SPHERES:

A Testbed for Spacecraft Formation Flight Research in Microgravity Conditions

Allen Chen and Stuart Jackson

Space-based telescopes require large, heavy mirrors to deliver the angular resolution and light-collecting power necessary for applications such as interplanetary observation or ground surveillance. The higher the resolution desired, the larger the primary mirror, or aperture, must be. Large mirrors are difficult to deploy in space. The size and weight of the spacecraft scale with the size of the mirror, making it prohibitively expensive to develop, manufacture, and launch large single-aperture telescopes. Instead of developing these expensive single-aperture telescopes, both NASA and the Air Force are studying the use of separated spacecraft interferometers, which could deliver the performance provided by very large single-aperture telescopes. These systems use a number of smaller, cheaper telescopes that work collectively to synthesize a much larger aperture at a great reduction in overall system cost and in individual spacecraft size and complexity. Two missions designed to use space based interferometers or distributed arrays are shown in Figure 1. The resolution provided by an interferometer is a function of the distance between the apertures, or baseline: The longer the baseline, the higher the resolution. As a result, it is desirable to have as long a baseline as possible. One possible implementation would be to structurally connect the apertures; however, this would result in large supporting structures and a complicated deployment system. Additionally, large structures tend to vibrate, especially in space, where damping sources are not noticeably present. Vibrations degrade the performance of interferometers, since high precision optical alignment is needed.

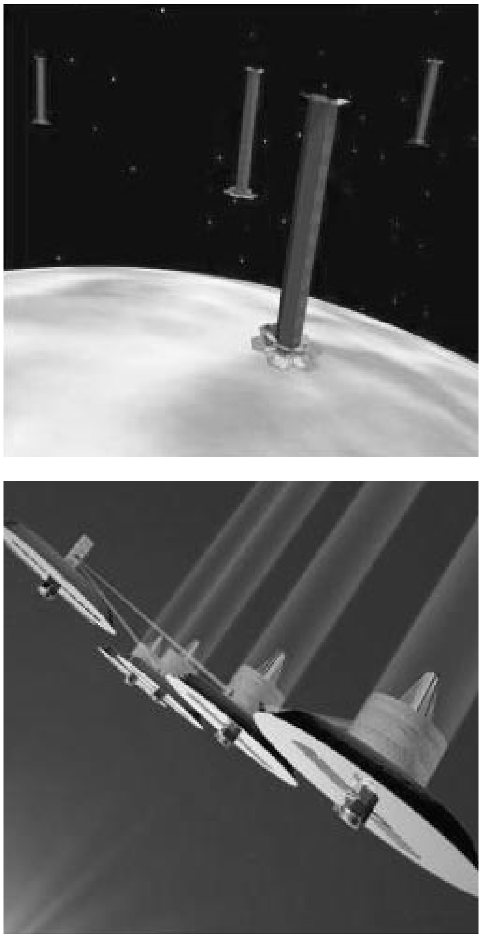


Figure 1 The Air Force's TechSat 21 Mission (top) and NASA's Terrestrial Planet Finder Mission (bottom) hope to utilize space based interferometery and distributed arrays

By contrast, interferometers made up of separated spacecraft have simplified dynamics, since structural vibrations have been eliminated. They also have increased system redundancy. Because of the high optical precision needed, a separated spacecraft interferometry system would require precise control of both the position and the attitude of all the constituent spacecraft. To achieve the required control precision, new formation flight control and metrology algorithms must be developed and tested. SPHERES is a formation flight testbed developed over the past two years by the Space Systems Laboratory and the Department of Aeronautics and Astronautics at MIT. The SPHERES program is driven by the need for testbeds to validate algorithms pertinent to formation flying spacecraft. The testbed provides a lo-risk, cost-effective, long-duration, replenishable, and easily reconfigurable platform with representative dynamics for the development and validation of algorithms relevant to formation flight. More specifically, SPHERES will allow testing of (1) relative altitude control and station-keeping between satellites, (2) retargeting and image plane filling maneuvers, (3) collision avoidance and fuel balancing algorithms, and (4) array geometry estimators. The use of SPHERES in a microgravity environment closely resembles the dynamics of future missions, except for the orbital dynamics. Still, it does allow the designers of the missions to validate the algorithm design, initialization, debugging, and refinement process. The validation of control algorithms and their development processes is an essential step in reducing the risk of future formation flight missions.


