensure that the optimization solutions are always feasible, and reduce the LP solution times. Furthermore, the dynamics for the control problem are analyzed in terms of two key issues: 1) what dynamics model should be used to specify the desired state to maintain a passive aperture; and 2) what dynamics model should be used in the LP to represent the motion about this state. Several linearized models of the relative dynamics are considered in this analysis, including Hill's equations for circular orbits, modified linear dynamics that partially account for the J2 effects, and Lawden's equations for eccentric orbits.
DTIC
*Optimization; Formation Flying; Spacecraft Control; Automatic Control; Trajectory Control*

**20020085365** AI Solutions, Inc., Lanham, MD USA
**Preliminary Study for a Tetrahedron Formation: Quality Factors and Visualization**
Guzman, Jose J.; Schiff, Conrad; Bauer, Frank, Technical Monitor; [2002]; In English; AIAA/AAS Astrodynamics Specialist Conference, 5-8 Aug. 2002, Monterey, CA, USA
Contract(s)/Grant(s): NASS-01090; NAS5-01090; No Copyright; Avail: CASI; A03, Hardcopy

Spacecraft flying in tetrahedron formations are excellent for electromagnetic and plasma studies. The quality of the science recorded is strongly affected by the tetrahedron evolution. This paper is a preliminary study on the computation of quality factors and visualization for a formation of four or five satellites. Four of the satellites are arranged geometrically in a tetrahedron shape. If a fifth satellite is present, it is arbitrarily initialized at the geometric center of the tetrahedron. The fifth satellite could act as a collector or as a spare spacecraft. Tetrahedron natural coordinates are employed for the initialization. The natural orbit evolution is visualized in geocentric equatorial inertial and in geocentric solar magnetospheric coordinates.
Author
*Formation Flying; Satellite Control; Tetrahedrons; Scientific Visualization; Computerized Simulation; Coordinates; Q Factors*

**20020082933** NASA Goddard Space Flight Center, Greenbelt, MD USA
**A Closed-Loop Hardware Simulation of Decentralized Satellite Formation Control**
Ebimuma, Takuji; Lightsey, E. Glenn; Baur, Frank, Technical Monitor; [2002]; In English; American Astronautical Society Guidance and Control Conference, Feb. 2003, Breckenridge, CO, USA
Contract(s)/Grant(s): NAG5-11287; No Copyright; Avail: Other Sources; Abstract Only

In recent years, there has been significant interest in the use of formation flying spacecraft for a variety of earth and space science missions. Formation flying may provide smaller and cheaper satellites that, working together, have more capability than larger and more expensive satellites. Several decentralized architectures have been proposed for autonomous establishment and maintenance of satellite formations. In such architectures, each satellite cooperatively maintains the shape of the formation without a central supervisor, and processing only local measurement information. The Global Positioning System (GPS) sensors are ideally suited to provide such local position and velocity measurements to the individual satellites. An investigation of the feasibility of a decentralized approach to satellite formation flying was originally presented by Carpenter. He extended a decentralized linear-quadratic-Gaussian (LQG) framework proposed by Speyer in a fashion similar to an extended Kalman filter (EKE) which processed GPS position fix solutions. The new decentralized LQG architecture was demonstrated in a numerical simulation for a realistic scenario that is similar to missions that have been proposed by NASA and the U.S. Air Force. Another decentralized architecture was proposed by Park et al. using carrier differential-phase GPS (CDGPS). Recently, Busse et al demonstrated the decentralized CDGPS architecture in a hardware-in-the-loop simulation on the Formation Flying TestBed (FFTB) at Goddard Space Flight Center (GSFC), which features two Spirent Cox 16 channel GPS signal generator. Although representing a step forward by utilizing GPS signal simulators for a spacecraft formation flying simulation, only an open-loop performance, in which no maneuvers were executed based on the real-time state estimates, was considered. In this research, hardware experimentation has been extended to include closed-loop integrated guidance and navigation of multiple spacecraft formations using GPS receivers and real-time vehicle telemetry. A hardware closed-loop simulation has been performed using the decentralized LQG architecture proposed by Carpenter in the GPS test facility at the Center for Space Research (CSR). This is the first presentation using this type of hardware for demonstration of closed-loop spacecraft formation flying.
Author
*Hardware-in-the-Loop Simulation; Formation Flying; Satellite Control; Global Positioning System*

**20020071070** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Simulation of Guidance, Navigation, and Control Systems for Formation Flying Missions**
Burns, Rich; Bauer, Frank H., Technical Monitor; [2002]; In English; International Symposium on Formation Flying Missions and Technologies, 29-31 Oct. 2002, USA; No Copyright; Avail: Other Sources; Abstract Only

Concepts for missions of distributed spacecraft flying in formation abound. From high resolution interferometry to spatially distributed in-situ measurements, these mission concepts levy a myriad of guidance, navigation, and control (GNC) requirements on the spacecraft/formation as a single system. A critical step toward assessing and meeting these challenges lies in realistically simulating distributed spacecraft systems. The Formation Flying TestBed (FFTB) at NASA Goddard Space Flight Center's (GSFC) Guidance, Navigation, and Control Center is a hardware-in-the-loop simulation and development facility focused on GNC issues relevant to formation flying systems. The FFTB provides a realistic simulation of the vehicle dynamics and control for formation flying missions in order to: (1) conduct feasibility analyses of mission requirements, (2) conduct and answer mission and spacecraft design trades, and (3) serve as a host for GNC software and hardware development and testing. The initial capabilities of the FFTB are based upon an integration of high fidelity hardware and software simulation, emulation, and test platforms developed or employed at GSFC in recent years, including a high-fidelity Global Positioning System (GPS) simulator which has been a fundamental component of the GNC Center's GPS Test Facility. The FFTB will be continuously evolving over the next several years from a tool with capabilities in GPS navigation

hardware/software-in-the-loop analysis and closed loop GPS-based orbit control algorithm assessment. Eventually, it will include full capability to support all aspects of multi-sensor, absolute and relative state determination and control, in all (attitude and orbit) degrees of freedom, as well as information management for satellite clusters and constellations. A detailed description of the FFTB architecture is presented in the paper.
Author
*Formation Flying; Flight Management Systems; Computerized Simulation; Spacecraft Guidance; Control Simulation; Applications Programs (Computers)*

**20020067776** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Results of NASA's First Autonomous Formation Flying Experiment: Earth Observing-1 (EO-1)**
Folta, David; Hawkins, Albin; Bauer, Frank, Technical Monitor; [2002]; In English; AIAA/AAS Astodynamics Specialist Conference, 5-8 Aug. 2002, Monterey, CA, USA; No Copyright; Avail: Other Sources; Abstract Only

NASA's first autonomous formation flying mission completed its primary goal of demonstrating an advanced technology called enhanced formation flying. To enable this technology, the Flight Dynamics Analysis Branch at the Goddard Space Flight Center implemented a universal 3-axis formation flying algorithm in an autonomous executive flight code onboard the New Millennium Program's (NMP) Earth Observing-1 (EO-1) spacecraft. This paper describes the mathematical background of the autonomous formation flying algorithm, the onboard flight design and the validation results of this unique system. Results from fully autonomous maneuver control are presented as comparisons between the onboard EO-1 operational autonomous control system called AutoCon, its ground-based predecessor used in operations, and the original standalone algorithm. Maneuvers discussed encompass reactionary, routine formation maintenance, and inclination control. Orbital data is also examined to verify that all formation flying requirements were met.
Author
*Autonomy; Formation Flying; Earth Observing System (EOS); Algorithms; NASA Programs*

**20020067714** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Formation Flying Satellite Control Around the L2 Sun-Earth Libration Point**
Hamilton, Nicholas H.; Folta, David; Carpenter, Russell; Bauer, Frank, Technical Monitor; [2002]; In English; AIAA/AAS Astrodynamics Specialist Conference, 5-8 Aug. 2002, Monterey, CA, USA; No Copyright; Avail: Other Sources; Abstract Only

