Appendix I

SPHERES EXPERIMENTAL RESULTS

I.1 Results at the MIT SSL

The SPHERES facilities have operated at the MIT SSL since the Spring of 2000 utilizing the original prototypes. During this time research was done on the effects of communications on formation flight systems (2000), formation flight algorithms (2000+), docking algorithms (2002+), system identification and fault detection (2003+), tether prototypes (2003+), and began research to support the Mars Orbiting Sample Return mission (2004+). Table I.1 summarizes the research conducted at the MIT SSL facilities in Cambridge, MA since 2000.

TABLE I.1 Research conducted at the MIT SSL

Research	Year	Application	Guest Scientist
F.F. Communications	2000	DSS	
F.F. Control	2000	TPF	JPL
Docking Control	2002 +	Orbital Express (DARPA)	
Mass ID / FDIR	2003 +	Modeling	Ames
Tethers	2003 +	SPECS	Goddard
MOSR	2004 +	Mars Sample Return	

The tests on communications during 2000 provided an initial understanding of simple communications issues regarding formation flight. The goal of the tests was to determine the effects between high frequency transfer or state information and the size of the state being transferred. To this purpose five experiments were setup; a number of tests for each setup was performed. The final results evaluated the difference in performance between the different experimental setups. [Saenz-Otero, 2000]

Development of formation flight algorithms began in the Spring of 2000 in preparation for tests aboard the KC-135 reduced gravity airplane (RGA) and later on for tests at the MSFC Flat Floor. These tests included control of one, two, or three degrees of freedom between two spacecraft (2000+, for the RGA) and formation flight of three and five spacecraft (2003+, for the MSFC Flat Floor). [Hilstad, 2003], [Kong, 2004a]

The formal development of docking algorithms began during 2002 [Nolet, 2004]. While previous tests conducted sets of maneuvers that resulting in docking, these did not follow the full scientific process, but were rather a demonstration of the facility's capabilities.

Work with NASA Ames Research Center provided the first complete cycle of remote investigation using SPHERES. Through 2003 and 2004 researchers at NASA Ames paired with a member of the SPHERES team to conduct experiments at the MIT SSL while they worked from their home facility. The Ames investigators developed their own algorithms in house, and incorporated them into the SPHERES Core using the provided API. For several months the algorithms were sent electronically to MIT, debugged over a few days, and then experiments conducted. Once the algorithms were close to mature, the Ames investigators visited the MIT SSL facilities to finalize their design. After the final design was complete, the researchers returned to NASA Ames, and the SPHERES team conducted further tests to obtain more data. The Ames algorithms were also tested aboard the RGA. [Berkovitz, 2003]

Development of tether mechanism that utilize the SPHERES satellites' expansion port began at the MIT SSL during 2003. Prototype designs were developed and used both at the MIT SSL facilities and at the MSFC Flat Floor. These prototypes utilize power and signals from the SPHERES expansion port to incorporate the tether mechanism as an integral part of the satellite. Development at the MIT SSL has provided the knowledge necessary to create medium fidelity models of tethered spacecraft systems; these models were utilized for tests in the MSFC Flat Floor.

Research to support the Mars Orbiting Sample Return mission (MOSR) began in 2004 by the creation of an initial design of a capture mechanism and the development of algorithms to simulate impact forces. Tests at the MIT SSL include the development of control algorithms that ensure a SPHERE satellite will impact a target in a fixed location at a pre-specified velocity and angular rate, representative of what is expected in the actual space capture. At this point one substantial thread of iterations has occurred to present the MOSR team with a proof-of-concept on the use SPHERES to support their research.

I.2 Results aboard the KC-135

Both the prototype and the flight units have been used for experiments aboard the KC-135 reduced gravity airplane over the course of six weeks. Table I.2 presents the month and year of each flight week, as well as the type of satellites (prototype or flight equipment) used in each flight. A short description of each week's research is presented next.