Figure 2 Stanford formation flight testbed using blimps

Other Research in Formation Flight

Currently, a number of formation flight tools and testbeds are being developed and/or operated by a variety of groups in government, industry, and university settings. These testbeds have different strengths and weaknesses in their ability to aid the development of formation flight technologies. The SPHERES project looks to complement these other testbed development programs. NASA's Goddard Space Flight Center (GSFC) is developing a computer-based formation flight simulation tool.[1] The tool is based on the commercial-of-the-shelf (COTS) product VirtualSat Pro, produced by the Hammers Company. VirtualSat is a real-time simulator that can be used to model a spacecraft formation or array. This software-based testbed allows easy expansion and refinement to the simulation, while also providing a cost-effective platform for developing formation flight algorithms; however, it relies solely upon software simulation to accurately depict the dynamics of the system and space environment.

Stanford University's Formation Flying Testbed (FFTB) is a ground-based testbed that consists of three free-floating vehicles that move on a granite table by firing compressed air thrusters.[2] The vehicles are autonomous and self-contained. The testbed was created to study guidance navigation and control issues by simulating microgravity dynamics in a 2-D plane; the 2-D nature of the testbed limits its ability to capture dynamics that are closely representative of space-borne vehicles.

A second Stanford University ground-based testbed allows demonstration of formation flight in three dimensions by using blimps as autonomous, self contained vehicles.[3] This testbed, shown in Figure 2, has been used to demonstrate robust Carrier-Phase Differential GPS (CDGPS) formation sensing and investigate basic formation control strategies; these investigations are limited by the blimp dynamics, which can vary widely from the dynamics of space-borne vehicles.

The New Millennium Program EO-1 mission, scheduled for launch in 2001, will demonstrate autonomous navigation and formation flying between EO-1 and Landsat.[4,5,7] The mission will validate autonomy algorithms and software tools, provided by GSFC, the Jet Propulsion Laboratory, and the Air Force Research Lab, that are key to formation flight. EO-1's testing of various algorithms in space provides realistic dynamics and results that can be directly applied to future space missions; however, EO-1's imaging mission limits the types of maneuvers that can be performed.

The Orion mission, currently being developed by Stanford University, seeks to validate key formation flight control and sensing issues with the use of low-cost microsatellites.[6] Orion will provide an on-orbit testbed for the development of autonomy and other distributed spacecraft technologies; however, the space-borne nature of the program limits the lifetime of the mission, increases the risk associated with testing control algorithms, and also increases the cost of developing and operating the testbed.

SPHERES will complement these testbeds by providing a cost-effective bridge between ground-based testbeds, whose dynamics are not truly representative of space-borne vehicles, and space-based testbeds, which are limited by lifetime, configuration, and cost. SPHERES provides full six degree of freedom (DOF) dynamics in a microgravity environment, while remaining easily replenishable and reconfigurable.

SPHERES Systems Overview

The SPHERES satellites are self-contained with on-board propulsion, processing, RF communication, and metrology.[7] In addition, the testbed has four metrology transmitters that provide global metrology reference and a laptop computer that acts as a “ground station” and provides experiment control.

A partially assembled SPHERES unit is shown next to a fully assembled unit in Figure 3. Some panels and hardware have been removed from the partially assembled unit to provide a clearer view of the components. The partially assembled SPHERES unit photo is of a prototype model; many of the cables and hoses have been shrunk and shortened for the flight models.