A growing interest in formation flying satellites demands development and analysis of control and estimation algorithms for station-keeping and formation maneuvering. This paper discusses the development of a discrete linear-quadratic-regulator control algorithm for formations in the vicinity of the L2 sun-earth libration point. The development of an appropriate Kalman filter is included as well. Simulations are created for the analysis of the station-keeping and various formation maneuvers of the Stellar Imager mission. The simulations provide tracking error, estimation error, and control effort results. From the control effort, useful design parameters such as delta V and propellant mass are determined. For formation maneuvering, the formation spacecraft track to within 4 meters of their desired position and within 1.5 millimeters per second of their desired zero velocity. The filter, with few exceptions, keeps the estimation errors within their three-sigma values. Without noise, the controller performs extremely well, with the formation spacecraft tracking to within several micrometers. Each spacecraft uses around 1 to 2 grams of propellant per maneuver, depending on the circumstances.
Author
*Formation Flying; Sun; Earth (Planet); Libration; Satellite Attitude Control; Algorithms*

**20020051734** Air Force Inst. of Tech., Wright-Patterson AFB, OH USA
**Stability of a Tethered Satellite Formation about the Likins-Pringle Equilibria**
Tuncay, Ayhan; Mar. 2002; In English; Original contains color images
Report No.(s): AD-A401589; AFIT/GSO/ENY/02-4; No Copyright; Avail: CASI; A05, Hardcopy

Previous efforts have been directed at the guidance and control of free flying satellites clusters using reaction thrusters. A tethered formation of satellites has great potential to enhance surveillance and imaging of earth objects. To maintain the shape of formation and keep the tethers in tension, the system needs to be spinning. General study has been focused on a planar formation and the results showed that Earth pointing configurations are not stable. This study demonstrates that spin stabilization and the use of gravity gradient for formation flight with tethered satellites reduce the necessity of thrusters for station keeping maneuvers. A tethered satellite formation, which consists of three satellites at the corners of an equilateral triangle, and two end bodies at the opposite side of this triangular plane is studied to obtain the stability based on the

Likins-Pringle relative equilibrium for rigid satellites, for long period. Depending on the size of the formation and the mass ratio of the satellites to end bodies, tethered satellite formation showed that long-term stability is achievable for a continuously earth-pointing system.
DTIC
*Artificial Satellites; Tethered Satellites; Imaging Techniques*

**20020050776** Illinois Univ., Urbana, IL USA
**Pulsed Electric Microthrusters With Solid Propellant for Microsats and Nanosats**
Burton, Rodney L.; Apr. 02, 2002; In English; Original contains color images
Contract(s)/Grant(s): F49620-99-1-0123
Report No.(s): AD-A401337; AFRL-SR-BL-TR-02-0154; No Copyright; Avail: CASI; A03, Hardcopy

This report describes progress, in experimental development, plasma diagnostics, and modeling, in advanced pulsed plasma thrusters (PPT) for application to formation-flying satellite constellations such as TechSat21. The research concentrated on coaxial Teflon PPTs, predominantly of the electrothermal (high thrust) type, with an average power of 100 watts. During this effort, performance advances were made both in the thruster design and in the pulsed circuitry driving the discharge, aided by increased understanding derived from a two-fluid model. The results of this research led to the development, under separate contract to CU Aerospace, of a PPT flight test model (PPT-8) which was tested at the AFRL Electric Propulsion Laboratory.
DTIC
*Electric Propulsion; Plasma Diagnostics; Pulsed Plasma Thrusters*

**20020048542** Air Force Inst. of Tech., Wright-Patterson AFB, OH USA
**Periodic Methods for Controlling a Satellite in Formation**
Carraher, Erin Y.; Mar. 2002; In English; Original contains color images
Report No.(s): AD-A401461; AFIT/GA/ENY/02-1; No Copyright; Avail: Defense Technical Information Center (DTIC)

Precise position determination and control is necessary to accomplish proposed satellite formation flying missions of ground movement target indication and synthetic aperture radar. This thesis combines the estimation and control techniques of past AFIT theses with various time-varying and time-invariant LQG control methods. Linear time-invariant control is ideal for on-board satellite estimation and control applications, freeing-up the satellite's limited computational capacity. Using a dynamics frame transformation from the nodal frame to an orbital frame, a higher fidelity, time-periodic model produced nearly identical results for either time-varying or time-invariant control for many scenarios. Scenarios included initial perturbations in the radial, in-track, and cross-track directions as well as increased magnitude perturbations; step size increase from 0.2 seconds to 2 seconds; and increased and reduced measurement noise level scenarios versus the standard absolute GPS receiver noise level.
DTIC
*Linear Quadratic Gaussian Control; Satellite Control; Formation Flying; Satellite Tracking; Satellite Constellations*

**20020031243** NASA Glenn Research Center, Cleveland, OH USA
**Networks for Autonomous Formation Flying Satellite Systems**
Knoblock, Eric J.; Konangi, Vijay K.; Wallett, Thomas M.; Bhasin, Kul B.; [2001]; In English, 17-20 Apr. 2001, Toulouse, France
Contract(s)/Grant(s): NCC3-595; RTOP 755-1B-00
Report No.(s): AIAA Paper 2001-0920; Copyright; Avail: CASI; A02, Hardcopy

The performance of three communications networks to support autonomous multi-spacecraft formation flying systems is presented. All systems are comprised of a ten-satellite formation arranged in a star topology, with one of the satellites designated as the central or 'mother ship.' All data is routed through the mother ship to the terrestrial network. The first system uses a TCP/lP over ATM protocol architecture within the formation the second system uses the IEEE 802.11 protocol architecture within the formation and the last system uses both of the previous architectures with a constellation of geosynchronous satellites serving as an intermediate point-of-contact between the formation and the terrestrial network. The simulations consist of file transfers using either the File Transfer Protocol (FTP) or the Simple Automatic File Exchange (SAFE) Protocol. The results compare the IF queuing delay, and IP processing delay at the mother ship as well as

application-level round-trip time for both systems, In all cases, using IEEE 802.11 within the formation yields less delay. Also, the throughput exhibited by SAFE is better than FTP.
Author
*Communication Networks; Satellite Communication; Protocol (Computers); Formation Flying*

**20020030290** NASA Glenn Research Center, Cleveland, OH USA
**Network Configuration Analysis for Formation Flying Satellites**
Knoblock, Eric J.; Wallett, Thomas M.; Konangi, Vijay K.; Bhasin, Kul B.; [2001]; In English, 10-17 Mar. 2001, Big Sky, MT, USA
Contract(s)/Grant(s): NCC3-595; RTOP 755-1B-00; No Copyright; Avail: CASI; A02, Hardcopy

The performance of two networks to support autonomous multi-spacecraft formation flying systems is presented. Both systems are comprised of a ten-satellite formation, with one of the satellites designated as the central or 'mother ship.' All data is routed through the mother ship to the terrestrial network. The first system uses a TCP/EP over ATM protocol architecture within the formation, and the second system uses the IEEE 802.11 protocol architecture within the formation. The simulations consist of file transfers using either the File Transfer Protocol (FTP) or the Simple Automatic File Exchange (SAFE) Protocol. The results compare the IP queuing delay, IP queue size and IP processing delay at the mother ship as well as end-to-end delay for both systems. In all cases, using IEEE 802.11 within the formation yields less delay. Also, the throughput exhibited by SAFE is better than FTP.
Author
*Formation Flying; Network Analysis; Protocol (Computers); Satellite Constellations; Data Transfer (Computers)*

**20010106922** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Distributed Spacecraft Control Architectures**
Carpenter, James Russell; Bauer, Frank H., Technical Monitor; [2001]; In English; 5th SIAM Conference Control and Its Applications, 12-14 Jul. 2001; No Copyright; Avail: Other Sources; Abstract Only

A fundamental issue for estimation and control of distributed systems such as formation flying spacecraft is the information exchange architecture. In centralized schemes, each subordinate need only share its measurement data with a central hub, and the subordinates depend on the center to direct their actions. In decentralized schemes, all nodes participate in the data exchange, so that each has the same in by formation as the center, and may thereby self-direct the same action that the center would have commanded, assuming all share a common goal. This talk compares and contrasts the centralized and decentralized schemes in the context of autonomously maintaining a distributed satellite formation.
Author
*Natural Satellites; Distributed Parameter Systems*

**20010084989** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Preliminary Results of NASA's First Autonomous Formation Flying Experiment: Earth Observing-1 (EO-1)**
Folta, David; Hawkins, Albin; 2001 Flight Mechanics Symposium; June 2001, 409-422; In English; No Copyright; Avail: CASI; A03, Hardcopy