TABLE I.2 KC-135 flight weeks and satellites operated

Dates	Prototype	Flight
Feb. 2000	2	-
Mar. 2000	2	-
Oct. 2001	2	-
July 2002	2	1
Feb. 2003	-	3
Nov. 2003	-	2

February 2000

The February 2000 flights were performed as a proof-of-concept flight for the SPHERES satellites. This week of flights did not concentrate on the development of control algorithms, but rather on the thorough testing of all the SPHERES systems. These tests were the first time that the SPHERES hardware was exposed to a 6DOF environment, and therefore the first time that a controller had to operate more than two thrusters at a time. It was also the first time that the operators were required to use the interfaces and control software in a stressful environment. Table I.3 summarizes the tests conducted with the prototype units during the February 2000 flights.

TABLE I.3 February 2000 flight results

Feb. 2000	Test Topics	Experiment Repetitions
Flight 1	1 DOF Open Loop Rotations	20
	1 DOF Open Loop Translations	20
Flight 2	1 DOF Open Loop Rotations	40
Flight 3	1 DOF Closed Loop Rotations	20
	3 DOF Rotation Damp	15
	2 SPHERES Rotation Comparison	5
Flight 4	3 DOF Closed Loop Rotations	20
	2 SPHERES Rotation Comparison	20

The resulting information led to the first major iteration in the design of the SPHERES facilities. The satellites were upgraded prior to the next flight to increase the reliability of the propulsion, communications, and power systems, which presented failures during the February 2000 flights. The graphical user interface went through its first iteration: the type of data presented changed (presented more processed data, instead of raw information), although the type of interface remained basically unchanged.

March 2000

The March 2000 tests were the first tests where science was conducted aboard the KC-135. These flights concentrated on two main topics: to test the global frame metrology system in a 3D environment and to perform angular rotation formation flight maneuvers. The tests of the global metrology system included tests that consisted solely of data collection as well as tests that attempted to control the satellites with respect to the global frame. The formation flight maneuvers began with initial development of 3DOF angular rotation controllers and the collection of data from the KC-135 frame of reference. The formation flight tests used the knowledge obtained from the angular rotation and frame measurements tests to perform relative maneuvers between two satellites. Table I.4 summarizes the experiments conducted during March 2000.

TABLE I.4 March 2000 flight results

Mar 2000	Test Topics	Experiment Repetitions
Flight 1	Global System ID	4
	Global Frame Control	5
	Angular regulation (Euler)	15
	Angular regulation (Quadrenniums)	10
	KC Frame ID	20
Flight 2	Global System ID	5
	Global Frame Control	25
	KC Frame ID	30
Flight 3	Master/Slave FF Tests	20
	Global Frame Control	20
Flight 4	Angular regulation	10
	Global Frame Control	20
	Minimum Gas Turn	10

October 2001

The February and March 2000 flights both demonstrated that one of the most challenging sub-systems in the SPHERES testbed was global metrology. While several tests during 2000 demonstrated the ability for inertial control using the gyroscopes, SPHERES had not been able to control consistently with respect to the global metrology system. Therefore, in what can be considered a long-term iteration, the SPHERES team updated the global metrology system to experiment once more in the KC-135.

Table I.5 summarizes the experiments conducted on October 2001. The majority of the October 2001 tests concentrated on testing the global metrology system. Having learned that the SPHERES satellites lacked enough authority to perform complex maneuvers in the KC-135 frame (mostly due to airplane turbulence), the new tests concentrated on 1DOF maneuvers and station keeping. Throughout the week tests were run and data analyzed. The data included both free-float data to determine if the global metrology system had enough bandwidth to capture the motion of the satellites during turbulence, as well as data when control was attempted. Data analysis indicated further need to refine the metrology system before being able to determine if the units had enough authority. During the last day of flights the global frame control was mostly limited to attitude control (with respect to the global frame), which was deemed possible through analysis of data earlier in the week.

The second set of tests was to calculate the inertia of the satellites. This information was obtained over two days, with data analysis in between to ensure the right data was obtained. This analysis time was essential, since it led to new tests that collected data not considered necessary on the first day. The data helped develop the attitude control tests of the last day of experiments.