The SPHERES satellites and related testbed equipment were designed to fit in a Space Shuttle middeck locker, with room for expendables like propellant tanks and batteries. Each individual satellite is roughly the size of a volleyball, but more dense. The physical properties and other specifications for each satellite can be found in Table 1. Many of the purchased components have been modified for SPHERES use. Figure 4 shows and identifies many of the various subsystem components. In order to demonstrate formation flying, a series of maneuvers must be performed. These complex maneuvers can be viewed as a series or combination of less complicated maneuvers. This flow-down continues until each operation is a sum of basic level operations. In order to achieve the ultimate goal of formation flying, each tier of operations must be accomplished by steadily increasing the difficulty of the subsequent maneuver. Below are examples of each category of maneuver.

Basic Vectored Maneuvers
- Maintaining position/orientation
- Point-to-point translation/rotation
- Combination rotation-translation

Time-Dependent Maneuvers
- Tracing out a specified path
- Disturbance rejection

Coordinated Maneuvers
- Maintaining position/orientation relative to another satellite
- Follow the leader

Formation Flying
- Multiple satellites flying in rigid body formation
- Position swapping
- Simulated satellite failure

During the preliminary design phase, a set of “strawman” operations was defined. This strawman, which flows down from the SPHERES Requirements Document 8, defines the minimum requirements for mission operations. These minimum requirements ensure that meaningful maneuvers can be performed within the 20-second limitation of the KC-135:

- The satellites must be able to translate 1 m in 5 s, from start to stop.
- The satellites must be able to rotate 360° in 5 s, from start to stop.
- The tolerances on the satellites are .5 cm on position and 3° on attitude.

Based on these requirements, the subsystem teams completed their initial designs.

Subsystems Overview

The structure is an aluminum frame covered by Lexan panels. The frame provides numerous mounting locations for the various subsystems. The structure was designed using ProEngineer and procured professionally. Figure 5 shows a ProEngineer schematic of the internal aluminum frame accompanied by a photograph of the resulting assembled structure.

The propulsion subsystem consists of twelve solenoid-actuated valves that expel carbon dioxide through machined nozzles. The thrusters are grouped in six pairs of opposing thrusters to provide attitude and station-keeping control. The propellant is stored in Department of Transportation (DoT)-approved steel tanks that hold 74 grams of liquid CO_2 at 860 psig. A regulator drops this pressure to 70 psig prior to distribution via a manifold. The tanks are replaceable and provide between 20 seconds and 30 minutes of operations, depending on the maneuvers. Figure 6 shows an overview of the propulsion subsystem components and outlines how the CO_2 propellant is distributed through the pressure system and out to the various thrusters.