NASA's first autonomous formation flying mission is completing a primary goal of demonstrating an advanced technology called enhanced formation flying. To enable this technology, the Guidance, Navigation, and Control center at the Goddard Space Flight Center has implemented an autonomous universal three-axis formation flying algorithm in executive flight code onboard the New Millennium Program's (NMP) Earth Observing-1 (EO-1) spacecraft. This paper describes the mathematical background of the autonomous formation flying algorithm and the onboard design and presents the preliminary validation results of this unique system. Results from functionality assessment and autonomous maneuver control are presented as comparisons between the onboard EO-1 operational autonomous control system called AutoCon(tm), its ground-based predecessor, and a stand-alone algorithm.
Author
*Algorithms; Autonomy; Spacecraft Control*

**20010084986** Hammers Co., USA
**Getting the Most Out of Four Thrusters on the Earth Observing-1 Spacecraft**
Blackman, Kathie; Hunt, Teresa; Sanneman, Paul; 2001 Flight Mechanics Symposium; June 2001, 361-375; In English; No Copyright; Avail: CASI; A03, Hardcopy

The NASA New Millennium Program (NMP) Earth Observing-1 (EO-1) spacecraft was launched in November 2000 on its primary mission to validate advanced remote sensing instruments. One of the critical mission requirements is formation flying with respect to the LandSat-7 mission for instrument image comparison. Due to the nature of the small spacecraft design, only four thrusters could be accommodated on the EO-1 spacecraft. This presented a challenge to the design of the Delta-V controller. This paper presents the design, development, and on-orbit performance of this thruster based control mode. The control algorithm utilizes an a-priori open loop firing pattern combined with closed loop feedback control. The observed attitude performance has been well within the five degree requirement, and the delivered Delta-V has been within 1% of the goal. This success will allow the EO-1 Enhanced Formation Flying experiment to proceed with a higher degree of accuracy and precision than would have otherwise been possible.
Author
*Satellite Orientation; Feedback Control; Algorithms*

**20010084968** NASA Goddard Space Flight Center, Greenbelt, MD USA
**A Preliminary Formation Flying Orbit Dynamics Analysis for Leonardo-BRDF**
Hughes, Steven P.; Mailhe, Laurie M.; 2001 Flight Mechanics Symposium; June 2001, 131; In English; No Copyright; Abstract Only; Available from CASI only as part of the entire parent document

Leonardo-BRDF is a NASA mission concept proposed to allow the investigation of radiative transfer and its effect on the Earth's climate and atmospheric phenomenon. Enabled by the recent developments in small-satellite and formation flying technology, the mission is envisioned to be composed of an array of spacecraft in carefully designed orbits. The different perspectives provided by a distributed array of spacecraft offer a unique advantage to study the Earth's albedo. This paper presents the orbit dynamics analysis performed in the context of the Leonardo-BRDF science requirements. First, the albedo integral is investigated and the effect of viewing geometry on science return is studied. The method used in this paper, based on Gauss quadrature, provides the optimal formation geometry to ensure that the value of the integral is accurately approximated. An orbit design approach is presented to achieve specific relative orbit geometries while simultaneously satisfying orbit dynamics constraints to reduce formation-keeping fuel expenditure. The relative geometry afforded by the design is discussed in terms of mission requirements. An optimal two-burn initialization scheme is presented with the required delta-V to distribute all spacecraft from a common parking orbit into their appropriate orbits in the formation. Finally, formation-keeping strategies are developed and the associated delta-V's are calculated to maintain the formation in the presence of perturbations.
Author
*Radiative Transfer; Orbital Mechanics; Earth Atmosphere; Radiation Effects; Mission Planning*

**20010084967** Texas A&M Univ., College Station, TX USA
**Relative Navigation for Formation Flying of Spacecraft**
Alonso, Roberto; Du, Ju-Young; Hughes, Declan; Junkins, John L.; Crassidis, John L.; 2001 Flight Mechanics Symposium; June 2001, 115-129; In English
Contract(s)/Grant(s): NCC5-448; AFOSR-32525-57200; 000512-0004-1999; No Copyright; Avail: CASI; A03, Hardcopy

This paper presents a robust and efficient approach for relative navigation and attitude estimation of spacecraft flying in formation. This approach uses measurements from a new optical sensor that provides a line of sight vector from the master spacecraft to the secondary satellite. The overall system provides a novel, reliable, and autonomous relative navigation and attitude determination system, employing relatively simple electronic circuits with modest digital signal processing requirements and is fully independent of any external systems. Experimental calibration results are presented, which are used to achieve accurate line of sight measurements. State estimation for formation flying is achieved through an optimal observer design. Also, because the rotational and translational motions are coupled through the observation vectors, three approaches are suggested to separate both signals just for stability analysis. Simulation and experimental results indicate that the combined sensor/estimator approach provides accurate relative position and attitude estimates.
Author
*Satellite Attitude Control; Autonomous Navigation; Computerized Simulation*

**20010084960** NASA Goddard Space Flight Center, Greenbelt, MD USA
**A Non-Linear Approach to Spacecraft Trajectory Control in the Vicinity of a Libration Point**
Luquette, Richard J.; Sanner, Robert M.; 2001 Flight Mechanics Symposium; June 2001, 15-24; In English; No Copyright; Avail: CASI; A02, Hardcopy

An expanding interest in mission design strategies that exploit libration point regions demands the continued development of enhanced, efficient, control algorithms for station-keeping and formation maintenance. This paper discusses the development of a non-linear, station-keeping, control algorithm for trajectories in the vicinity of a libration point. The control law guarantees exponential convergence, based on a Lyaponov analysis. Controller performance is evaluated using FreeFlyer(R) and MATLAB(R) for a spacecraft stationed near the L2 libration point in the Earth-Moon system, tracking a pre-defined reference trajectory. Evaluation metrics are fuel usage and tracking accuracy. Simulation results are compared with a linear-based controller for a spacecraft tracking the same reference trajectory. Although the analysis is framed in the context of station-keeping, the control algorithm is equally applicable to a formation flying problem with an appropriate definition of the reference trajectory.
Author
*Algorithms; Computerized Simulation; Spacecraft Trajectories; Trajectory Control*

**20010084958** NASA Goddard Space Flight Center, Greenbelt, MD USA
**2001 Flight Mechanics Symposium**
Lynch, John P., Editor; June 2001; In English, 19-21 Jun. 2001, Greenbelt, MD, USA
Report No.(s): NASA/CP-2001-209986; Rept-2001-02668-0; NAS 1.55:209986; NONP-NASA-CD-2001126425; No Copyright; Avail: CASI; A25, Hardcopy

This conference publication includes papers and abstracts presented at the Flight Mechanics Symposium held on June 19-21, 2001. Sponsored by the Guidance, Navigation and Control Center of Goddard Space Flight Center, this symposium featured technical papers on a wide range of issues related to attitude/orbit determination, prediction and control; attitude simulation; attitude sensor calibration; theoretical foundation of attitude computation; dynamics model improvements; autonomous navigation; constellation design and formation flying; estimation theory and computational techniques; Earth environment mission analysis and design; and, spacecraft re-entry mission design and operations.
Author
*Attitude (Inclination); Guidance (Motion); Navigation; Orbit Calculation; Satellite Orientation; Flight Mechanics*

**20010073392** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Considerations and Architectures for Inter-Satellite Communications in Distributed Spacecraft Systems**
Edwards, Bernard; Horne, William; Israel, David; Kwadrat, Carl; Bauer, Frank H., Technical Monitor; [2001]; In English; 2002 IEEE Aerospace Conference, 9-16 Mar. 2001, Big Sky, MT, USA; No Copyright; Avail: Other Sources; Abstract Only

