Chapter 6

ASSESSMENT OF SPHERES

This chapter starts by presenting an overview of the programs supported by SPHERES and the results obtained to date in several operational environments. Next, the chapter uses the design framework presented in Chapter 5 to make an assessment of the design of SPHERES with respect to the microgravity laboratory design principles. Although the framework is applied to an existing design, the application of the design framework to the SPHERES testbed illustrates the process which would take place in iterating the design through one full cycle of the design framework. It demonstrates the ability of the framework to capture all the features expected in a successful microgravity laboratory by identifying issues not considered in the initial design. Lastly, the evaluation framework is applied to the SPHERES testbed. The evaluation provides insight into how future ISS evaluators must consider the success of a mission and balance it with the need to utilize the ISS correctly.

6.1 SPHERES Results to Date

SPHERES satellites have operated continuously since the Spring of 2000. The prototype satellites were designed and built between the Spring of 1999 to the Spring of 2000. They were used to conduct proof-of-concept and initial research from the Spring of 2000 to the Summer of 2002, at which point the prototype units were retired. The flight units were designed and built from the Fall of 2000 to the Spring of 2002, and are currently in operation. The following sections present the current programs supported by the SPHERES laboratory, future programs expected to take place in the short term, and results obtained in the three operational environments currently supported.

6.1.1 Current Programs

This section presents overviews of the three programs currently supported by SPHERES at the MIT-SSL. These three programs include supporting guest researchers from NASA Ames to implement Mass Property Identification algorithms onboard the SPHERES testbed, algorithm development for Autonomous Spacecraft Rendezvous and Docking funded by DARPA, and spacecraft formation flight work in support of the Terrestrial Planet Finder mission. Algorithms from these programs are scheduled to be tested during the first SPHERES flight onboard the ISS; they do not require additional hardware or payload development, allowing the algorithms to be tested upon deployment aboard the station.

Mass Property Identification

The idea of using a characterized model of a system to augment a controller becomes much more powerful if one can perform on-line real-time characterizations. This method allows the use of changing system parameters to be tracked (e.g., center of mass and moment of inertia due to fuel depletion or docking of two spacecraft), thus allowing for better controller performance. The identification of these parameters using only gyroscope measurements is proposed in [Wilson, 2002]. Online mass property identification algorithms have been implemented and tested at MIT-SSL and aboard the RGA (KC-135). The first set of algorithms for testing onboard the ISS has been successfully implemented on the ground-based facilities. Figure 6.1 shows an example of estimating the z-axis inertia of a satellite when it is attached to the air carriage during a test session performed at the MIT-SSL. Future research includes updated filter coefficients for determining angular acceleration, using accelerometer data to improve the identification, and combining it with other autonomy algorithms such as thruster Fault Detection Identification and Recovery (FDIR).

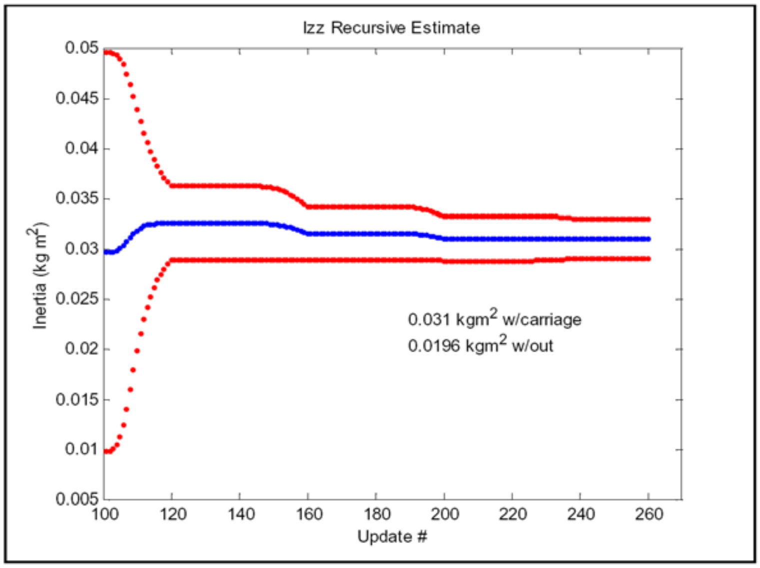

Figure 6.1 Z-axis inertia estimate from ground-based tests

Autonomous Rendezvous and Docking

The ultimate goal of the SPHERES ARD research, supported by the DARPA Orbital Express program [Shoemaker, 2004], is to develop a control architecture consisting of various algorithms that will enable safe and fuel efficient docking of a thruster based spacecraft with a free tumbling target in presence of obstacles and contingencies. Three classes of algorithms have been developed: metrology, control and autonomy. Metrology class algorithms consist of a series of extended Kalman filters that derive the state vector from the different sensor suites available for spacecraft. The control class algorithms include path planning [Hablani, 2001] as well as close-loop control algorithms. A series of PD controllers coupled with a pulse-width modulator control the attitude and the lateral alignment during the approach. Figure 6.2 shows sample results of this approach. Autonomy algorithms are used to determine the mode of operation (type of docking and phase), as well as executing the plan generated by the control class algorithms [Nolet, 2004].

Future work in this program focuses on the integration of optimal path planning algorithms that account for constraints such as obstacle avoidance and plume impingement

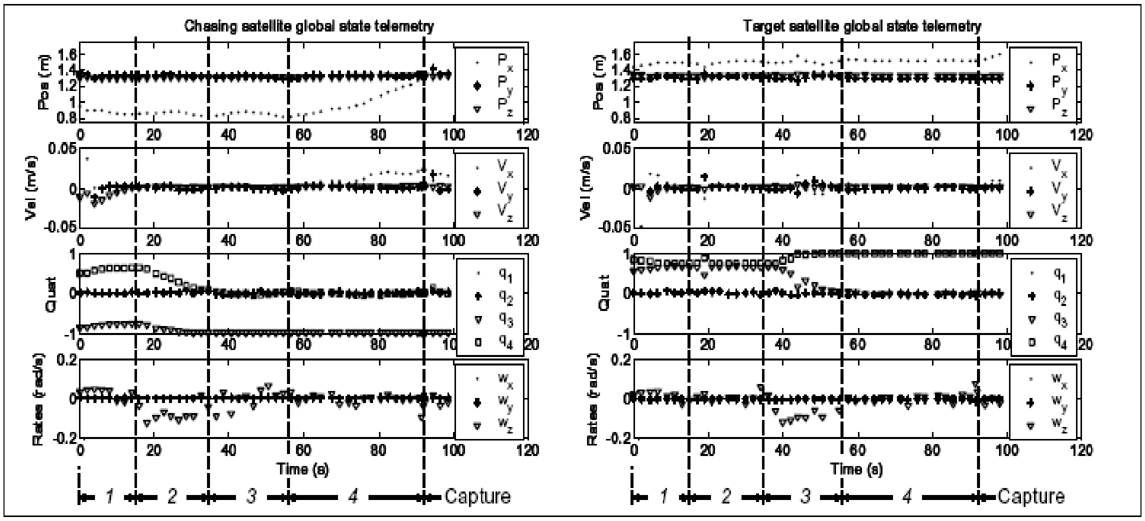

Figure 6.2 Sample results of docking algorithms at the MIT SSL

using techniques such as Model Predictive Control and parametric programming [Bemporad, 2002]. Integration of FDIR algorithms will also be of interest [Wilson, 2003].

Terrestrial Planet Finder Multiple Spacecraft Maneuvers

The TPF Mission [Beichman, 1999] will support a long baseline separated interferometer for space observation. The coordination between the spacecraft in such a system is crucial. To this end, the MIT-SSL, under the sponsorship of NASA JPL, has developed and tested algorithms for several key TPF maneuvers on the RGA and also on the MSFC flat floor facility. These key TPF maneuvers include:

- *lost in space* - the spacecraft in the array are to determine their orientations with respect to each immediately after deployment
- *array spin-up* - the array is spun up to the desired rotation rate
- *array rotation* - continuous control actuation will be required to maintain the separations between the spacecraft
- *array re-sizing* - the array size is tuned to survey the different extra-solar systems
- *array re-target* - the most complicated maneuver where the line-of-sight of the array is changed during capture to allow for different systems to be surveyed without having to stop the entire array

To date, SPHERES has been used to demonstrate a limited version of the lost-in-space maneuver, array spin-up, array rotation and array re-sizing maneuvers; Figure 6.3 shows a five satellite setup ready for tests at MSFC. The array re-target maneuver has yet to be tested due to the limited zero-gravity period currently available. Once array maneuvers are successful, plans call to add an optical pointing payload and develop multi-staged control algorithms.