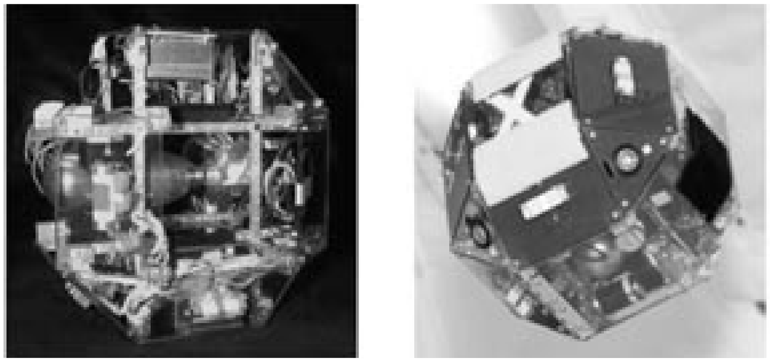
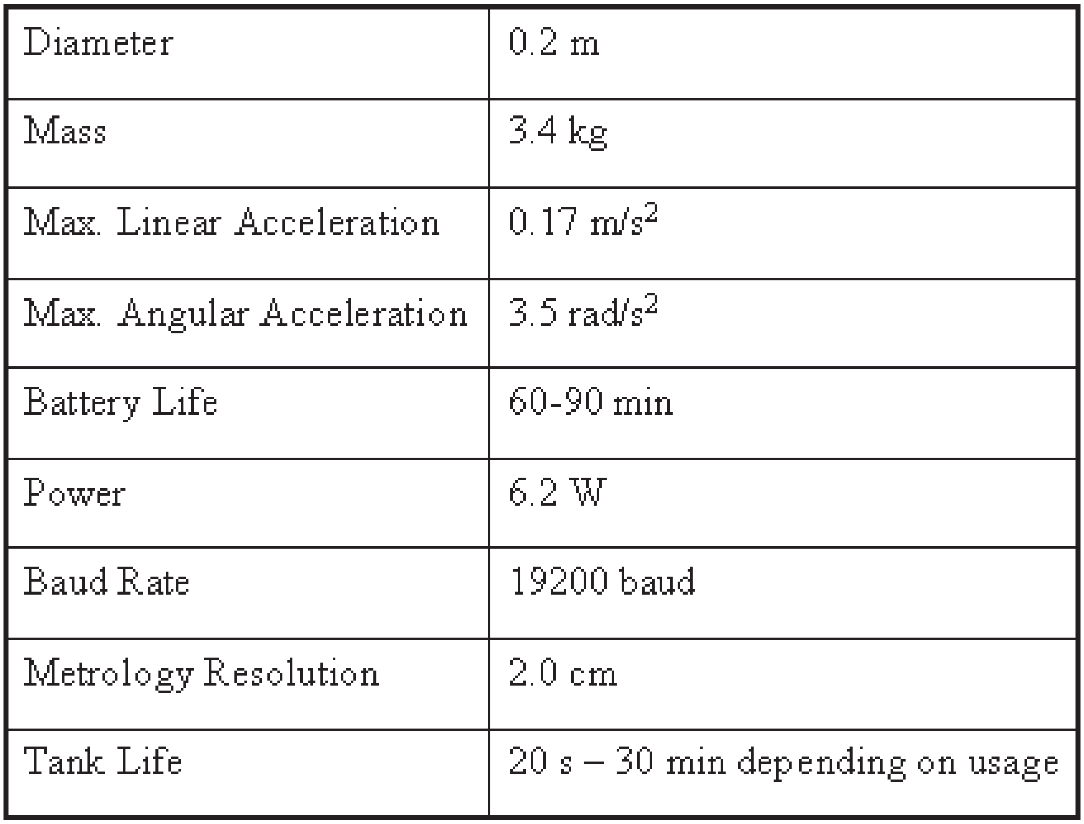


Figure 3 Photographs of partially assembled SPHERE (left) and flight model SPHERE (right)

The metrology subsystem has global and

Table 1

SPHERES SPECIFICATIONS



Diameter	0.2 m
Mass	3.4 kg
Max. Linear Acceleration	0.17 m/s^2
Max. Angular Acceleration	3.5 rad/s^2
Battery Life	60-90 min
Power	6.2 W
Baud Rate	19200 baud
Metrology Resolution	2.0 cm
Tank Life	20 s – 30 min depending on usage

inertial elements. The global metrology system measures the time of flight of 40 kHz ultrasonic pulses emitted by four externally located metrology transmitters. Infrared transmitters provide precise synchronization pulses. Eight ultrasonic microphones distributed on the surface of the satellite are used to derive a total of thirty-two propagation delays, which are then used to derive position and attitude. Additionally, each satellite has an internal inertial measurement unit (IMU) consisting of a three-axis accelerometer and three rate gyros. The independent global and local systems can be configured to work in concert to provide real-time metrology data. The power subsystem consists of two battery packs and four voltage regulators. The battery packs each contain six Duracell Ultra AA alkaline batteries and are located on opposite sides of the satellite. Voltage is regulated to 3.3V, 5V, 12V, and 22V. The 5V and 12V regulators are COTS, while the 3.3V and 22V regulators are custom circuitry. Each SPHERES unit consumes six to nine watts under nominal operation. Given this power consumption, each SPHERES unit has a lifetime of approximately 60-90 minutes.