This paper will identify the important characteristics and requirements necessary for inter-satellite communications in distributed spacecraft systems and present analysis results focusing on architectural and protocol comparisons. Emerging spacecraft systems plan to deploy multiple satellites in various 'distributed' configurations ranging from close proximity formation flying to widely separated constellations. Distributed spacecraft configurations provide advantages for science exploration and operations since many activities useful for missions may be better served by distributing them between spacecraft. For example, many scientific observations can be enhanced through spatially separated platforms, such as for deep space interferometry. operating multiple distributed spacecraft as a mission requires coordination that may be best provided through inter-satellite communications. For example, several future distributed spacecraft systems envision autonomous operations requiring relative navigational calculations and coordinated attitude and position corrections. To conduct these operations, data must be exchanged between spacecraft. Direct cross-links between satellites provides an efficient and practical method for transferring data and commands. Unlike existing 'bent-pipe' relay networks supporting space missions, no standard or widely-used method exists for cross-link communications. Consequently, to support these future missions, the characteristics necessary for inter-satellite communications need to be examined. At first glance, all of the missions look extremely different. Some missions call for tens to hundreds of nano-satellites in constant communications in close proximity to each other. Other missions call for a handful of satellites communicating very slowly over thousands to hundreds of thousands of kilometers. The paper will first classify distributed spacecraft missions to help guide the evaluation and definition of cross-link architectures and approaches. Based on this general classification, the paper will examine general physical layer parameters, such as frequency bands and data rates, necessary to support the missions. The paper will also identify classes of communication architectures that may be employed, ranging from fully distributed to centralized topologies. Numerous factors, such as number of spacecraft, must be evaluated when attempting to pick a communications architecture. Also important is the stability of the formation from a communications standpoint. For example, do all of the spacecraft require equal bandwidth and are spacecraft allowed to enter and leave a formation? The type of science mission being attempted may also heavily influence the communications architecture. In addition, the paper will assess various parameters and characteristics typically associated with the data link layer. The paper will analyze the performance of various multiple access

techniques given the operational scenario, requirements, and communication topologies envisioned for missions. This assessment will also include a survey of existing standards and their applicability for distributed spacecraft systems. An important consideration includes the interoperability of the lower layers (physical and data link) examined in this paper with the higher layer protocols(network) envisioned for future space internetworking. Finally, the paper will define a suggested path, including preliminary recommendations, for defining and developing a standard for intersatellite communications based on the classes of distributed spacecraft missions and analysis results.
Author
*Satellite Communication; Systems Engineering; Autonomy; Spacecraft Configurations; Communication Networks*

**20010069328** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Spacecraft Formation Flying Maneuvers Using Linear-Quadratic Regulation with No Radial Axis Inputs**
Starin, Scott R.; Yedavalli, R. K.; Sparks, Andrew G.; Bauer, Frank H., Technical Monitor; 2001; In English; AIAA Guidance, Navigation and Control Conference, 6-9 Aug. 2001, Montreal, Quebec, Canada
Report No.(s): AIAA Paper 6504; Copyright; Avail: CASI; A02, Hardcopy

Regarding multiple spacecraft formation flying, the observation has been made that control thrust need only be applied coplanar to the local horizon to achieve complete controllability of a two-satellite (leader-follower) formation. A formulation of orbital dynamics using the state of one satellite relative to another is used. Without the need for thrust along the radial (zenith-nadir) axis of the relative reference frame, propulsion system simplifications and weight reduction may be accomplished. Several linear-quadratic regulators (LQR) are explored and compared based on performance measures likely to be important to many missions, but not directly optimized in the LQR designs. Maneuver simulations are performed using commercial ODE solvers to propagate the Keplerian dynamics of a controlled satellite relative to an uncontrolled leader. These short maneuver simulations demonstrate the capacity of the controller to perform changes from one formation geometry to another. This work focusses on formations in which the controlled satellite has a relative trajectory which projects onto the local horizon of the uncontrolled satellite as a circle. This formation has potential uses for distributed remote sensing systems.
Author
*Spacecraft Maneuvers; Linear Quadratic Regulator; Controllability; Satellite Observation; Controllers*

**20010049373** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Design of a LQR Controller of Reduced Inputs for Multiple Spacecraft Formation Flying**
Starin, Scott R.; Yedavalli, R. K.; Sparks, Andrew G.; Bauer, Frank H., Technical Monitor; [2001]; In English; 2001 American Control Conference, 25-27 Jun. 2001, USA; No Copyright; Avail: CASI; A02, Hardcopy

Regarding multiple spacecraft formation flying, the observation is made that control thrust need only be applied coplanar to the local horizon to achieve complete controllability of a two-satellite formation. Without the need for zenith-nadir (radial) thrust, simplifications and reduction of the weight of the propulsion system may be accomplished. This work focuses on the validation of this radial-excluding control system on its own merits, and in comparison to a related system which does provide thrust parallel to the orbital radius. Simulations are performed using commercial ODE solvers to propagate the Keplerian dynamics of a controlled satellite relative to an uncontrolled, leader satellite. The conclusion is drawn that, despite the exclusion of the radial thrust axis, the remaining control thrust available still provides enough control to design a gain matrix of adequate performance using linear-quadratic regulator (LQR) techniques.
Author
*Linear Quadratic Regulator; Prediction Analysis Techniques; Thrust Control; Control Systems Design*

**20010046998** NASA Langley Research Center, Hampton, VA USA
**Use of a GCM to Explore Sampling Issues in Connection with Satellite Remote Sensing of the Earth Radiation Budget**
Fowler, Laura D.; Wielicki, Bruce A.; Randall, David A.; Branson, Mark D.; Gibson, Gary G.; Denn, Fredrick M.; Journal of Geophysical Research; Aug. 27, 2000; ISSN 0148-0227; Volume 105, Issue No. D16, 20,757-20,772; In English; Original contains color illustrations
Contract(s)/Grant(s): NAG1-1266
Report No.(s): Paper-2000JD900239; Copyright; Avail: Other Sources

Collocated in time and space, top-of-the-atmosphere measurements of the Earth radiation budget (ERB) and cloudiness from passive scanning radiometers, and lidar- and radar-in-space measurements of multilayered cloud systems, are the required combination to improve our understanding of the role of clouds and radiation in climate. Experiments to fly multiple satellites ‘in formation’ to measure simultaneously the radiative and optical properties of overlapping cloud systems are being

designed. Because satellites carrying ERB experiments and satellites carrying lidars- or radars-in space have different orbital characteristics, the number of simultaneous measurements of radiation and clouds is reduced relative to the number of measurements made by each satellite independently. Monthly averaged coincident observations of radiation and cloudiness are biased when compared against more frequently sampled observations due, in particular, to the undersampling of their diurnal cycle, Using the Colorado State University General Circulation Model (CSU GCM), the goal of this study is to measure the impact of using simultaneous observations from the Earth Observing System (EOS) platform and companion satellites flying lidars or radars on monthly averaged diagnostics of longwave radiation, cloudiness, and its cloud optical properties. To do so, the hourly varying geographical distributions of coincident locations between the afternoon EOS (EOS-PM) orbit and the orbit of the ICESAT satellite set to fly at the altitude of 600 km, and between the EOS PM orbit and the orbits of the PICASSO satellite proposed to fly at the altitudes of 485 km (PICA485) or 705 km (PICA705), are simulated in the CSU GCM for a 60-month time period starting at the idealistic July 1, 2001, launch date. Monthly averaged diagnostics of the top-of-the-atmosphere, atmospheric, and surface longwave radiation budgets and clouds accumulated over grid boxes corresponding to satellite overpasses are compared against monthly averaged diagnostics obtained from hourly samplings over the entire globe. Results show that differences between irregularly (satellite) and regularly (true) sampled diagnostics of the longwave net radiative budgets are the greatest at the surface and the smallest in the atmosphere and at the top-of-the-atmosphere, under both cloud-free and cloudy conditions. In contrast, differences between the satellite and the true diagnostics of the longwave cloud radiative forcings are the largest in the atmosphere and at the top-of-the-atmosphere, and the smallest at the surface. A poorer diurnal sampling of the surface temperature in the satellite simulations relative to the true simulation contributes a major part to sampling biases in the longwave net radiative budgets, while a poorer diurnal sampling of cloudiness and its optical properties directly affects diagnostics of the longwave cloud radiative forcings. A factor of 8 difference in the number of satellite overpasses between PICA705 and PICA485 and ICESAT leads to a systematic factor of 3 difference in the spatial standard deviations of all radiative and cloudiness diagnostics.
Author
*Atmospheric General Circulation Models; Earth Radiation Budget; Radiation Effects; Optical Properties; Earth Observing System (EOS); Surface Temperature*

**20010037725** Honeywell, Inc., Plymouth, MN USA
**MEMS Mega-Pixel Micro-Thruster Array**
Youngner, Daniel W.; Oct. 14, 2000; In English
Contract(s)/Grant(s): F49620-99-C-0012
Report No.(s): AD-A386952; AFRL-SR-BL-TR-01-0028; No Copyright; Avail: CASI; A02, Hardcopy