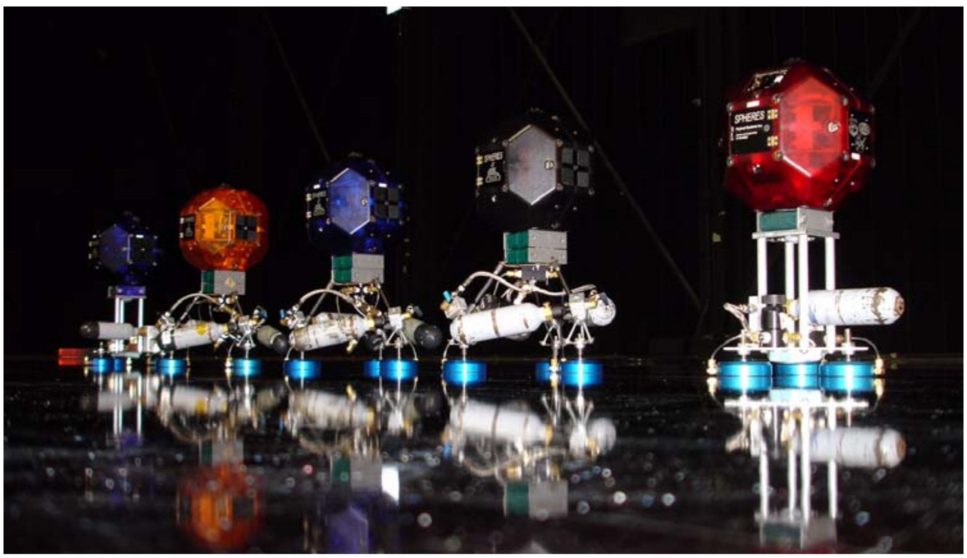

Figure 6.3 Five satellite TPF maneuvers at the MSFC Flat Floor

6.1.2 Future Programs

The SPHERES expansion port enables additional testing capabilities with the SPHERES laboratory. In most cases, only incremental payload development work is needed since the core facilities (satellites and beacons) remain onboard the ISS. This section presents three new programs for potential testing onboard the ISS. The first is the addition of a precision pointing payload to compliment the TPF maneuvers program. Second, the SPHERES team expects to study the dynamics and control of tethered spacecraft. Lastly, SPHERES will support tests of the Mars Orbit Sample Retrieval mechanism.

TPF Multi-staged Control

The TPF work described in the previous section provides only the coarse actuation of a SSI system. As the follow-on work to the TPF maneuvers demonstration, NASA JPL has funded an optical pointing payload for use with the SPHERES satellites' expansion ports, to facilitate the development of a multi-staged control testbed onboard the ISS. The ultimate goal will be to perform the TPF maneuvers through thruster actuations while maintaining precision pointing between the satellites onboard the ISS. Note that only the incremental optical pointing payload will need to be launched to the ISS to complement the core facilities.

Tethered Formation Flight

A tethered system is a trade-off between using a structurally connected interferometer, which allows for very limited baseline changes, and a separated spacecraft system where the usage of propellant can be prohibitively expensive. A tethered system is currently being considered for NASA's Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) mission [Mather, 1998] to maneuver the sub-apertures out to separations of a kilometer, thereby achieving very high resolution. Under the guidance of NASA Goddard Spaceflight Center, the SPHERES program will be used to research tethered systems by the addition of two major components:

- tether deployment and retraction mechanism with tether tension sensors, latch plate, and momentum wheel package
- momentum wheel package

Initial tests at the MSFC Flat Floor facilities (Figure 6.4) took place in 2004 with a prototype deployment and retraction mechanism.

Mars Orbit Sample Retrieval

To obtain and analyze samples of Mars surface elements, the Mars Orbit Sample Return program (MOSR) must overcome the challenge of autonomous search, acquisition, rendezvous, and docking of the sample return spacecraft with the sample. Terminal-phase

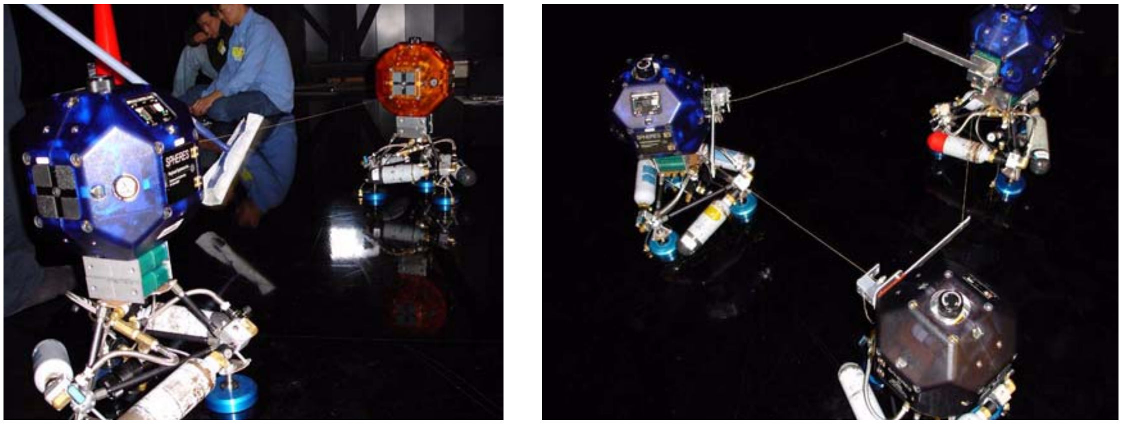

Figure 6.4 Two and three satellite tethered setups at the MSFC Flat Floor

multi-body trajectories and physical contact dynamics between the orbital sample and retrieval system can only be represented with high fidelity in a 6 DOF physical environment. Under the guidance of JPL, the SPHERES program is being utilized to test the capture mechanism of the Mars Orbit Sample Retrieval (MOSR) system (Figure 6.5). Force and torque sensors will be placed on the capture mechanism to measure the impact of the satellite on the cone as the velocity and rotation speed changes. The orbit sample in this experiment is represented by a SPHERES satellite. Since the satellite has the dimensions and mass properties similar to those expected for the final system, full scale emulation of a sample by the satellite can be achieved.

Figure 6.5 Artist's conception of MOSR aboard the ISS

6.1.3 Experimental Results

Appendix I presents the results of experiments conducted using the SPHERES laboratory at the MIT SSL, aboard the RGA, and at the MSFC Flat Floor facilities. Table 6.1 summarizes the experiments conducted with the SPHERES laboratory since 2000. The experiments included tests of formation flight and ARD control algorithms at all three locations. The RGA was used considerably to aid in the design and demonstration of the global metrology system. As the table shows, guest scientist involvement began in 2003 with the participation of NASA Ames, Goddard, and JPL staff in several reduced gravity campaigns.

TABLE 6.1 Summary of SPHERES Experimental Results

Date	Research	Location	Application	Guest Scientist
2000	F.F. Communications	SSL	DSS	
2000	F.F. Control	SSL	TPF	
Feb. 2000	Satellite Demonstration	RGA	SPHERES	
Mar. 2000	Metrology System Test F.F. Control	RGA	SPHERES DSS	
Oct. 2001	Metrology System Test Satellite System ID	RGA	SPHERES	
2002 +	Docking Control	SSL	Orbital Express (DARPA)	
Jul. 2002	Metrology System Test Docking Control	RGA	SPHERES DARPA	
2003 +	Mass ID / FDIR	SSL	Modeling	Ames
Feb. 2003	FDIR Global Frame Control	RGA	Modeling TPF	Ames
Nov. 2003	F.F. Communications F.F. Control FDIR	RGA	DSS TPF Modeling	Goddard Ames
2003 +	Tethers	SSL	SPECS	Goddard
2004 +	MOSR	SSL	Mars Sample Return	
June 2004	F.F. Control Docking	MSFC	TPF DARPA	JPL
Nov. 2004	F.F. Control Tethers	MSFC	TPF SPECS	JPL

6.2 Design Framework

Chapter 4 describes all the features of the SPHERES Laboratory for Distributed Satellite Systems which enable it to fulfill the definition of a laboratory. The previous section presents the range of research conducted with SPHERES to date; it also shows the ability of the SPHERES facilities to operate in several locations to accomplish different research goals. This information enables a thorough examination of the SPHERES Laboratory's ability to fulfill the design principles based on the design framework presented in Chapter 5 and suggest design changes if SPHERES could go through one more design iteration.

6.2.1 Step 1 - Identify a Field of Study

- *Principle of Enabling a Field of Study*

Principle of Enabling a Field of Study

At its conception, SPHERES was planned to be a testbed for the development of spacecraft docking and autonomous rendezvous algorithms. At that point, the SPHERES team identified several areas of study necessary to develop these types of algorithms:

- Metrology
- Control
- Autonomy
- Artificial Intelligence
- Communications
- Human/Machine Interfaces

These areas of study are described in Section 4.3.3.

As the design of SPHERES matured to fulfil the MIT SSL Laboratory Design Philosophy the field of study progressed from docking and rendezvous to distributed satellite systems. The areas of study supported by the laboratory should not only cover those topics which allow docking and rendezvous, but also the different configurations that comprise DSS. The SPHERES team identified the following configurations:

- Docking and rendezvous
- Formation flight
- Separated spacecraft telescopes
- Tethered spacecraft
- Sample capture

For each of these areas, the SPHERES laboratory must allow, at least, the study of the metrology, control, autonomy, and communications requirements to mature the technology.

To support this range of areas of study, SPHERES clearly needs to allow the participation of multiple scientists. Therefore, the SPHERES team created the Guest Scientist Program (Section 4.3.3.1) to provide scientists with:

- A simulation to create models of their experiments in their home locations and the ability to conduct experiments at the MIT SSL as the models mature.
- The SPHERES Core software which features a high-level applications programming interface (API) and multiple libraries to support scientists in the implementation of their algorithms.
- The ability to define their own telemetry data structures.
- A flexible schedule with continuous support by the SPHERES team.