The avionics subsystem consists of a TI C40 DSP, a Motorola Tattletale computer, a propulsion circuit board, a metrology board, a power distribution board, a UART internal digital communications board, two external RF communications circuits, and eight boards to connect the metrology infrared and ultrasound receivers. The custom boards were designed using OrCAD and procured from professional board manufacturers. The boards are placed around the internal structural supports and are interconnected to one another.

The software subsystem is multirate. The real-time software executes a 1.0 kHz interrupt to actuate the thrusters via pulse width modulation. The control algorithms are updated using a 50 Hz interrupt. State estimation occurs at a rate of 50 Hz from the IMU with 1 Hz updates from global metrology.

The communications subsystem is multichannel. Satellite-to-satellite (STS) communications as well as satellite-to-ground (STG) communications are updated at one to ten hertz rates. The communications system uses a token ring architecture for both the STG as well as the STS

References

1. Bauer F, Hartman K, How J, et al. Enabling Spacecraft Formation Flying through Spaceborne GPS and Enhanced Automation Technologies. Proc ION GPS-00 Conf; Sept 1999.
2. Corazzini T, Robertson A, Adams J, et al. GPS Sensing for Spacecraft Formation Flying. Proc ION GPS-97 Conf; Sept 1997.
3. Olsen E, Park C, How J. 3-D Formation Flight Using Differential Carrier-Phase GPS Sensors. Proc ION GPS-98 Conf; Sept 1998.
4. http://eo1.gsfc.nasa.gov/Technology/FormFly.html

communications. STG communication is used to archive measured telemetry and to send commands to the SPHERES units.

Operational Environments

The SPHERES testbed is operable in three different environments: a 2-D laboratory platform, the KC-135, and the ISS. Each of these environments provides unique advantages that can be utilized in different phases of the testing of control algorithms with the SPHERES system. The advantages and disadvantages of each environment are summarized in Table 2. Duration refers to the length of the experiment that can be performed in each environment. Contact refers to the level of interaction possible between the algorithm designer and the actual experimental run being performed. Dynamics and DOF assess how well the environmental conditions match those found in a potential formation flying mission. Frame rotation considers the motion of the global metrology frame, the experiment environment, with respect to the inertial frame.

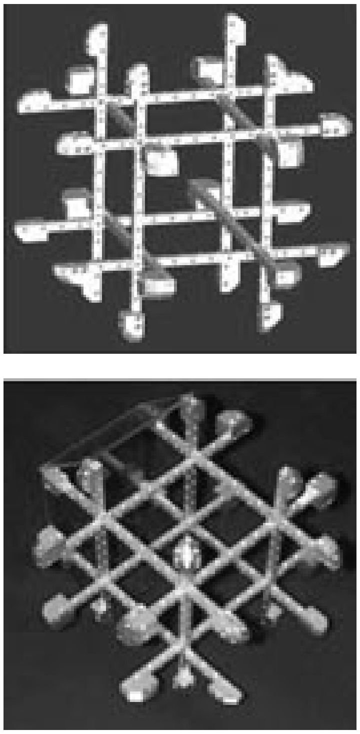


Figure 5 ProEngineer schematic and photo of partially assembled structure

2-D Laboratory Platform

The SPHERES prototypes can be tested on a 2-D frictionless table at the MIT Space Systems Laboratory. This allows for some simulated effects of microgravity while in a 1-g environment. It provides 3 degrees of freedom-2 translational and 1 rotational. The SPHERES system, as well as each individual unit, can be tested before going into the expensive environments of the KC-135 and ISS. First-run tests of control algorithms can also be implemented using the 2-D testbed. It allows for long-duration testing and gives the researchers direct contact with the SPHERES system while running tests. It is a cost-effective device to work out any unforeseen problems in both the SPHERES system itself and in any control algorithms being tested.