Small satellites flying in clusters require periodic 'stationkeeping' to keep them in place. The required impulse is very small - the goal is not to keep the individual satellites in rigid formation, but only to keep them in well-defined orbitals with respect to one another. The necessary impulse, therefore, is only the amount needed to overcome the difference in drag between the most-affected and the least-affected satellites in the cluster. Estimates are that the differential drag can be overcome by providing -l uNsec (micro-Newton second) to -l mN sec (milli-Newton gecond) every 10 to 100 seconds throughout each satellite's mission. The system we are developing will do that. The thrusters have very low power and energy thresholds for ignition ( 10 mWatts, 100 Joules), and no moving parts so they are expected to be highly reliable. A single thruster array contains a quarter of a million separate thrusters.
DTIC
*Artificial Satellites; Spacecraft Propulsion; Microrocket Engines; Thrustors*

**20010028699** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Spacecraft Formation Flying Maneuvers Using Linear Quadratic Regulation With No Radial Axis Inputs**
Starin, Scott R.; Yedavalli, R. K.; Sparks, Andrew G.; Bauer, Frank H., Technical Monitor; [2001]; In English; Flight Dynamics Conference, Aug. 2001, Canada; No Copyright; Avail: Other Sources; Abstract Only

Regarding multiple spacecraft formation flying, the observation has been made that control thrust need only be applied coplanar to the local horizon to achieve complete controllability of a two-satellite (leader-follower) formation. A formulation of orbital dynamics using the state of one satellite relative to another is used. Without the need for thrust along the radial (zenith-nadir) axis of the relative reference frame, propulsion system simplifications and weight reduction may be accomplished. This work focuses on the validation of this control system on its own merits, and in comparison to a related system which does provide thrust along the radial axis of the relative frame. Maneuver simulations are performed using commercial ODE solvers to propagate the Keplerian dynamics of a controlled satellite relative to an uncontrolled leader. These short maneuver simulations demonstrate the capacity of the controller to perform changes from one formation geometry to

another. Control algorithm performance is evaluated based on measures such as the fuel required to complete a maneuver and the maximum acceleration required by the controller. Based on this evaluation, the exclusion of the radial axis of control still allows enough control authority to use Linear Quadratic Regulator (LQR) techniques to design a gain matrix of adequate performance over finite maneuvers. Additional simulations are conducted including perturbations and using no radial control inputs. A major conclusion presented is that control inputs along the three axes have significantly different relationships to the governing orbital dynamics that may be exploited using LQR.
Author
*Spacecraft Maneuvers; Simulation; Linear Quadratic Regulator; Differential Equations; Controllability; Algorithms*

**20010022253** NASA Goddard Space Flight Center, Albuquerque, NM USA
**Automating Trend Analysis for Spacecraft Constellations**
Davis, George; Cooter, Miranda; Updike, Clark; Carey, Everett; Mackey, Jennifer; Rykowski, Timothy; Powers, Edward I., Technical Monitor; [2001]; In English; 6th AI, Robotics and Automation in Space, Jun. 2001, Montreal, Canada; No Copyright; Avail: Other Sources; Abstract Only

Spacecraft trend analysis is a vital mission operations function performed by satellite controllers and engineers, who perform detailed analyses of engineering telemetry data to diagnose subsystem faults and to detect trends that may potentially lead to degraded subsystem performance or failure in the future. It is this latter function that is of greatest importance, for careful trending can often predict or detect events that may lead to a spacecraft's entry into safe-hold. Early prediction and detection of such events could result in the avoidance of, or rapid return to service from, spacecraft safing, which not only results in reduced recovery costs but also in a higher overall level of service for the satellite system. Contemporary spacecraft trending activities are manually intensive and are primarily performed diagnostically after a fault occurs, rather than proactively to predict its occurrence. They also tend to rely on information systems and software that are oudated when compared to current technologies. When coupled with the fact that flight operations teams often have limited resources, proactive trending opportunities are limited, and detailed trend analysis is often reserved for critical responses to safe holds or other on-orbit events such as maneuvers. While the contemporary trend analysis approach has sufficed for current single-spacecraft operations, it will be unfeasible for NASA's planned and proposed space science constellations. Missions such as the Dynamics, Reconnection and Configuration Observatory (DRACO), for example, are planning to launch as many as 100 'nanospacecraft' to form a homogenous constellation. A simple extrapolation of resources and manpower based on single-spacecraft operations suggests that trending for such a large spacecraft fleet will be unmanageable, unwieldy, and cost-prohibitive. It is therefore imperative that an approach to automating the spacecraft trend analysis function be studied, developed, and applied to missions such as DRACO with the intent that mission operations costs be significantly reduced. The goal of the Constellation Spacecraft Trend Analysis Toolkit (CSTAT) project is to serve as the pathfinder for a fully automated trending system to support spacecraft constellations. The development approach to be taken is evolutionary. In the first year of the project, the intent is to significantly advance the state of the art in current trending systems through improved functionality and increased automation. In the second year, the intent is to add an expert system shell, likely through the adaptation of an existing commercial-off-the-shelf (COTS) or government-off-the-shelf (GOTS) tool to implement some level of the trending intelligence that humans currently provide in manual operations. In the third year, the intent is to infuse the resulting technology into a near-term constellation or formation-flying mission to test it and gain experience in automated trending. The lessons learned from the real missions operations experience will then be used to improve the system, and to ultimately incorporate it into a fully autonomous, closed-loop mission operations system that is truly capable of supporting large constellations. In this paper, the process of automating trend analysis for spacecraft constellations will be addressed. First, the results of a survey on automation in spacecraft mission operations in general, and in trending systems in particular will be presented to provide an overview of the current state of the art. Next, a rule-based model for implementing intelligent spacecraft subsystem trending will be then presented, followed by a survey of existing COTS/GOTS tools that could be adapted for implementing such a model. The baseline design and architecture of the CSTAT system will be presented. Finally, some results obtained from initial software tests and demonstrations will be presented.
Author
*Satellite Constellations; Trend Analysis; Mission Planning; Autonomy*

**20010020064** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Advance Formation Flying Concepts**
Wiscombe, Warren; Einaudi, Franco, Technical Monitor; [2000]; In English; NIAC Workshop, 7-9 Nov. 2000, Atlanta, GA, USA; No Copyright; Avail: Other Sources; Abstract Only

Some of the suggested formation flying missions for the next 10 years will be presented. Most of these are in the space

science area. The reasons for the lesser interest from Earth scientists will be listed and critiqued. The needs for space infrastructure to service formations of low-Earth-orbit satellite will be brought out, including possible uses of the International Space Station.
Author
*Satellite Constellations; Stationkeeping*

**20010017835** NASA Goddard Space Flight Center, Greenbelt, MD USA
**A Hardware-in-the-Loop Testbed for Spacecraft Formation Flying Applications**
Leitner, Jesse; Bauer, Frank H., Technical Monitor; [2001]; In English; Aerospace, 10-17 Mar. 2001, Big Sky, MT, USA; Original contains color illustrations; No Copyright; Avail: CASI; A02, Hardcopy

The Formation Flying Test Bed (FFTB) at NASA Goddard Space Flight Center (GSFC) is being developed as a modular, hybrid dynamic simulation facility employed for end-to-end guidance, navigation, and control (GN&C) analysis and design for formation flying clusters and constellations of satellites. The FFTB will support critical hardware and software technology development to enable current and future missions for NASA, other government agencies, and external customers for a wide range of missions, particularly those involving distributed spacecraft operations. The initial capabilities of the FFTB are based upon an integration of high fidelity hardware and software simulation, emulation, and test platforms developed at GSFC in recent years; including a high-fidelity GPS simulator which has been a fundamental component of the Guidance, Navigation, and Control Center's GPS Test Facility. The FFTB will be continuously evolving over the next several years from a too[ with initial capabilities in GPS navigation hardware/software- in-the- loop analysis and closed loop GPS-based orbit control algorithm assessment to one with cross-link communications and relative navigation analysis and simulation capability. Eventually the FFT13 will provide full capability to support all aspects of multi-sensor, absolute and relative position determination and control, in all (attitude and orbit) degrees of freedom, as well as information management for satellite clusters and constellations. In this paper we focus on the architecture for the FFT13 as a general GN&C analysis environment for the spacecraft formation flying community inside and outside of NASA GSFC and we briefly reference some current and future activities which will drive the requirements and development.
Author
*Computerized Simulation; Computers; Crosslinking; Degrees of Freedom; Feedback Control; Navigation*