July/August 2002

These flights carried out the first 6DOF tests of the flight units. The first flight unit was tested in this environment for full operations, especially for repeatability and reliability of

TABLE I.5 October 2001 flight results

Oct. 2001	Test Topics	Experiment Repetitions
Flight 1	Inertia Measurement	6
	Closed Loop Inertial Control	12
	Global Frame Control	20
Flight 2	Hardware Tests	10
	Global Frame Control	30
Flight 3	Inertia Measurements	10
	Global Frame Control	30
Flight 4	Global Frame Control	40

its sub-systems. While not a direct part of the science, it demonstrated the success of a major design iteration from the prototype units to the flight units. The flight unit was used in the first flight training videos for astronauts. These videos were improved over future flights.

The science conducted in these flights, using the prototype units, once again concentrated on the global metrology system, but also included a substantial amount of docking control. Lessons were learned from past experiences with the global metrology system, and the experiments were modified to better fit the environment of the KC-135. The global metrology tests during these flights were conducted solely as relative flight between the units, attempting to maintain formation as a system. The total system was not controlled to maintain a certain position or attitude with respect to the global frame; rather, the units were required to maintain formation. The tests were more successful than in the past, but the limited test time of 20 second prevented substantial data from being collected. A summary of these tests is presented in Table I.6.

The success of the relative motions in the initial days led to the development of docking controllers which, as with the past global system controllers, performed docking maneuvers controlling only the distance between the units, and not the absolute position of the system. These tests completed successfully over a few parabolas. The relevant part of

TABLE I.6 July/August 2002 flight results

Jul./Aug. 2002	Test Topics	Experiment Repetitions
Flight 1	Global Frame Control	40
Flight 2	Global Frame Control	40
Flight 3	Global Frame Control	20
	Docking	20
Flight 4	Global Frame Control	20
	Docking	20

these tests is that they utilized the iterative nature of SPHERES over a wide range of time frames: the success of the algorithms was due to the better understanding of the KC-135 environment over multiple flights, to the development of the relative motion controllers, and to the ability to iterate over one day on the docking algorithms.

February 2003

The February 2003 experiments were conducted solely with the flight units, and the tests were geared mostly to conducting small amounts of science each day. There were three main areas of study during these flights: high level system identification via one-degree-of-freedom maneuvers, to later be used in FDIR algorithms; high-speed collection of inertial data to fully identify the thrusters with the goal to create a B matrix in the standard state-space equations, while also helping fully identify the dynamics of each satellite and the behavior of the inertial sensors; and control within the global frame was once again attempted in two manners, one setup using the KC-135 frame, and another setup using the ultrasound system only between units, without referencing the KC-135 frame at all. Table I.7 summarizes the tests conducted during February 2003.

The tests suffered a setback during the second flight, when the communications system failed for the majority of the flight and no data collection was possible. The SPHERES designed hardware did not fail; it was the COTS laptop computer that served as a control station which failed. While this was a setback of the individual flight, it provided direct

TABLE I.7 February 2003 flight results

Feb. 2003	Test Topics	Experiment Repetitions
Flight 1	1DOF System ID	20
	Thruster ID	10
	Global Frame Control	10
Flight 2	1DOF System ID	3
	3 SPHERE Handling Ops.	33
Flight 3	1DOF System ID	16
	Thruster ID	15
	Relative Frame Control	6
Flight 4	1DOF System ID	7
	Thruster ID	14
	Global & Relative Frame Control	15

feedback of the one-fault tolerant parts of the SPHERES facilities and resulted in a change of the manifest of flight equipment that will be sent to the ISS.

The system identification tests were ran multiple times the first day of tests. Analysis of this data resulted in changes of the type of data captured during the last day of tests. The thruster identification tests were conducted all week to obtain as much data as possible and create a good model of the SPHERES actuators/sensors transfer functions. The collection of this data was not necessarily iterative, since the type of data collected and the methods to collect them did not change throughout the week; rather, these sets of tests ran into the time limitations of the KC-135 to the point where tests had to be repeated multiple days. Lastly, the global frame control did go through real iterations, leading to the execution of several formation flight algorithms that used the on-board beacons of the satellites to maintain both pointing and separation relative to each other.