The design utilizes pucks that “float” by expelling compressed gas downward onto the testbed’s glass surface. The finalized design is an air-bearing levitation vehicle, in which three CO_2 tanks feed three pucks via a single regulator. The pucks lift the vehicle off the glass surface on which it sits. A SPHERE satellite sits atop the vehicle for testing. Figure 7 shows the air-bearing vehicle and a SPHERE structure mounted to the vehicle. The testbed allows for three SPHERES units to operate simultaneously on the ground in a 1-g, 3-DOF environment.

KC-135

Unlike the 2-D laboratory environment, which is limited in its ability to provide realistic dynamics, the KC-135 environment provides six DOF dynamics that more closely resemble real missions, at a fraction of the cost of placing SPHERES on the ISS. Unfortunately, each experiment is limited to the duration of the microgravity segment of one parabola, approximately 20 seconds. Additionally, the parabolic motion of the aircraft causes the fuselage and global metrology frame to rotate ~900 in 30 seconds.

This causes a discrepancy between the global metrology reference frame and the inertial reference frame. Additionally, turbulence and imperfect parabolas due to pilot error provide a very active disturbance environment. The KC-135 provides a cost-effective option for first-run tests and operational checkouts in 6-DOF. The KC-135, shown in Figure 8, has been used to test and verify that the SPHERES system is functional and operational. Tests run verified autonomy, control in 6-DOF, and metrology systems. In addition, basic control algorithms were tested; however, more complicated control algorithms will require more than 20 seconds to verify. The results of the initial testing are discussed below.

International Space Station

Free of the time constraints imposed by the KC-135’s microgravity parabolas, the SPHERES testbed will provide the most research capability in the shirt-sleeve environment onboard the International Space Station (ISS). This environment will provide long-term, hands-on, microgravity research. The experiment can run on the ISS for several hours at a time by simply replacing exhausted tanks and/or batteries when needed. The procedures for replacing both propellant

5. Folta D, Newman L, Gardner T. Foundations of Formation Flying for Mission to Planet Earth and New Millennium. AIAA/AAS Astrodyn Spec Conf; July 1996.

6. How J, Twiggs R, Weidow D, et al. Orion: A Low-Cost Demonstation of Formation Flying in Space Using GPS. AIAA/AAS Astrodyn Conf; 1998.

7. SPHERES Design Document, ver. 2.0. SSL Internal Doc; 1999.

8. SPHERES Requirement Document, ver. 2.1. SSL Internal Document; 1999.

9. Miller D, Saenz-Otero A, Wertz J, et al. SPHERES: A Testbed for Long-Duration Satellite Formation Flying in Microgravity Conditions. AIAA/AAS Space Flt Mech Mtg AAS 00-110; Jan 2000.

tanks and batteries are simple and quick. Since astronauts will be working directly with the SPHERES testbed, troubleshooting and maintenance become very simple through direct interaction with the experiment. Algorithm errors or mechanical problems that could cause catastrophic failures in space-based platforms are easily managed in the SPHERES testbed: The astronaut need only reach out to stop and reset the experiment. Additionally, the hands-on nature of the testbed makes downloading data and uploading new control algorithms trivial. The SPHERES testbed is also cost-effective on the ISS because it can be run indefinitely with the resupply of expendables, such as batteries and compressed gas tanks, and is run inside the shirt-sleeve environment of the station rather than outside. While the inside of the station still provides the needed 6-DOF microgravity environment, it eliminates the need for expensive thermal and radiation-hardened spacecraft that can survive the harsh environment of space. The ISS is the best microgravity environment for a formation flying testbed, because it allows all 6 DOF and closely simulates the dynamics of a satellite system, while still remaining an environment where long-term, hands-on research can be conducted.