**20010016288** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Flight Dynamics Analysis for Leonardo-BRDF**
Hughes, Steven P.; Mailhe, Laurie; Bauer, Frank H., Technical Monitor; [2000]; In English; 2001 Aerospace Conference, 10-17 Mar. 2001, Big Sky, MT, USA; No Copyright; Avail: Other Sources; Abstract Only

Leonardo-BRDF (Bidirectional Reflectance Distribution Function) is a new NASA mission concept proposed to allow the investigation of radiative transfer and its effect on the Earth's climate and atmospheric phenomenon. Enabled by the recent developments in small-satellite and formation flying technology, the mission is envisioned to be composed of an array of spacecraft in carefully designed orbits. The different perspectives provided by a distributed array of spacecraft offer a unique advantage to study the Earth's albedo. This paper presents the flight dynamics analysis performed in the context of the Leonardo-BRDF science requirements. First, the albedo integral is investigated and the effect of viewing geometry on science return is studied. The method used in this paper, based on Gauss quadrature, provides the optimal formation geometry to ensure that the value of the integral is accurately approximated. An orbit design approach is presented to achieve specific relative orbit geometries while simultaneously satisfying orbit dynamics constraints to reduce formation-keeping fuel expenditure. The relative geometry afforded by the design is discussed in terms of mission requirements. An optimal Lambert initialization scheme is presented with the required Delta-V to distribute all spacecraft from a common parking orbit into their appropriate orbits in the formation. Finally, formation-keeping strategies are developed and the associated Delta-V's are calculated to maintain the formation in the presence of perturbations.
Author
*Mission Planning; Radiative Transfer; Climatology; Atmospheric Effects*

**20010015231** Virginia Polytechnic Inst. and State Univ., Blacksburg, VA USA
**Formations of Free-Flying Gyrostat Telescopes**
Hall, Christopher D.; Oct. 20, 2000; In English
Contract(s)/Grant(s): F49620-98-1-0213
Report No.(s): AD-A384113; AFRL-SR-BL-TR-00-0569; No Copyright; Avail: CASI; A03, Hardcopy

In this project, we have investigated a variety of problems arising in the orbital and attitude dynamics and control of formation flying. We established important collaborations, and leveraged this AFOSR support with support from NASA and the NSF to strengthen space-related research projects at Virginia Tech. Continued work with former AFIT students (J. Beck, K. Ford, and M. Marasch) was directly tied to projects of the Space Vehicles Directorate (AFRL/VS) interest, and resulted in archival publications and conference presentations. Collaboration with Professor P. Tsiotras of Georgia Tech resulted in two conference presentations, one archival publication and an additional article in preparation. Work with graduate students at Virginia Tech resulted in archival and conference publications. Publication details are given at the end of this report. This research project has direct tie-in to other projects supported by AFOSR and DARPA (University Nanosatellite Project), AFRL (PowerSail), NASA Goddard Space Flight Center (Distributed Spacecraft), Universities Space Research Associates (University Nanosatellite Project), and the National Science Foundation (Analysis of Momentum Exchange in Spacecraft Attitude Dynamics and Control). We continue to attract high-quality US civilian and Air Force graduate students to these pace-related projects. Furthermore, in teaching senior space design at Virginia Tech, we have supported several projects at both NASA's Goddard Space Flight Center and AFRL's Space Vehicles Directorate.
DTIC
*Telescopes; Gyroscopes; Attitude (Inclination); Dynamic Control; Attitude Control*

**20010012829** Air Force Office of Scientific Research, Bolling AFB, Washington, DC USA
**An Innovative Approach to Satellite Technology**
Janni, Joseph F.; King, Yolanda Jones; Witt, Gerald; Space-Based Observation Technology; October 2000, 17-1 - 17-7; In English; Copyright; Avail: CASI; A02, Hardcopy

Innovation and rapid prototyping using advanced technologies are the hallmarks of new initiatives coming from the USAF Research Laboratory's Office of Scientific Research (AFOSR). University Nanosatellite Program AFOSR, in conjunction with DARPA, is sponsoring ten universities, formed into small teams and challenged with paving the way to novel space capabilities. The satellites leverage innovative thinking within our universities, leading to flight experiments of state-of-technologies and advanced mission concepts. Experiments range from micro-propulsion to formation flying. These miniaturized satellites will be prototyped and launched. We describe the philosophy, approach, and results to date of the program. TechSat21 Program. Recent progress in the miniaturization of key satellite technologies enables innovative solutions for space missions. AFOSR, in Conjunction with ARFL'S Space Vehicles Directorate, has developed the TechSat 21 program. This low-cost, lightweight cluster of cooperating microsatellites may eventually replace today's heavy and more expensive systems. Each microsatellite will communicate with other members of the cluster to share information and mission functions, thus comprising a 'virtual' satellite. TechSat 21 offers the flexibility to incorporate cutting edge technology in a reconfigurable constellation. This unusual approach offers multi-mission capability as well as a reduced life cycle cost. It is envisioned that new technology may be inserted by replacing members of the cluster with enhanced versions. Research and technology investments include sparse aperture sensing, local communications in space and microsatellite bus technologies. The investment in innovative. basic research areas to make TechSat 21 a viable alternative as well as the overall program approach will be covered. Many of the techniques and technologies being demonstrated in the University Satellite program have application to the TechSat2l program.
Derived from text
*Microsatellites; Microminiaturization; Small Satellite Technology; Nanosatellites*

**20000119102** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Recent Results From The Nasa Earth Science Terra Mission and Future Possibilities**
Salomonson, Vincent V.; [2000]; In English, 19-21 Sep. 2000, Long Beach, CA, USA; No Copyright; Avail: Other Sources; Abstract Only

The NASA Earth Sciences Enterprise has made some remarkable strides in recent times in using developing, implementing, and utilizing spaceborne observations to better understand how the Earth works as a coupled, interactive system of the land, ocean, and atmosphere. Notable examples include the Upper Atmosphere Research (UARS) Satellite, the Topology Ocean Experiment (TOPEX) mission, Landsat-7, SeaWiFS, the Tropical Rainfall Monitoring Mission (TRMM), Quickscatt, the Shuttle Radar Topography Mission (SRTM), and, quite recently, the Terra'/Earth Observing System-1 mission. The Terra mission, for example, represents a major step forward in providing sensors that offer considerable advantages and progress over heritage instruments. The Moderate Resolution Imaging Spectrometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), the Measurements of Pollution in the Troposphere (MOPITT), the Advanced Spaceborne Thermal Emissions and Reflections (ASTER) radiometer, and the Clouds and Earth's Radiant Energy System (CERES) radiometer are the instruments involved. Early indications in March indicate that each of these instruments are working well and will be

augmenting data bases from heritage instruments as well as producing new, unprecedented observations of land, ocean, and atmosphere features. Several missions will follow the Terra mission as the Earth Observing mission systems complete development and go into operation. These missions include EOS PM-1/'Aqua', Icesat, Vegetation Canopy Lidar (VCL), Jason/TOPEX Follow-on, the Chemistry mission, etc. As the Earth Observing systems completes its first phase in about 2004 a wealth of data enabling better understanding of the Earth and the management of its resources will have been provided. Considerable thought is beginning to be placed on what advances in technology can be implemented that will enable further advances in the early part of the 21st century; e.g., in the time from of 2020. Concepts such as 'constellation' missions or 'formation flying' with 'sensorcraft', 'sensor webs', autonomous operation of satellites, more on-board processing and delivery to individual users, data synthesis and analysis in real-time, etc. are being considered. With the data now having been and soon to be received plus the very real possibilities of further advances in use and applicability of data the potential for very significant gains in knowledge for Earth studies and applications looks quite high in the next decade or two.
Author
*Spacecraft Performance; Earth Observations (From Space); Earth Sciences; Postlaunch Reports; Air Land Interactions; Air Water Interactions; Technology Utilization*