Further, SPHERES allows full software reconfiguration (Section 4.3.4.7), which has enabled scientist to conduct research in multiple areas of study without any hardware changes (docking and rendezvous, formation flight, and sample capture on the high-level areas; metrology, control, autonomy, communications within the low-level areas). The SPHERES Expansion Port (Section 4.3.3.2) enables hardware reconfiguration. Through the use of the expansion port, SPHERES has already enabled ground-based research on docking and rendezvous with an advanced docking port, tethered spacecraft formations, and complex formation flight maneuvers. The areas of artificial intelligence, human/machine interfaces, and separated spacecraft telescopes have not had experiments at this point; their study with SPHERES will require the addition of hardware and/or creation of special software.

This information allows the calculation of the costs for the development of the SPHERES Laboratory for DSS. Table 6.2 summarizes the areas of study supported by SPHERES in two groups: high level configuration of distributed satellite systems, and low-level areas of study within each configuration. The *guests* column indicates that a guest scientists is currently conducting research on the subject or that the SPHERES team expects a guest scientist to be a primary researcher for that area. The *current* column indicates an area of study currently being researched with SPHERES. The last two columns provides information on the cost to enable each area of study within SPHERES (based on existing contracts) and or as standalone ISS projects (based on past MIT SSL projects).

TABLE 6.2 Areas of study supported by SPHERES

Area of Study	Guests	Current	SPHERES[a]	Standalone[a]
Docking and rendezvous		✓	$2.5	$2.0
Formation flight	✓	✓	$0.6	$2.0
Separated spacecraft telescopes	✓		$1.0	$4.0
Tethered spacecraft		✓	$0.6	$3.0
Sample capture	✓	✓	$1.2	$3.0
Metrology		✓	$0.0	$0.5
Control	✓	✓	$0.0	$0.5
Autonomy	✓	✓	$0.0	$0.5
Artificial Intelligence			$0.5	$2.0
Communications		✓	$0.5	$2.0
Human Machine/Interface			$1.0	$4.0

a. Costs in US $ millions

The costs to enable docking and rendezvous research represent the original cost to develop the SPHERES Laboratory of approximately $2.5m. This initial cost included the ability to test metrology, control, and autonomy algorithms. It is estimated that enabling research on each of these specific areas in a standalone project will cost at least $0.5m. The cost to support formation flight with SPHERES is covered by contracts approximating $0.6 million; but development of a standalone facility would require a complete new project to be delivered to station; the project cost would be similar to that of SPHERES, at $2m. The development of the optical systems to model a separated telescope has been proposed at a cost of approximately $1.0m; the complexity of a standalone system would require no less investment than that used for MACE, at $4.0m. The development of expansion port items to support tethered spacecraft is done under a project funded with $0.6m; the complexity of this project is estimated between that of SPHERES and MACE, at $3.0m, due to the added hardware requirement. The sample capture system used for MOSR requires the development of the capture station, of a new satellites with a fully spherical shell, and the launch of these items to the ISS. Therefore, the cost of this system within SPHERES is based on contracts for $1.2m. The deployment of a standalone system is expected at $3.0m. SPHERES lacks the data storage capacity for successful artificial intelligence (AI) tests; therefore, it requires an investment of approximately $0.5m to develop the expansion port items to provide the increased storage space necessary to support AI. A standalone project would require no less investment than that used for SPHERES. While tests on the area of communications have already taken place with SPHERES, these tests are limited to the default hardware provided. The expansion port can be used to provide different types of communications hardware to test different technologies and protocols. This expansion would require approximately $0.5m. A standalone project would require an investment similar to SPHERES at $2.0m. The area of human/machine interfaces has not been considered for testing with SPHERES in the short term, but initial estimates require approximately $1.5m to develop expansion port hardware for the satellites as well as new interfaces for the operators. The complexity of this project as a standalone experiment would be closer to that of MACE, at $4.0m.

Figure 6.6 shows the fractional cost of SPHERES with respect to launching standalone projects to study the areas of study identified in Table 6.2 utilizing equation 5.1. The figure shows that at least five, preferably six areas of study must be covered to obtain a reasonable benefit from supporting multiple investigators in the laboratory. It is also noticeable how adding the last area of study (human/machine interfaces) adds little value, given its higher cost. The SPHERES team has demonstrated the ability to conduct science on at least the following areas: docking and rendezvous, formation flight, tethered spacecraft, metrology, controls, autonomy, and communications. SPHERES is further expected to be used to demonstrate sample capture and separated spacecraft telescope systems. Therefore, the SPHERES laboratory allows research in a sufficient number of research areas to warrant the costs to make it a laboratory, rather than a docking and rendezvous testbed.

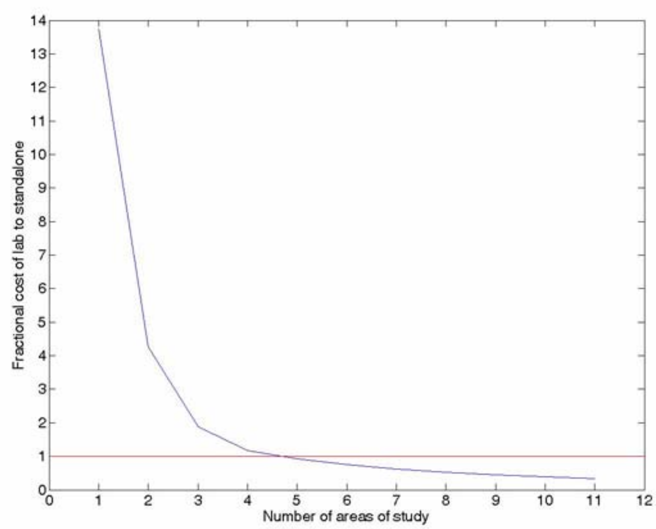

Figure 6.6 Fractional cost of enabling multiple areas of study

6.2.2 Step 2 - Identify Main Functional Requirements

- *Principle of Enabling Iterative Research*
- *Principle of Optimized Utilization*
- *Principle of Incremental Technology Maturation*

Principle of Enabling Iterative Research

The principle of iterative research is composed of three parts: development of data collection and analysis tools, enabling reconfiguration, and having a flexible operations plan. The following section describe how SPHERES fulfills these requirements.

Data Collection and Analysis Tools

Section 4.3.2.1 describes the metrology sub-system, which is used for all data collection in the satellites. The metrology sub-system provides a 6DOF IMU system with a bandwidth of 300Hz, and the precision to observe an impulse bit of the propulsion solenoids. The global metrology system, which measures the state of the satellites with respect to a reference frame, has a bandwidth of up to 2Hz with 0.5cm linear and 2.5° angular precision.

SPHERES counts with several features to ensure the integrity of data and minimize the transfer time. As explained in Section 4.3.2.3, the laptop programs (both ground-based and ISS) save all received data; data files are not corrupted if an experiment terminates unexpectedly. Further, the GSP program provides a clearly defined set of data packages as well as user-defined packages. This allows scientists to quickly identify the data necessary to perform analysis. For ISS operations, SPHERES stylizes the existing communications resources of the station to minimize data transfer times.

Enable Reconfiguration

The iterative research process presented under this principle consists of three iterative loops:

- Repetition of experiments
- Modification of experiments
- Modification of the hypothesis

This section analyzes the ability to close each of those three loops with the SPHERES laboratory.

Repetition of experiments. By following the MIT SSL Laboratory Design Philosophy, the SPHERES design considers the repetition of tests as an essential aspect of its facilities. Section 4.3.1.4 details the features of SPHERES which directly enable efficient test repetitions. The software sub-system most directly facilitates test repetitions by providing operators with simple tools to start and stop tests. Section 4.3.2.8 presents the two separate user interfaces, each designed to simplify repetitions of tests in their respective operational environments. Section 4.3.2.7 explains test synchronizations to help guarantee initial conditions of tests with multiple units. Lastly, the ability of SPHERES to re-supply all of its consumables (Section 4.3.2.9) allows for multiple repetitions with reduced risk that a single test will deplete all available consumables.

Modification of experiments. The ability to run families of tests, explained in detail in Section 4.3.1.3, allows each operating session to test a range of algorithms, allowing multiple experiments to be conducted during each iteration. Section 4.3.4.7 presents the ability of SPHERES to change the software easily. The use of the ISS communications system (Section 4.3.1.5) to upload new experiments and the lack of NASA safety controls on software (Section 4.3.1.6) minimize the time to reconfigure the satellites. Lastly, the physical nature of SPHERES allows to easily change initial conditions. The addition of passive hardware is easily performed by using the velcro of the docking port; adding active hardware can be done via the expansion port (Section 4.3.3.2).

Modification of the hypothesis. Modification of they hypothesis implies that substantial changes can be made to the facilities of a laboratory. The principle calls for the ability to modify sensors and actuators, to enable software and hardware changes to represent new models derived by the scientists, and to allow modification of the operation plans. Software modifications can be made if the desired dynamics of the new sensors and/or actuators are within the limits of the avionics used in SPHERES (Section 4.3.4.5). Further, the SPHERES sensors and actuators can potentially be modified by using the expansion port (Section 4.3.3.2), although these changes require delivery of new hardware.

The satellites can be modified to represent new models, with certain limitations. SPHERES provides the ability to fully change the software (Section 4.3.4.7), which allows software based model to be fully modified. As presented above, the docking port and expansion port can be used to add hardware, but this will require the delivery of the expansion items to the ISS. Further, hardware modifications are limited to the general capabilities of the satellites basic design (Section 4.2.1).