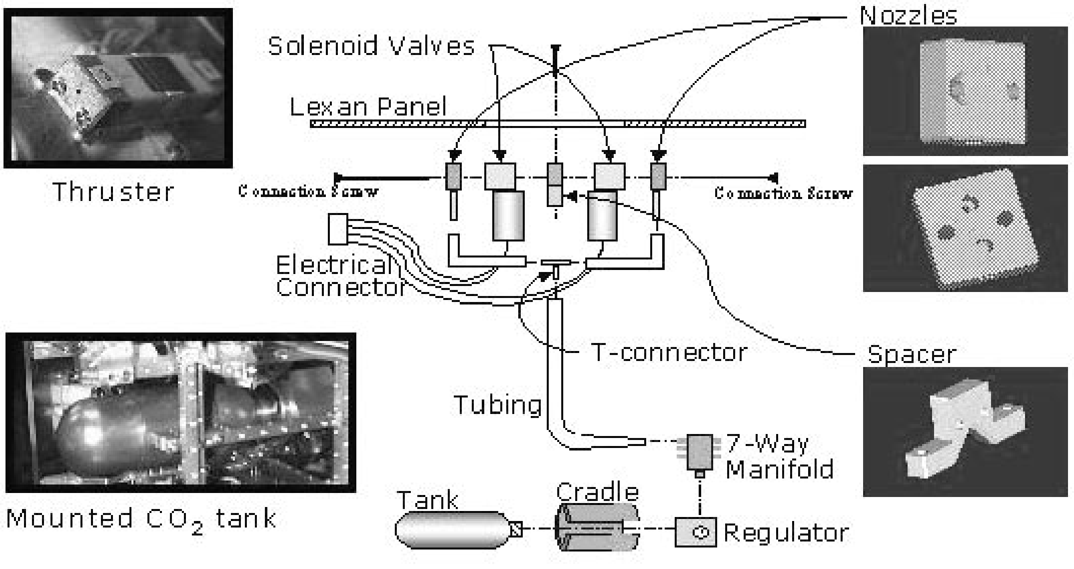


Figure 6 Overview of the propulsion system

KC-135 Operational Testing

In February and March 2000, the SPHERES testbed was flown on board the KC-135 to demonstrate the operability of the testbed in a microgravity environment. Figure 9 shows the SPHERES team operating the testbed on the KC-135. The tests performed included assessing the satellites' ability to propel themselves in full 6

Table 2

COMPARISON OF ENVIRONMENTS

	Duration	*Contact*	*Dynamics*	*DOF*	*Frame Rotation*	*Cost*
2-D Platform	Long	High	Average	3	Slow	Low
KC-135	Short	High	Good	6	Fast	Medium
ISS	Medium	Low	Good	6	Moderate	High

DOF, verifying the testbed's ability to obtain metrology readings correctly, verifying the satellites' ability to communicate while rotating and translating in all directions, and demonstrating the ability to operate fully untethered for reasonable periods of time.

The results of the tests proved full operation of the majority of SPHERES systems. The propulsion system demonstrated the ability to maneuver in a microgravity environment, though it sometimes failed to overcome turbulence effects experienced by the airplane. Propellant tanks lasted for approximately ten parabolas, though the exact thrusting lifetime is difficult to calculate given the variety of maneuver profiles.

The metrology system's inertial and global systems were tested separately. The rate gyroscopes were shown to be reliable and sufficiently sensitive to allow rotational control of the satellites in all three rotational DOF. The global metrology tests indicated that the system could locate the 3-D position of the SPHERES, but only within a limited section of the test area. The limitation has been attributed to the field of view of the ultrasound receivers, indicating a need to increase their field of view.

Satellite-to-ground and intersatellite communications were successfully demonstrated, with only a few breaks during tests. Most problems were encountered during the initialization of the communications units, indicating a need to correct the initial synchronization of the communications system. The power, software, avionics, and structures subsystems demonstrated full functionality with virtually no problems. Battery packs lasted in excess of one hour. A single C40 processor was able to command a variety of maneuvers. The avionics system performed well, with the exception of one wiring defect. The SPHERES structures proved able to survive both the microgravity environment at the top of the parabolas and the high-gravity (~1.8 g) pull-out at the bottom of the parabolas.