**20000091540** NASA Goddard Space Flight Center, Greenbelt, MD USA
**2000 Survey of Distributed Spacecraft Technologies and Architectures for NASA's Earth Science Enterprise in the 2010-2025 Timeframe**
Ticker, Ronald L.; Azzolini, John D.; August 2000; In English
Report No.(s): NASA/TM-2000-209964; Rept-2000-03777-0; NAS 1.15:209964; No Copyright; Avail: CASI; A04, Hardcopy

The study investigates NASA's Earth Science Enterprise needs for Distributed Spacecraft Technologies in the 2010-2025 timeframe. In particular, the study focused on the Earth Science Vision Initiative and extrapolation of the measurement architecture from the 2002-2010 time period. Earth Science Enterprise documents were reviewed. Interviews were conducted with a number of Earth scientists and technologists. fundamental principles of formation flying were also explored. The results led to the development of four notional distribution spacecraft architectures. These four notional architectures (global constellations, virtual platforms, precision formation flying, and sensorwebs) are presented. They broadly and generically cover the distributed spacecraft architectures needed by Earth Science in the post-2010 era. These notional architectures are used to identify technology needs and drivers. Technology needs are subsequently grouped into five categories: Systems and architecture development tools; Miniaturization, production, manufacture, test and calibration; Data networks and information management; Orbit control, planning and operations; and Launch and deployment. The current state of the art and expected developments are explored. High-value technology areas are identified for possible future funding emphasis.
Derived from text
*Surveys; Technology Utilization; Technological Forecasting*

**20000091037** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Semi-Major Axis Knowledge and GPS Orbit Determination**
Carpenter, J. Russell; Schiesser, Emil R.; Bauer, F., Technical Monitor; [2000]; In English
Contract(s)/Grant(s): RTOP 315-90-12-01; No Copyright; Avail: CASI; A03, Hardcopy

In recent years spacecraft designers have increasingly sought to use onboard Global Positioning System receivers for orbit determination. The superb positioning accuracy of GPS has tended to focus more attention on the system's capability to determine the spacecraft's location at a particular epoch than on accurate orbit determination, per se. The determination of orbit plane orientation and orbit shape to acceptable levels is less challenging than the determination of orbital period or semi-major axis. It is necessary to address semi-major axis mission requirements and the GPS receiver capability for orbital maneuver targeting and other operations that require trajectory prediction. Failure to determine semi-major axis accurately can result in a solution that may not be usable for targeting the execution of orbit adjustment and rendezvous maneuvers. Simple formulas, charts, and rules of thumb relating position, velocity, and semi-major axis are useful in design and analysis of GPS receivers for near circular orbit operations, including rendezvous and formation flying missions. Space Shuttle flights of a number of different GPS receivers, including a mix of unfiltered and filtered solution data and Standard and Precise Positioning, Service modes, have been accomplished. These results indicate that semi-major axis is often not determined very accurately, due to a poor velocity solution and a lack of proper filtering to provide good radial and speed error correlation.
Author
*Global Positioning System; Flight Paths; Orbit Determination; Satellite Tracking; Spacecraft Position Indicators; Orbital Position Estimation*

**20000086214** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Enabling Spacecraft Formation Flying through Position Determination, Control and Enhanced Automation Technologies**
Bristow, John; Bauer, Frank; Hartman, Kate; How, Jonathan; [2000]; In English; 15th, 26-30 Jun. 2000, Biarritz, France; No Copyright; Avail: CASI; A03, Hardcopy

Formation Flying is revolutionizing the way the space community conducts science missions around the Earth and in deep space. This technological revolution will provide new, innovative ways for the community to gather scientific information, share that information between space vehicles and the ground, and expedite the human exploration of space. Once fully matured, formation flying will result in numerous sciencecraft acting as virtual platforms and sensor webs, gathering significantly more and better science data than call be collected today. To achieve this goal, key technologies must be developed including those that address the following basic questions posed by the spacecraft: Where am I? Where is the rest of the fleet? Where do I need to be? What do I have to do (and what am I able to do) to get there? The answers to these questions and the means to implement those answers will depend oil the specific mission needs and formation configuration. However, certain critical technologies are common to most formations. These technologies include high-precision position and relative-position knowledge including Global Positioning System (GPS) mid celestial navigation; high degrees of spacecraft autonomy inter-spacecraft communication capabilities; targeting and control including distributed control algorithms, and high precision control thrusters and actuators. This paper provides an overview of a selection of the current activities NASA/DoD/Industry/Academia are working to develop Formation Flying technologies as quickly as possible, the hurdles that need to be overcome to achieve our formation flying vision, and the team's approach to transfer this technology to space. It will also describe several of the formation flying testbeds, such as Orion and University Nanosatellites, that are being developed to demonstrate and validate many of these innovative sensing and formation control technologies.
Author
*Autonomy; Space Flight; Position (Location); Active Control; Space Missions*

**20000084327** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Semi-Major Axis Knowledge and GPS Orbit Determination**
Carpenter, J. Russell; Schiesser, Emil R.; Bauer, F., Technical Monitor; [2000]; In English
Contract(s)/Grant(s): RTOP 315-90-12-01; No Copyright; Avail: CASI; A03, Hardcopy

In recent years spacecraft designers have increasingly sought to use onboard Global Positioning System receivers for orbit determination. The superb positioning accuracy of GPS has tended to focus more attention on the system's capability to determine the spacecraft's location at a particular epoch than on accurate orbit determination, per se. The determination of orbit plane orientation and orbit shape to acceptable levels is less challenging than the determination of orbital period or semi-major axis. It is necessary to address semi-major axis mission requirements and the GPS receiver capability for orbital maneuver targeting and other operations that require trajectory prediction. Failure to determine semi-major axis accurately can result in a solution that may not be usable for targeting the execution of orbit adjustment and rendezvous maneuvers. Simple formulas, charts, and rules of thumb relating position, velocity, and semi-major axis are useful in design and analysis of GPS receivers for near circular orbit operations, including rendezvous and formation flying missions. Space Shuttle flights of a number of different GPS receivers, including a mix of unfiltered and filtered solution data and Standard and Precise Positioning Service modes, have been accomplished. These results indicate that semi-major axis is often not determined very accurately, due to a poor velocity solution and a lack of proper filtering to provide good radial and speed error correlation.
Author
*Global Positioning System; Orbital Maneuvers; Circular Orbits; Orbit Determination*

**20000083880** NASA Goddard Space Flight Center, Greenbelt, MD USA
**Formation Flying With Decentralized Control in Libration Point Orbits**
Folta, David; Carpenter, J. Russell; Wagner, Christoph; [2000]; In English; 15th, 26-30 Jun. 2000, Biarritz, France; No Copyright; Avail: CASI; A03, Hardcopy

A decentralized control framework is investigated for applicability of formation flying control in libration orbits. The decentralized approach, being non-hierarchical, processes only direct measurement data, in parallel with the other spacecraft. Control is accomplished via linearization about a reference libration orbit with standard control using a Linear Quadratic Regulator (LQR) or the GSFC control algorithm. Both are linearized about the current state estimate as with the extended Kalman filter. Based on this preliminary work, the decentralized approach appears to be feasible for upcoming libration missions using distributed spacecraft.
Author
*Libration; Linear Quadratic Regulator; Research; Orbit Determination; Flight Characteristics*

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**Autonomy Architectures for a Constellation of Spacecraft**

Barrett, Anthony; June 2000; In English; No Copyright; Avail: Other Sources; Abstract Only