Flexible Operations Plan

SPHERES operates in a multitude of ground based facilities, all of which have demonstrated its capability to produce multiple iterations. The locations where experiments have been conducted include: the MIT SSL laboratory facilities, the KC-135 reduced gravity airplane, and the Marshal Space Flight Center flat floor facility. Research operations at the MIT SSL are described in Section 4.3.1.1; iterative loops are presented for the cases where the researcher is both on-site and off-site. These loops show the ability of SPHERES to provide a flexible operations plan for ground-based research at the MIT SSL. Scientists have the ability to determine the time they need for data analysis, while the SPHERES team minimizes the time to transfer data and update algorithms. The only hard limitation on ground-based tests at the MIT SSL are due to the limited test time of approximately 20 minutes (operation of the air carriages). Similar iterative loops can be created for the two operational environments not considered an integral part of the ISS operations, but which appeared during ground-based operations of SPHERES:

Iterative Research Utilizing the KC-135. The KC-135 operational environment (described in Appendix B) provides the ability to perform 6DOF tests with the presence of the researcher. But it is a relatively harsh environment, where test time is heavily constrained. The SPHERES operations in this platform required a pre-specified plan to be strictly followed during each test session; only one or two programs were planned for testing each day, without the ability to modify the programs. After the tests are performed, video and data analysis occurs and programs are modified in the evening, for testing the next day. Therefore, while multiple tests are performed each day in the KC-135 itself, the process has a minimum iteration period of one day. In some cases, the iterations occurred over two days, as one day was left in between for data analysis. A further limitation of the KC-135 is that tests can only be performed over a one week period, and subsequent tests, which require further sponsorship of new campaigns, are usually no less than six months apart. The KC-135 follows the four steps of the iterative process (as presented in Figure 4.8 on page 118) as follows:

1. **Running tests** - Limited to 20 seconds; useful data of 5-10s. 60s between tests, with three 5-10 minute periods every ten parabolas.
2. **Data collection** - Data is collected in real-time or between tests within the KC-135; available to the researcher until after the flight.
3. **Data analysis and algorithm modification** - Inflexible: average time between iterations is less than 24 hours and maximum of 72 hours.
4. **Algorithm implementation and update** - Algorithms cannot be modified aboard the RGA; updating the satellites can only be performed during the three long pauses (five to ten minutes).

Figure 6.7 presents the modified iterative research process aboard the ISS. Of special note is the addition of data evaluation outside the standard loop, and the separation of the data analysis and algorithm modifications into a different location than where tests are conducted. The figure illustrates the need to maximize the science time aboard the KC-135, while leaving the data collection, analysis, and algorithm modification for a later time.

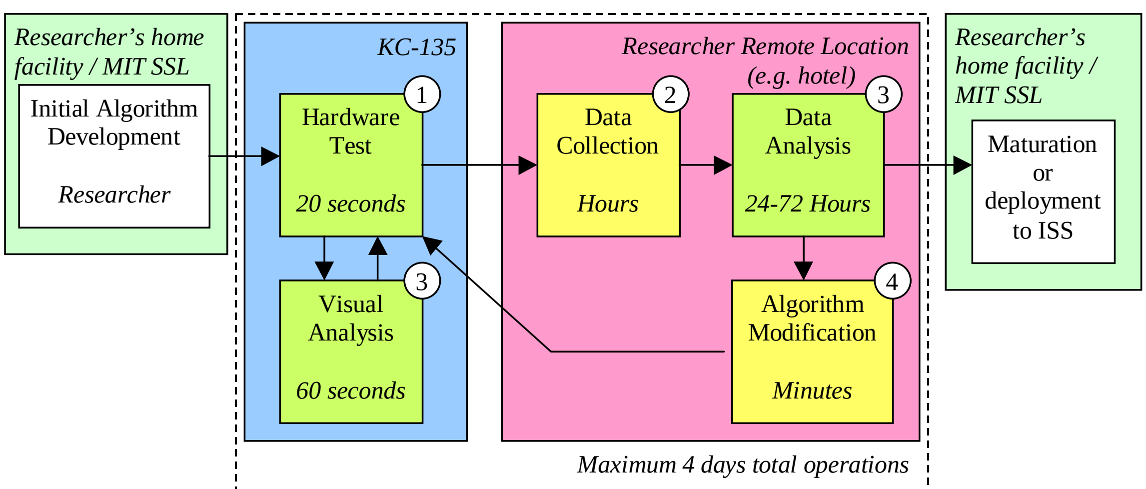

Figure 6.7 KC-135 iterative research loop

Table 6.3 summarizes the *research iterations* conducted during the five week-long campaigns at the KC-135 reduced gravity airplane. Although all experiments were repeated multiple times (between 5 and 80 times each week), the table shows the number of research iterations after data was analyzed each night and new algorithms were uploaded for tests on a subsequent flight. The maximum number of research iterations is three; several experiments achieved this number of iterations, although the majority only had one or two iterations.

TABLE 6.3 Research iterations aboard the KC-135

Flight	Test Topics	Research Iterations
March 2000	Global System ID	1
	Global Frame Control	3
	Angular regulation (Euler vs. Quaternions)	2
	KC Frame ID	1
	Formation Flight Tests	3[a]
	Minimum Gas Turn	-
October 2001	Inertia Measurement	1
	Closed Loop Inertial Control	-
	Hardware Tests	-
	Global Frame Control	3
July/August 2002	Global Frame Control	3
	Docking	1
February 2003	1DOF System ID	3
	Global Frame Control	2
	Thruster ID	n/a
November 2003	Beacon Track	1
	Docking	2
	Lost in Space	2
	Inertia ID	3
	Distributed Control Architecture	2

a. *KC frame identification and angular regulation tests culminated in the ability to perform formation flight tests.*

Research on the KC-135 also had iterations at a different scale. The metrology system design went through three major iterations, with cycles of approximately twelve months each. These revisions were directly affected by the data and results obtained from operations aboard the RGA.

Iterative Research at the MSFC Flat Floor. A description of the facilities and benefits of the MSFC Flat Floor are presented in Appendix B. The MSFC Flat Floor environment is relatively stress free. The schedule test time is usually in terms of full days, allowing scientists to iterate on their algorithms after every test run. Scientists are not required to run one test after another. Further, the facility also allows all consumables to be replenished with ease and resupply is practically unlimited. While time is not as critical as in the case of the KC-135, the number of tests and data analysis/algorithm modification times are limited to the length of the visit to MSFC; scheduling of the facility usually requires a few months of advance notice. Lastly, tests are again limited by the air carriages ability to operate friction-less; in the case of the MSFC installations the operational time is approximately 10 minutes, since the conditions of the flat floor are different than those at MIT. The steps of the iterative research process (as presented in Figure 4.8) at the MSFC Flat Floor are as follows:

1. **Running tests -** Up to 10 minutes (carriage gas limitations).
2. **Data collection -** Two possible time scales: can take a few minutes while at MSFC or after the end of the work day.
3. **Data analysis and algorithm modification -** Two possible options: full quick iterations on-site at MSFC or extended analysis off-site overnight or over a few days. Limited by travel time.
4. **Algorithm implementation and update** - Updated within minutes at both the MSFC Flat Floor location or at the researcher's remote location.

Two possible iterative research loops result from operating at the MSFC Flat Floor; these are presented in Figure 6.8. A research loop can be closed at the MSFC facilities, in a similar fashion to on-site research at the MIT SSL. If more time is necessary, a second research loop can be closed with data analysis taking place at the researcher's remote location (e.g. hotel) in increments of days.