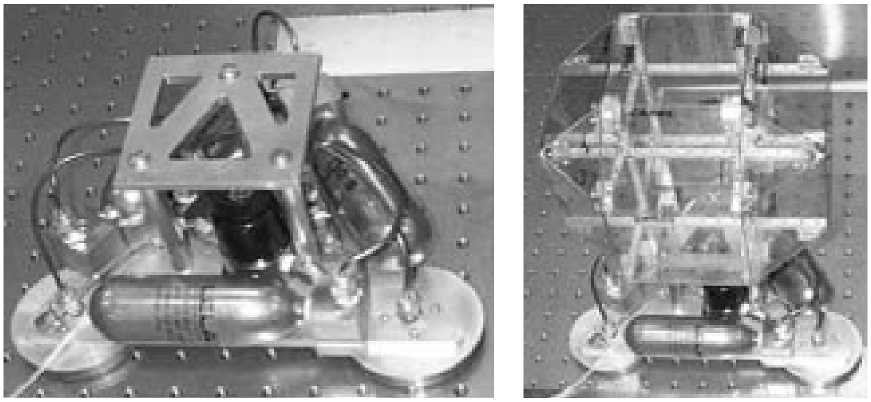


Figure 7 2-D testbed air bearing with and without a SPHERE structure mountd to the top

Limited algorithm testing was also performed using the testbed. A Master/Slave architecture, where one satellite follows the motions of the "master" satellite, was successfully tested to demonstrate the use of SPHERES as a formation flight testbed. Two different tests were performed. In the first, a team member manually maneuvered the master SPHERE and the motion of the slave was observed. The test clearly revealed the "slave" emulating the motion of the master. In the second type of test, the master satellite was attached to the KC-135 frame. Thus, the slave followed the rotation of the KC-135 as it pitched over the top of the parabolas at a moderately high rate. This made the slave SPHERE appear to hold orientation with the rest of the airplane, regardless of turbulence and imperfect parabolas.

Figure 8 NASA's KC-135 Reduced Gravity Aircraft (the "Vomit Comet")

Future Work

Following last spring's KC-135 flights, the project entered a period of transition and refinement where it was handed over by the undergraduates of the CDIO class to the graduate students and researchers of the MIT Space Systems Lab. The metrology, propulsion, and communications subsystems are the primary focus of the SPHERES hardware improvements now underway. In addition, control algorithms from outside agencies such as NASA Goddard Research Center will be tested along with new MIT-developed algorithms. Optical components will also be added to the SPHERES 2-D testbed to aid in evaluating the performance of these algorithms. Additional SPHERES hardware upgrades will also be necessary before the testbed can be flown on the space shuttle or International Space Station in the next two to five years.

MIT SPHERES was developed through a unique educational experiment at the Massachusetts Institute of Technology (MIT). Undergraduate Aerospace Engineering students are exposed to the full life cycle of an aerospace product through Conception, Design, Implementation, and Operation (CDIO) phases. Students not only learn about design, teamwork, and communication, but also interact with potential customers from government and industry, appreciate the constraints of integrating to a carrier, exercise professional computer-aided design tools, and struggle with the iterative process of design improvement and system-wide

Acknowledgments

The SPHERES project is the result of a team effort by graduate and undergraduate students and staff of MIT, with the support of staff from Payload Systems, Inc.

The members of the team are:

Chief Systems Engineer
Prof. David Miller
Undergraduate Students
(Class of 2000):
George Berkowski
Chad Brodel
Sarah Carlson
David Carpenter
Allen Chen
Stephanie Chen
Shannon Cheng
Daniel Feller
Stuart Jackson
Fernando Perez
Brad Pitts
Jason Szuminski
Julie Wertz
Teaching Assistant
Alvar Saenz Otero
MIT Staff
Paul Bauer
Dr. Ray Sedwick
Prof. Dava Newman
Payload System Staff
Dr. Javier deLuis
Steve Sell
Graduate Students
Mark Hilstad
Mitch Ingham
Edmund Kong
Alice Liu