November 2003

The November 2003 flights were dedicated to conducting formation flight maneuvers and FDIR data collection. Tests on the best methods to send critical data for a distributed system were also conducted. Table I.8 summarizes the tests conducted during this week of experiments. Since the formation flight maneuvers were only relative, the global metrology system was not used during this week of flights.

TABLE I.8 November 2003 flight results

Nov. 2003	Test Topics	Experiment Repetitions
Flight 1	Beacon Track	9
	Docking	6
	Lost in Space	5
	Inertia ID	7
	Distributed Control Architecture	10
Flight 2	Beacon Track	20
	Distributed Control Architecture	10
	Inertia ID	10
Flight 3	Docking	11
	Lost in Space	8
	Distributed Control Architecture	10
	Inertia ID	10
Flight 4	Docking	12
	Lost in Space	17
	Inertia ID	10

A formation flight system would follow each of these steps in sequence: lost in space maneuver, beacon tracking to capture the other unit, and then perform formation flight or docking. Due to the limited 20 seconds experiment test time, the different maneuvers of a formation flight deployment sequence were separated and tests conducted individually. The data of each individual test were collected to demonstrate how the different algorithms create a formation flight system. The tests began with the demonstration over two days of the ability of two units to track their angular position with respect to each other (beacon track). Docking algorithms were also tested, to demonstrate control of separation between units. The "Lost in Space" algorithms demonstrated different ways in which two satellites, deployed in space with a random attitude, can find each other by following a prescribed 3DOF rotation; the goal was to balance fuel consumption and duration of the maneuver. The ability of the SPHERES software to separate the tests into these steps allowed significant tests to be conducted in the short test-time of the KC-135.

I.3 Results at the MSFC Flat Floor

The Marshall Space Flight Center Flat Floor provides an environment similar to that of the MIT SSL: 3DOF tests under 1g conditions utilizing air carriages. But the MSFC facility provides a substantially expanded operational area of over 10 meter square (30 feet square). This extended area allows scientists to perform tests with up to five SPHERES, which is not physically possible at the MIT SSL; it enables more realistic lost-in-space demonstrations and docking maneuvers; and it allows the use of tethers several meters in length. The SPHERES team took advantage of these three options during two campaigns: three days in June 2004 and five days during December 2004. Tests included demonstration of formation flight maneuvers with two, three, and five spacecraft relevant to the TPF mission, docking algorithms over large separations, and tethered formations with two and three satellites. Table I.9 summarizes the tests conducted at the MSFC Flat Floor.

TABLE I.9 MSFC flat floor experiments

	Week 1			**Week 2**				
Algorithm	**Day 1**	**Day 2**	**Day 3**	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**
TPF Rotations	✓	✓	✓	✓	✓	✓	✓	✓
Docking		✓	✓					
Tether				✓	✓	✓	✓	✓

The formation flight maneuvers consisted of satellite deployment and tracking of a circular path. Tests with two units involved constant and expanding separations of 0.5m, 1m, and 1.5m to demonstrate both deployment and image capture maneuvers. The three and five satellite tests used constant separations to demonstrate formation flight algorithms.

The three unit tests utilized a separation of 1m between units, for a total array separation of 2m; five units formations maintained constant separations of 1m, for an array size of 4m.

The docking experiments demonstrated docking maneuvers with a free rotating target; this was achieved incrementally through four steps over two days. The first experiment consisted of 2 units performing a cooperative docking maneuver starting about 1.5m apart, with the chaser unit pointing in a random direction. The second configuration was close proximity tracking of a free rotating target to tune the control algorithm which controls movement in the tangential direction. Next, docking maneuvers with uncooperative targets were performed. For the third set of tests, the target was slowly drifting but not rotating; this allowed tests of the control algorithms in the presence of perturbations caused by plume impingement on the target. Finally, multiple docking maneuvers with a slowly rotating target were successfully performed.