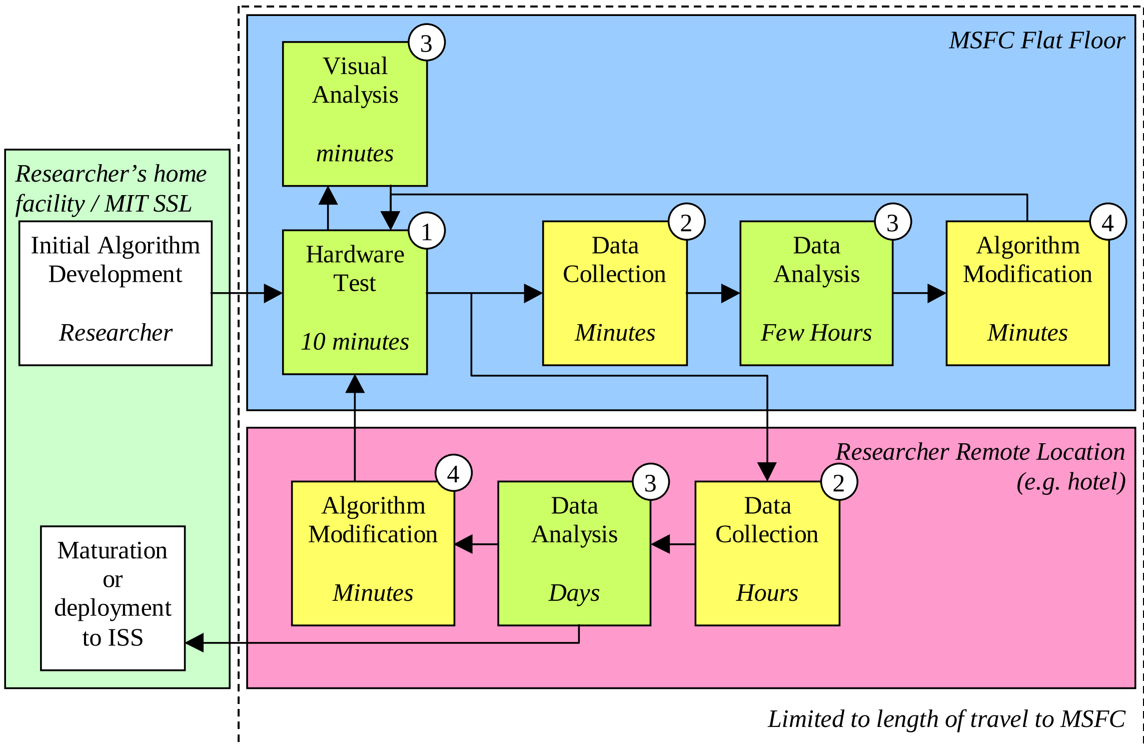

Figure 6.8 MSFC Flat Floor iterative research loops

Table 6.4 presents the iterations that took place during the two weeks of operations at the MSFC Flat Floor. TPF rotations were iterated twice each week; the iterations required a substantial amount of repetitions to collect the necessary data, therefore, although tests were conducted daily, only two iterations took place each week. Docking algorithms, tested during the first week only, were iterated once as tests were done the first day, data analyzed during the third day, and new algorithms tested the third day. Tether experiments iterated four times during the second week of tests at the MSFC Flat Floor. Data was analyzed every night and new algorithms tested each day. These first two weeks of tests did not take advantage of the on-site iterative options for research iterations, but the ability to modify experiments on site was essential to debug the algorithms used each day.

TABLE 6.4 MSFC flat floor iterations

Algorithm	Iters
TPF Rotations	2/2
Docking	1
Tether	4

Operations Summary. SPHERES provides a wide range of iterative loops at different fidelity levels. The operational plans make the steps of improving the fidelity of the test manageable by always keeping the researcher in the loop with minimal overhead times. The availability of the MIT SSL facilities allows scientists to test their algorithms in flight-identical hardware prior to deployment to the ISS. The operational plans for the ISS calls for a flexible iteration time with minimal overhead in the order of days, compared to weeks of science time. Further, the portability of SPHERES has allowed a wider range of operational environments than the three principal locations, further expanding the range of science and overhead times. A summary of the demonstrated science and overhead in ground-based facilities, and the expected times of ISS operations is presented in Table 6.5.

TABLE 6.5 Summary of operational environments and iterative research

	Step				
Location	**1**	**2**	**3**	**4**	**Comments**
Simulation	Researcher	Minutes	Researcher	Hours	Low fidelity models
MIT SSL - Off Site	20 min	Hours	Researcher	Days	SPHERES team member runs tests
MIT SSL - On Site	20 min	Minutes	Travel	Minutes	Maximum level of support
ISS	30 min	2 days	2-4 weeks	2 days	Analysis time in increments of 2 weeks
KC-135	20 sec	Hours	24-72 Hours	Minutes	Challenging environment provides operational feed-back
MSFC Flat Floor	10 min	Minutes / Hours	Hours / Days	Minutes	Possibility of two iterative loops: on site at MSFC and at remote location

Step 1: Test Duration (science time)
Step 2: Data Collection (overhead time)
Step 3: Data Analysis and Hypothesis Update (science time)
Step 4: New Algorithm Upload (overhead time)

Figure 6.9 shows where each of these locations lie within the curve of effective iterations. The simulation provides a large number of iterations with very flexible time. Operations at the MIT-SSL with the research on-site provide many iterations with the time limited by experiment time and researcher travel, neither being critical. Off-site research at the MIT-SSL can provide a larger number of iterations, only limited by test time, although overhead time does become larger. The ISS schedule is expected to allow a reasonable number of iterations (although less than those available in ground facilities), with flexible science time and manageable overhead time. The KC-135 provides up to four iterations (KC-135-1) once a day, or one iteration every year (KC-135-2). Similarly, tests at the MSFC allow a small number of iterations over short periods of time, or one iteration every several months.

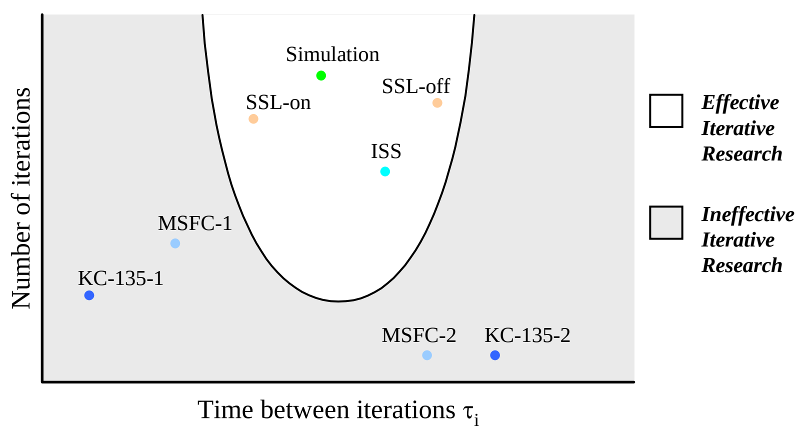

Figure 6.9 Effectiveness of iterations with SPHERES

Iterative Research Conclusions

After several iterations in the design of the SPHERES facilities (the satellites and different user interfaces), the resulting laboratory closely follows the guidelines of the Principle of Iterative Research. The metrology and communications systems provide sufficient data collection and transfer tools to facilitate iterative research. While the systems do have hard limitations, and their operation in the ISS still must be demonstrated, research in several ground facilities has shown the ability of SPHERES to collect the necessary data.

SPHERES clearly allows not only repetition of experiments, but also modification of both the experiments and the hypothesis. While these changes are limited to the capabilities of the satellites to accept new software and hardware, they have proven enough to iterate on the hypothesis behind several areas of study.

The SPHERES operations plan has demonstrated great flexibility. Not only has iterative research been conducted at the MIT SSL, but also at two remote facilities. At all locations, the SPHERES operations plans work to minimize the overhead time to collect data and update modifications. The available science time varies greatly between facilities, each providing wide ranges of experiment time and data analysis. Each of the facilities has been used to successfully accomplish iterations.

Principle of Optimized Utilization

The use of the ISS resources is as follows:

- **Crew** - Interaction with the crew is an essential element of the SPHERES facilities aboard the ISS as presented in Sections 4.2.1.4 and 4.3.1.2. The presence of the crew is essential to allow scientists to push their algorithms to the limits; if the algorithms fail, the crew can stop a test. The SPHERES program has been designed so that astronauts can provide substantial feedback to the SPHERES team. The astronaut will be allowed to make decisions on the progression of tests, based on information provided by the scientists.

  Test sessions at the ISS have been scheduled for two hours of science every two weeks, plus setup and brakedown. Therefore, SPHERES expects to use approximately six hours per month of astronaut time.

- **Power** - The SPHERES facilities at the ISS utilize a minimal amount of power, but this power is provided by custom battery packs. A full system with three satellites, five beacons, and one laptop transceiver consumes at most 51W. This amount of power is well below the *standard* power supplies of 3kW provided for each ISPR.

  The SPHERES flight hardware does not utilize rechargeable batteries. Therefore, out of the 51W used by a full setup, the only power supplied by the ISS is that of the laptop transceiver (1W), which accounts for less than

2% of the total power. The use of disposable batteries increased the upload mass of SPHERES by approximately 20kg, more than a 30% increase in total upload mass.

The use of liquid carbon dioxide as propellant was a decision made after substantial trade-offs. Fans, air compressors, and available gases in the ISS (mainly nitrogen) did not prove feasible solutions. Therefore, although the CO_2 represents an additional lack of use of available ISS resources, it was selected as the only propellant which provided the necessary combination of operations time, volume, and thrust.

- **Telemetry -** The SPHERES interface operates directly on a laptop computer supplied by the ISS (Station Support Computer, SSC); SPHERES doe not use any other type of data storage. The SPHERES user interface places all the data files directly on the drive shared between the ISS and the ground control center. Therefore, all the experiment data is available as soon as the drives are synchronized.

  The SPHERES team requested real-time video of the first two operating sessions aboard the ISS in order to ensure correct operations of the facilities the first time they are used. The facility has been designed so that future operations do not require (but could use) real-time communications with the astronauts. Therefore, SPHERES will not utilize an undue amount of bandwidth during its operations.

  Based on operations at ground-based facilities, the expected total size of the data files to be downloaded each test session will be 1MB; new programs to upload are expected to be less than 5MB. These transfers can easily take place over several seconds at data rates between 100-200kbps. There is no real-time data download requirement from the ISS to ground.

- **Duration -** The base mission has been defined as ten two hour sessions every two weeks; the consumables have been sized for this operation. Therefore, the basic SPHERES mission is six months long, with the ability to extend the program if consumables can be delivered to the ISS.

- **Benign Environment / Atmospheres -** SPHERES makes full use of those aspects of the benign environment of the ISS that affect it directly: the ability to use a low-cost ultrasound-based metrology system; simple structural design; low-pressure propulsion system; and use of COTS avionics. Further, astronauts have limited access to the SPHERES satellites hardware and software is available to correct problems with the satellites. But the astronauts do not have the ability to correct hardware malfunctions.