Until the past few years, missions typically involved fairly large expensive spacecraft. Such missions have primarily favored using older proven technologies over more recently developed ones, and humans controlled spacecraft by manually generating detailed command sequences with low-level tools and then transmitting the sequences for subsequent execution on a spacecraft controller. This approach toward controlling a spacecraft has worked spectacularly on previous missions, but it has limitations deriving from communications restrictions - scheduling time to communicate with a particular spacecraft involves competing with other projects due to the limited number of deep space network antennae. This implies that a spacecraft can spend a long time just waiting whenever a command sequence fails. This is one reason why the New Millennium program has an objective to migrate parts of mission control tasks onboard a spacecraft to reduce wait time by making spacecraft more robust. The migrated software is called a 'remote agent' and has 4 components: a mission manager to generate the high level goals, a planner/scheduler to turn goals into activities while reasoning about future expected situations, an executive/diagnostics engine to initiate and maintain activities while interpreting sensed events by reasoning about past and present situations, and a conventional real-time subsystem to interface with the spacecraft to implement an activity's primitive actions. In addition to needing remote planning and execution for isolated spacecraft, a trend toward multiple-spacecraft missions points to the need for remote distributed planning and execution. The past few years have seen missions with growing numbers of probes. Pathfinder has its rover (Sojourner), Cassini has its lander (Huygens), and the New Millenium Deep Space 3 (DS3) proposal involves a constellation of 3 spacecraft for interferometric mapping. This trend is expected to continue to progressively larger fleets. For example, one mission proposed to succeed DS3 would have 18 spacecraft flying in formation in order to detect earth-sized planets orbiting other stars. A proposed magnetospheric constellation would involve 5 to 500 spacecraft in Earth orbit to measure global phenomena within the magnetosphere. This work describes and compares three autonomy architectures for a system that continuously plans to control a fleet of spacecraft using collective mission goals instead of goals or command sequences for each spacecraft. A fleet of self-commanding spacecraft would autonomously coordinate itself to satisfy high level science and engineering goals in a changing partially-understood environment making feasible the operation of tens or even a hundred spacecraft (such as for interferometry or plasma physics missions). The easiest way to adapt autonomous spacecraft research to controlling constellations involves treating the constellation as a single spacecraft. Here one spacecraft directly controls the others as if they were connected. The controlling 'master' spacecraft performs all autonomy reasoning, and the slaves only have real-time subsystems to execute the master's commands and transmit local telemetry/observations. The executive/diagnostics module starts actions and the master's real-time subsystem controls the action either locally or remotely through a slave. While the master/slave approach benefits from conceptual simplicity, it relies on an assumption that the master spacecraft's executive can continuously monitor the slaves' real-time subsystems, and this relies on high-bandwidth highly-reliable communications. Since unintended results occur fairly rarely, one way to relax the bandwidth requirements involves only monitoring unexpected events in spacecraft. Unfortunately, this disables the ability to monitor for unexpected events between spacecraft and leads to a host of coordination problems among the slaves. Also, failures in the communications system can result in losing slaves. The other two architectures improve robustness while reducing communications by progressively distributing more of the other three remote agent components across the constellation. In a teamwork architecture, all spacecraft have executives and real-time subsystems - only the leader has the planner/scheduler and mission manager. Finally, distributing all remote agent components leads to a peer-to-peer approach toward constellation control.

Author

*Architecture (Computers); Satellite Constellations; Autonomy; Spacecraft Control; Real Time Operation*

**20000057502** NASA Goddard Space Flight Center, Greenbelt, MD USA

**Autonomous Performance Monitoring System: Monitoring and Self-Tuning (MAST)**

Peterson, Chariya; Ziyad, Nigel A.; [2000]; In English, 19-23 Jun. 2000, Toulouse, France; No Copyright; Avail: CASI; A02, Hardcopy

Maintaining the long-term performance of software onboard a spacecraft can be a major factor in the cost of operations. In particular, the task of controlling and maintaining a future mission of distributed spacecraft will undoubtedly pose a great challenge, since the complexity of multiple spacecraft flying in formation grows rapidly as the number of spacecraft in the formation increases. Eventually, new approaches will be required in developing viable control systems that can handle the complexity of the data and that are flexible, reliable and efficient. In this paper we propose a methodology that aims to maintain the accuracy of flight software, while reducing the computational complexity of software tuning tasks. The proposed Monitoring and Self-Tuning (MAST) method consists of two parts: a flight software monitoring algorithm and a tuning

algorithm. The dependency on the software being monitored is mostly contained in the monitoring process, while the tuning process is a generic algorithm independent of the detailed knowledge on the software. This architecture will enable MAST to be applicable to different onboard software controlling various dynamics of the spacecraft, such as attitude self-calibration, and formation control. An advantage of MAST over conventional techniques such as filter or batch least square is that the tuning algorithm uses machine learning approach to handle uncertainty in the problem domain, resulting in reducing over all computational complexity. The underlying concept of this technique is a reinforcement learning scheme based on cumulative probability generated by the historical performance of the system. The success of MAST will depend heavily on the reinforcement scheme used in the tuning algorithm, which guarantees the tuning solutions exist.
Author
*Algorithms; Applications Programs (Computers); Flight Control; Procedures; Accuracy*

**20000040113** NASA Goddard Space Flight Center, Greenbelt, MD USA
**GPS Sounding Rocket Development at NASA with Simultaneous Multi-Payload Tracking Application**
Bull, Barton; Martel, Hugh; [2000]; In English, Breckenridge, CO, USA; No Copyright; Avail: Other Sources; Abstract Only

An inverse differential GPS system has been developed for Sounding Rocket use which includes the flight unit and a ground station capable of extracting GPS data from sounding rocket telemetry, performing a real time differential solution and graphically displaying the rocket's path relative to a predicted trajectory plot. Accuracy has been proven to within less than 10 meters. Postprocessing has increased the precision to within 10 - 20 centimeters. The system has been successfully flown several times and delivered to the Sounding Program Office for routine field use. In addition to providing position, velocity and time GPS data has been used on sounding rockets for vehicle performance analysis, effecting a one hundred fold improvement in data time tagging, and steering an optical tracking device to intercept payloads launched from over the horizon. Precise velocity separation information and timing has been provided to multiple payload systems. Future plans include its use for Range Safety and enabling of interferometric techniques. The technology and software developed also has potential application to small satellite navigation and formation flying.
Author
*Global Positioning System; Fabrication; Sounding Rockets; Reliability Analysis; Optical Tracking; Data Acquisition*

**20000032752** NASA Goddard Space Flight Center, Greenbelt, MD USA
**A Tethered Formation Flying Concept for the SPECS Mission**
Quinn, David A.; Folta, David C.; [2000]; In English; 23rd, 2-6 Feb. 2000, Breckenridge, CO, USA
Report No.(s): AAS-00-015; No Copyright; Avail: CASI; A03, Hardcopy

The Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) is a bold new mission concept designed to address fundamental questions about the Universe, including how the first stars formed from primordial material, and the first galaxies from pre-galactic structures, how the galaxies evolve over time, and what the cosmic history of energy release, heavy element synthesis, and dust formation is. Half of the luminosity and 98% of the post Big-Bang photons exit in the sub-millimeter range. The spectrum of our own Milky Way Galaxy shows this, and many galaxies have even more pronounced long-wavelength emissions. There can be no doubt that revolutionary science will be enabled when we have tools to study the sub-millimeter sky with Hubble- Space-Telescope-class resolution and sensitivity. Ideally, a very large telescope with an effective aperture approaching one kilometer in diameter would be needed to obtain such high quality angular resolution at these long wavelengths. However, a single aperture one kilometer in diameter would not only be very difficult to build and maintain at the cryogenic temperatures required for good seeing, but could actually turn out to be serious overkill. Because cosmic sub-millimeter photons are plentiful and the new detectors will be sensitive, the observations needed to address the questions posed above can be made with an interferometer using well established aperture synthesis techniques. Possibly as few as three 3-4 meter diameter mirrors flying in precision formation could be used to collect the light. To mitigate the need for a great deal of propellant, tethers may be needed as well. A spin-stabilized, tethered formation is a possible configuration requiring a more advanced form of formation flying controller, where dynamics are coupled due to the existence of the tethers between nodes in the formation network. The paper presents one such concept, a proposed configuration for a mission concept which combines the best features of structure, tethers and formation flying to meet the ambitious requirements necessary to make a future SPECS mission a success.
Author
*Tethering; Mathematical Models; Cosmic Rays; Submillimeter Waves; Spacecraft Configurations; Galactic Structure*

**20000031724** NASA Goddard Space Flight Center, Greenbelt, MD USA

**Enabling Spacecraft Formation Flying in Any Earth Orbit Through Spaceborne GPS and Enhanced Autonomy Technologies**

Bauer, F. H.; Bristow, J. O.; Carpenter, J. R.; Garrison, J. L.; Hartman, K. R.; Lee, T.; Long, A. C.; Kelbel, D.; Lu, V.; How, J. P.; Busse, F., et al.; Dec. 14, 2000; In English, Feb. 2000, Breckenridge, CO, USA

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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.

Author

*Global Positioning System; Earth Orbits; Autonomy; Spacecraft Launching; Technology Assessment*

# Subject Terms

# Corporate Sources

# Document Authors