SPHERES obtains substantial value from the correct use of most of the resources available at the ISS. Table 6.6 shows the *value* obtained from the use of each resource based on the charts presented in Figure 5.6. SPHERES slightly under utilizes crew time, for a value of 0.8. The total power of SPHERES is minimal, for a value of 0.99; but because it does not use ISS power sources, it obtains no value from the percentage power. The correct use of telemetry, with flexible download data rates and limited data sizes, give it a value of 0.99. The duration is considered slightly short, although well within the expected lifetime of an ISS mission, for a value of 0.9. Lastly, SPHERES utilizes the ISS environment to a large extent; this subjective measure is given a value of 0.8 since astronauts cannot fix hardware malfunctions. As a result, the SPHERES facilities obtain a value of 4.48 out of a possible 6.0, or a 75%, indicating an acceptable use of ISS resources.

TABLE 6.6 SPHERES value from ISS resource utilization

Resource	Amount	Value
Crew	6	0.8
Power (total)	0.051W	0.99
Power (%)	2%	0
Telemetry	100-200kbps	0.99
Duration	6 months	0.9
Environment	Used	0.8

Principle of Incremental Technology Maturation

The first step to evaluate the design of SPHERES is to determine how far up the TRL levels SPHERES allows a technology to mature. As presented in the definition of this principle, TRL's 5, 6, and 7 will be considered.

TRL 5:

1. *The "relevant environment" is fully defined.*

   SPHERES defines the relevant environment as that available at the ISS US Laboratory: a pressurized microgravity environment with a volume of approximately three meters cubed, full 6DOF dynamics, *no* orbital/celestial dynamics, *no* exposure to the radiation, vacuum, and external elements of a full space environment.

2. *The technology advance has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission.*

   The ability to run families of tests and update the algorithms used for those tests allows scientists to conduct tests throughout the necessary range of operating points to represent qualification for an operational mission.

3. *Analytical models of the technology advance replicate the performance of the technology advance operating in the "relevant environment"*

   The SPHERES simulation has been used to create preliminary models of experiments, prior to testing on physical facilities; the simulation has provided relevant results, with tests replicating the results several times. Therefore, it is expected that the results from models derived in the simulation and ground-based facilities will be able to be replicated in operations aboard the ISS, but this has not been demonstrated yet.

4. *Analytical predictions of the performance of the technology advance in a prototype or flight-like configuration have been made.*

   SPHERES provides an unique opportunity to test the metrology, control, and autonomy technologies of distributed satellite systems in a flight-like configuration for a wide range of missions. Two satellites fully represent docking, rendezvous, and sample capture missions. Three satellite missions provide flight-like configuration for separated space telescopes and the study of cluster formations.

Therefore, SPHERES allows a wide range of DSS technologies to mature to TRL 5.

TRL 6:

1. *The technology advance is incorporated in an operational model or prototype similar to the packaging and design needed for use on an operational spacecraft.*

   The SPHERES satellites are an operational model similar to the design of an operational spacecraft for the maturation of coarse metrology and control algorithms for formation flight, docking, and sample capture.

   The base satellites are *not* representative models for more complex missions, such as stepped control of optical telescopes, the use of active docking ports, or tethered spacecraft. Additional hardware is required to enable SPHERES to fully model the packaging and design of an operational spacecraft. These elements can be added to the SPHERES satellites through the Expansion Port, requiring only small investments in terms of design and launch costs.

2. *The system/subsystem model or prototype has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission.*

   As with TRL 5, the ability to run families of tests and change the programs that run these tests allows scientists to conduct all the necessary tests to cover a range of operating points representative of qualification of an operational mission.

3. *Analytical models of the function and performance of the system/subsystem model or prototype, throughout its operating region, in its most stressful environment, have been validated empirically.*

   The SPHERES satellites have been designed to represent general spacecraft; they do not model any specific mission. The capabilities of SPHERES allow it to demonstrate the capabilities of algorithms empirically, by creating a fully observable and controllable environment which provides data to validate the algorithms. The risk-tolerant environment created by the SPHERES facilities used inside the ISS allow scientists to push these algorithms to their most stressful environment, allowing for technology maturation.

   But SPHERES is not intended to demonstrate specific hardware equipment for use in a mission. While software can help model specific sensors and actuators, and additional hardware can be added to better model a system, the SPHERES facilities are not designed to demonstrate hardware technologies.

4. *The focus of testing and modeling has shifted from understanding the function and performance of the technology advance to examining the effect of packaging and design for flight and the effect of interfaces on that function and performance in its most stressful environment.*

   The SPHERES satellites present realistic limitations in the implementation of algorithms, including finite forces in actuators, bandwidth limited sensors, and constraints in the data processing system similar to that of other spacecraft buses. Therefore, SPHERES does allow scientists to start to concentrate on how to integrate their algorithms into a full system. The data collected can help evaluate the effects of interfaces between the different spacecraft bus sub-systems and ultimately help determine the performance requirements of the flight equipment based on the coupling between sub-systems.

SPHERES enables the maturation of metrology, controls, and autonomy algorithms, implemented through software, to reach TRL 6. The satellites provide the necessary understanding of the interactions between the sub-systems of a satellite through empirical tests under stressful operating conditions. But the facilities do not allow maturation of hardware technologies to TRL 6 unless these hardware elements can be operated through the SPHERES Expansion Port and the resources exist to deliver them to the ISS.

TRL 7:

TRL 7 requires both an actual system prototype and its demonstration in a space environment. The prototype should be at the same scale as the planned operational system and its operation must take place in space.

SPHERES has not been designed to be an actual system prototype; further, it operates inside the station, so experiments are not exposed to a *full* space environment. In general, SPHERES will not enable technologies to achieve TRL 7 by itself.

The case of MOSR is special, since the SPHERES satellites are of the same scale as the planned operational system, and the capture mechanism will be a prototype of the actual system. In this special case, SPHERES can allow MOSR to achieve TRL 7.

In summary, SPHERES allows a wide range of technologies to mature to TRL 5 with the baseline hardware and software provided in the current design. Projects which only require maturation of software technologies (e.g., algorithms, some artificial intelligence) can mature to TRL 6. Missions that can provide the resources to develop and launch expansion port modules to create the necessary operational models can also mature to TRL 6 with relatively minor investments. SPHERES allows only a limited set of missions to reach TRL 7 maturation, since only missions of the same scale as the SPHERES facilities (satellite size, communications bandwidth, and operations inside the ISS) can reach that level.

6.2.3 Step 3 - Refine Design

- *Principle of Focused Modularity*
- *Principle of Remote Operations and Usability*

Principle of Focused Modularity

The design of the SPHERES facilities consists of the following clearly delineated elements (or sub-systems) to be considered for modularity and reconfiguration:

- SPHERES satellites
  - Propulsion
  - Structures
  - Metrology
  - Data processing
  - Communications
  - Software
- Metrology Beacons
- Laptop Transceiver

The ability to make any of these systems modular and/or allow reconfiguration through them was balanced with the primary science objectives and constraints of operation aboard the ISS:

- Develop a set of multiple distinct spacecraft that interact to maintain commanded position, orientation, and direction.
- Allow reconfigurable control algorithms, data acquisition and analysis, acquisition of a truth measure.
- Enable the testbed to perform array capture, static array maintenance under disturbances (attitude control and station keeping), and retargeting maneuvers.
- Enable testing of autonomy tasks, including fault-detection and recovery, health and status reporting, and on-board replanning.
- Ensure traceability to flight systems via communication, propulsion, structural, avionics, guidance, control, and power capabilities.
- Design for operation in the KC-135, shuttle mid-deck, and ISS.
  - Allow full operations with only one astronaut.
  - Meet all NASA safety requirements.
  - Meet mass & volume requirements for launch aboard one MLE.
  - Account for remote operations.

The science objectives directly call for the software sub-system, through which algorithms are implemented, to be reconfigurable. But the other sub-systems required further analysis, to determine whether making them modular could provide a benefit without interfering with the original mission objectives.

The Principle of Reconfiguration and Modularity provides six specific criteria to test for modularity: interdisciplinary use, reconfiguration, obsoleteness, life-time, cost amortization, and maintenance of the original objectives. The design of the satellites was strongly driven by the constraints for operations aboard the ISS. Each of its sub-systems was developed almost independently of each other, resulting in four different modules (propulsion, communications, data processing, and metrology) with simple interfaces between them, physically put together using the structures sub-system and logically connected through the software sub-system. The interfaces can be easily replicated by other hardware implementations.

Safety constraints prevented any reasonable modularity or reconfiguration of the propulsion system. Not only does the physical reconfiguration of the propulsion system add little value to the main science requirements (since the original configuration allows full 6DOF operations), but physical changes of the propulsion system would require additional hardware (especially to meet safety requirements) which would have prevented the satellites from fitting inside one MLE, which directly conflicts with the original goals.

The communications sub-system interfaces through standard serial ports (UART) to the data processing stack and to the laptop computer. Internally within the satellite the communications hardware is fixed, it does not allow any modularity or reconfiguration because no added value was seen from allowing these elements of the satellites to change. But the development of the external laptop transceiver as an autonomous module which can communicate with any standard PC serial port and use power from a standard USB port does add value to the mission, since the operator’s control station is not limited to any specific computer and the life-time of the module is unlimited. Therefore, the modularity of the communications transceiver, together with the ground-based user interface, allows SPHERES operations by scientists in multiple areas (interdisciplinary use), while using the same hardware (prevent obsolescence and allow cost amortization) in multiple operating conditions.

Substantial effort was put into allowing the data processing unit to allow reconfiguration and provide a modular interface. Being able to reconfigure the main processing unit (the TI C6701 DSP board) would have been beneficial if the processor could easily be upgraded to newer DSP's. But the microprocessor is not modular itself because enabling direct physical access to the DSP board would have forced the satellites to be larger than the one MLE constraint for launch to the ISS. Further, there was no reason to develop the DSP as a modular system to be used in other projects because the DSP unit does not have any common interfaces (therefore it does not easily allow inter-disciplinary use) and its time to obsolescence is not long enough to warrant use in systems designed in future years. Therefore, rather than allowing upgrades of the DSP board itself, the avionics team created the Expansion Port, which provides several common interfaces to the DSP. The Expansion Port makes the satellites modular, as it allows the satellites, which were designed with a life-span of multiple years, to enable inter-disciplinary use and take advantage of cost amortization as multiple scientists use the facilities.

The metrology system interfaces with the data processing unit with simple time-of-flight signals, but their use requires custom hardware and algorithms to collect and process the data correctly. Further, correct metrology information depends on precise positioning of the sensors in the satellites, and allowing physical reconfiguration presented many challenges to ensure the data was collected correctly. Therefore, it was not easy to make the metrology hardware of the satellites modular for inter-disciplinary use nor allow its reconfiguration. On the other hand, the external beacons enable easy reconfiguration of the global metrology system to accommodate a wide range of operating environments. Their design uses standard track-mounts available in the ISS and space shuttle, and the SPHERES team acquired several of these tracks for use at the MIT SSL and the KC-135.

This allows easy reconfiguration of the global system. To enable modularity, all the beacons are identical. Selection of the beacon number is done through an operator accessible selection switch. This allows the beacons to be interchanged and to operate in different configurations.

As seen, the sub-systems of the SPHERES satellites are not modular elements. Their implementation as separate modules, rather than a single integrated satellites, would have violated the mass/volume constraints to fit within one MLE without adding substantial value to the science goals, to inter-disciplinary use, or to cost amortization. But the satellites as an element do take advantage of modularity. The satellites do allow inter-disciplinary use within the field of study; they are reconfigurable through the Expansion Port, docking port, and the software sub-system; the satellites are not expected to reach obsolescence before re-use with new programs; the life-time is expected to be several years; and the cost of the mission is amortized by allowing multiple scientists to use the equipment.

The software sub-system is reconfigurable to meet the mission's science goals. The software also clearly supports inter-disciplinary use. It has no finite life-time/obsolescence, as it depends on the operations of the satellites only, no other factors affect the time it is usable. The software is modular (Section 4.3.3.1, [Hilstad, 2003a]). It clearly identifies the modules which enable the controls, metrology, communications, and support functions. Scientists can select to use standard modules provided by the SPHERES team or develop their own.

Table 6.7 summarizes how each of the SPHERES sub-systems meets the criteria set forth in the Principle of Focused Modularity and Reconfiguration. The satellites as a whole provide modularity and reconfiguration by being identical satellites, interchangeable with each other, and by using the docking port and expansion port to allow reconfiguration. The propulsion and structures internal sub-systems would have violated the 1MLE constraint if they had been designed as modules, rather than integrated components. The internal metrology hardware requires precise alignment and special hardware to use the signals, therefore, it is not easily to use in an inter-disciplinary fashion and could cause violation of the 1 MLE constraint. The DSP unit suffered from both ISS constraints and the danger of obsolescence to warrant being a module, although allowing upgrades of the DSP would have been a positive effect of a modular data processing system. Making the communications system modular does not provide a clear value to the system; it does not truly enable reconfiguration. On the other hand, it could provide inter-disciplinary use for other projects, and its time to obsolescence and life-time are not of great concern. But the system was not designed in a modular fashion since it provided no benefits for the SPHERES project. The software sub-system is highly reconfigurable and modular as a direct result of the mission goals. The metrology beacons are modular in their ability to be interchanged and reconfigured with ease to provide accommodate different operational environments of the global metrology system. The laptop transceiver enables the use of the SPHERES facilities through any standard PC serial port at many locations.

TABLE 6.7 Modularity of SPHERES

Sub-System	Inter-discipline	Reconfig.	Obsolete	Life-time	Cost-Amortize	Original Goals	Implementation
Satellite	1	1	1	1	1	1	Identical, interchangeable satellites; docking port; expansion port.
Propulsion		0				0	Not Modular
Structures						0	Not Modular
Metrology	0	0				0	Not Modular
Data Processing			0			0	Not Modular
Communications		0					Not Modular
Software	1	1	1	1		1	FLASH memory for reconfiguration. Guest Scientist Program for modularity.
Metrology Beacons		1	1	1	1	1	Identical beacons with user-selectable configuration
Laptop Transceiver		1	1	1		1	Use of standard interface (UART) and power (USB).

Principle of Remote Operation and Usability

The SPHERES laboratory was specifically designed for operations aboard the International Space Station, where the operators and researchers are distinct individuals; it was also designed for operations at the MIT SSL and NASA's Reduced Gravity Airplane, where the operators are sometimes the researchers. Therefore, as presented in Section 4.3.2.8, there are different interfaces of the SPHERES laboratory to satisfy operations at the different locations.

The Principle of Remote Operations and Usability separates the requirements for operators and researchers:

- Operator
  O1. Provide necessary controls to conduct research efficiently
  O2. Ensure safe data transfer regardless of operator actions
  O3. Present relevant information for successful run of experiments
  O4. Enable operators to provide feedback
  O5. Allow real-time communications for selected operations
- Researcher
  R1. Minimize efforts to collect data
  R2. Allow upload of information
  R3. Enable real-time communications for selected operations
  R4. Allow scientists to predict results and compare with collected data

The prototype interface concentrated on the development of the facilities and immediate science feedback, rather than the operation at any specific location. While the interface had the ability to present custom data in real-time, the data did not aid in operations, rather, it distracted operators in environment such as the RGA (violating O3). This interface also violated requirement O2, since it saved only recognized data. Because the interface was used only by the SPHERES team, it required no direct feedback mechanism (O4) or real-time communications (O5, R3). The interface did meet requirement O1, as it allowed easy operation of the units, informed the operator when tests were running, and when data was received. By collecting processed data the interface attempted to satisfy requirement R1; data was easy to read from the stored files. The design tools necessary to load new programs (R2) were available since the prototype design. But the prototype systems did not include a simulation to allow scientists to predict their results and compare them, violating requirement R4.

The prototype interface evolved into two separate programs: a ground-based interface and an ISS interface (Section 4.3.2.8). Further, the SPHERES simulation (Section 4.3.3.1) was developed to account for the remote location of scientists who are not members of the SPHERES team. In this manner, the SPHERES laboratory meets all the requirements of this principle.

The ground-based interface was designed for operations at the MIT SSL, NASA RGA, MSFC Flat Floor, and other facilities where the operators are either the researchers and/or members of the SPHERES team. This interface addresses requirement O1 (control of the facilities) by enabling simple operations for all common tasks and incorporating program upload (R2) directly into the interface. The availability of optional windows with real-time state and debug data allows the interface to provide relevant data (O3) when the operators are the research scientist; otherwise the presented data is only that essential for the operation of the satellites. This interface saves data in its raw format, so that scientists can do substantial post-processing and do not loose any information (O2). The interface *does* require the operator to initiate data storage, therefore creating the potential situation where data is not stored due to operator error. To address R1, minimize data collection time, the SPHERES team developed several Matlab functions to collect the data from the raw data files created by the interface. The SPHERES simulation and the information provided with the Guest Scientist Program fulfills requirement R4, allowing the scientist to create models of their experiments and compare the information. Because this interface was designed for use in ground-facilities with scientists or SPHERES team members present, requirements O4, O5, and R3 are not applicable.

While ground operations depend almost entirely on the scientist and the SPHERES Team, ISS operations depend on more parties: the SPHERES Team, PSI, STP, NASA/ISS Mission Control, and the astronaut. Therefore, the interfaces for operations aboard the ISS satisfy the requirements in different ways, since they also must meet requirements set forth by other parties.

The design for control of the satellites (O1) had to meet NASA requirements, apart from the needs of SPHERES. Therefore, the ISS interface requires the use of several steps to start a test. These steps take into account the need to ensure the operator select the correct program and test and is aware of the expected results of each experiment. While the ground-based interface allows test and maintenance tasks to be performed from the main window, the ISS interface presents separate windows/processes.

The ISS interface stores data immediately upon starting. Regardless of the operator’s actions, the program will save all outgoing and incoming raw data, ensuring the data is safe regardless of the operator’s actions (O2). If a test terminates unexpectedly or is canceled by the operator, the file is saved automatically.

The flight GUI presents information to the operator (O3) in several sections. The state information of the satellites are presented permanently through a status bar. This ensures the operator is always aware of which units are operating and what program is in use. Descriptions of the tests allow the operators to know expected results and make decisions on the test performance. By providing sufficient details on the test, the interface reduces the dependency of real-time communications with the researcher.

The ISS interface presents a questionnaire to the astronaut at the end of each test, requiring the astronaut to provide feedback (O4). The questions are written specifically for each test so that the feedback from the astronaut provides the maximum amount of information to the scientist. Further, the astronaut is allowed to enter notes freely after the questionnaire, allowing feedback on topics not originally considered by the scientist. This feature effectively creates an electronic laboratory notebook.

Operations of the SPHERES laboratory does not require real-time communications in general (O5, R3). Through the data download and astronaut feedback mechanisms, the scientist can determine progress of the research. By interfacing directly with the ISS communications system, the SPHERES facilities can potentially download and upload data and programs in real-time (if the ISS channel is available at the time), even if telecommunications are not established.

Multiple steps were taken to minimize the data download time (R1). The flight interface packages all the data from each session. The use of the ISS telemetry system simplifies the operator's tasks. At that point the data transfer time is dependent on the NASA command center availability to distribute the data to PSI/STP and the SPHERES team. Once the data reaches the SPHERES team, it can be interpreted with the same Matlab tools that were used for initial testing in the ground facilities, since the flight interface uses the same file structures as the ground based interface.

The utilities to upload new programs (R2) are fully integrated into the flight interface. Because a multi-satellite test may require different executable files for each satellite, the interface maintains the structure of the program, making the existence of separate executables transparent to the operator. The interface also manages all the preview files and questionnaires as a single file, so that the astronaut does not have to manage any individual files.

The use of the simulation and MIT SSL ground-based facilities as an integral part of the ISS iterative loop (Figure 4.12 on page 127) allows scientists to predict their results prior to operations aboard the ISS (R4). The facilities are also available after the flight to reproduce allow comparison of results. Further, the availability of raw data allows the results of both ground-based tests and ISS tests to be compared analytically using tools such as Matlab.

6.2.4 Step 4 - Review Requirements and Design

- *Principle of Requirements Balance*

Principle of Requirements Balance

The current design of SPHERES consists of several dozen system-level functional requirements and over one hundred functional requirements for the sub-systems. This assessment concentrates on the system-level requirements derived from the mission objectives summarized in Figure 6.10 [SPHERES, 1999].

The system functional requirements consist of 21 hard requirements (those essential for mission success) and 10 soft requirements (those that would enhance the mission). The hard requirements stem directly from the need to demonstration formation flight algorithms in 6DOF within the KC-135 and the ISS while facilitating iterative research and allowing the study of several areas. The soft requirements derive from desire to demonstrate specific capabilities not fully defined at the time of development (e.g., the mission objective to demonstrate autonomy tasks) or the need to use ground-based facilities (e.g. the KC-135) prior to deployment aboard the ISS. Taken numerically, this is an acceptable division of hard and soft requirements; but one must ensure that the hard requirements drive the mission, while the soft requirements require only limited resources and effort to implement.

The following descriptions illustrate how SPHERES achieved requirement balance, even though it required trade-off's between the functional requirements, including the desire to implement several soft requirements.

> **One-time Use Alkaline Batteries.** Not only did the power sub-system team have a need for re-chargeable batteries, they had the capability to build a ground-based system which has been used continuously since 2001. But the flight hardware utilizes one-time use alkaline batteries. This decision was not a trivial one, but one considered necessary due to the high costs associated with certifying a recharging system for flight aboard the ISS. The SPHERES project team had to balance the need for battery power with the available development resources (both time and money were limited at the time of certification); therefore, while not ideal (especially when the *Principle of Optimized Utilization* is applied), the use of alkaline batteries balanced the efforts required to certify the power system for use aboard the ISS with the resources available.

- Develop a set of spacecraft that interact to maintain position, orientation, and direction.
  - Satellites require translational, rotational, and attitude control capabilities. (Hard)
  - Each satellite must contain its own propulsion, avionics, software, power, communication, and GNC systems within its own structure. (Hard)
  - Satellites must be able to communicate their relative positions. (Hard)
  - Satellites should employ handshaking and negotiation for decision-making. (Soft)
  - Array should consist of at least three distinct satellites. (Soft)
- Allow reconfigurable algorithms, data acquisition and analysis, and provide a truth measure.
  - Satellite must be able to receive control algorithms. (Hard)
  - Satellite must be able to acquire, analyze and send data. (Hard)
  - Allow measurement of relative orientations and positions between satellites. (Hard)
  - Allow measurement of the satellite states relative to the KC-135 / ISS. (Hard)
  - Some of the downloaded data must provide health status information. (Hard)
- Enable the testbed to perform array capture, static array maintenance under disturbances (attitude control and station keeping), and retargeting maneuvers.
  - Should perform self-diagnostic on power up. (Soft)
  - Must determine relative and absolute position. (Hard)
  - Must provide sufficient control authority to counteract environmental effects. (Hard)
- Enable testing of autonomy tasks, including fault-detection and recovery, health and status reporting, and on-board replanning.
  - Compensate for the failure of any other satellite(s). (Soft)
  - Detect a total failure of one of the others. (Soft)
  - Recognize and compensate for minor failures in its subsystems. (Soft)
  - Able to report any minor failures back to an external monitor. (Soft)
  - Able to regularly report the status of each of its subsystems. (Soft)
  - All of the satellites should be physically identical. (Soft)
- Ensure traceability to flight systems via communication, propulsion, structural, avionics, guidance, control, and power capabilities.
  - Enable traceable control algorithms to future missions. (Hard)
  - Provide representative dynamics of the propulsion. (Hard)
  - Provide precision metrology system equivalent to actual applications. (Hard)
  - Enable data communications equivalent to real missions. (Hard)
- Design for operation in the KC-135, shuttle mid-deck, and ISS.
  - ***KC-135***
  - Functionality needs to be demonstrated in <20 sec. (Hard)
  - Operate within the space confines of the KC-135. (Soft)
  - Allow for retrieval and restraint during 2g fall section of flight. (Hard)
  - Meet all applicable KC-135 safety requirements. (Hard)
  - ***ISS***
  - Satellites must fit into shuttle mid-deck locker. (Hard)
  - Enable demonstrations within the confines of the ISS. (Hard)
  - Must allow protocol test time of two hours. (Hard)
  - Meet all applicable ISS safety requirements. (Hard)

Figure 6.10 SPHERES Functional Requirements

Custom Metrology System. The need for a metrology system that identified the full state of the satellites for formation flight control is a hard requirement, but one that is not fully quantitative. The requirements for the metrology system were originally specified in "sub-centimeters" (range) and "degrees" (rotation), but the actual values were determined by the selected system. The final selection of a custom ultrasound and infrared time-of-flight system was mainly a trade-off between acquiring a COTS product and building a custom one. At the time of the development of SPHERES, only a handful of COTS products existed; the majority of them had a cost beyond 15% of the total SPHERES budget, making them unattainable. Further, all the reviewed systems required modifications from their original configuration. Therefore, the SPHERES team decided to develop a custom metrology system (Section 4.2.1.1) which would incorporate directly with the other sub-systems. The final design has demonstrated the ability to meet the design requirements, with specific quantitative resolutions provided (0.5cm, 2.5°) in ground-based 2D operations; 3D operations are yet to be demonstrated aboard the ISS. Ultimately, as the results of tests aboard the KC-135 show, the development of a custom metrology system utilized a substantial amount of resources and effort beyond that of any other sub-system. While metrology itself is part of the science being conducted with the SPHERES laboratory, this requirement did create an unbalance between metrology and all the other sub-systems.

Propellant Selection: CO_2. The Selection of carbon dioxide as propellant does not appear to be optimal. The use of CO_2 means increased safety requirements, including the use of a toxic gas and development of a pressurized system. Further, it is not possible to replenish CO_2 aboard the ISS. But this selection was due to the fulfillment of several other requirements: occupy at most one MLE (mass and volume), provide thrust to perform the strawman maneuvers, allow traceability to spacecraft, and maintain development costs in control. The selection of CO_2 over any other pressurized gas allowed the propulsion system to maintain the amount of resources and effort invested on it balanced with the other sub-systems, as little custom work was required and the technologies to handle carbon dioxide were clearly understood. While it required substantial more time investment in the safety process, it did not require substantial development efforts, which gave balance to the selection.

Expansion Port. While modularity and reconfiguration was initially built into SPHERES, it originally was only conceived as part of the software system. The development of the expansion port (Section 4.3.3.2), which enables hardware reconfiguration, came late in the process. Therefore, its implementation required that only minor changes be needed from the existing sub-systems. It was essential that the addition of an expansion port did not drive the mission beyond its constraints, especially the need to meet launch deadlines (such as CDR, safety reviews, etc.). This required the expansion port to use existent data channels and to fit within space available in the system. The resulting expansion port attempts to provide for future projects by using both simple and complex data channels, as well as several power voltages. The serial and power lines have been utilized in several projects, and their usefulness demonstrated; no projects have utilized the global memory bus as of yet. This discrepancy in the use of the expansion port data lines is due to an imbalance in the resources and effort put to develop the expansion port. The requirement for hardware modularity was given low priority and assigned only limited resources, while the other requirements drove the mission.

Communications Channel Frequency Selection. Enabling iterative research has always been a primary functional requirement for SPHERES. Yet, to meet this requirement two potentially conflicting requirements existed: de-couple the software from safety reviews to minimize the overhead time to upload new algorithms and provide the necessary tools to collect substantial data. The communications channel has a conflict between these two requirements since the use of an 802.11b wireless LAN interface card can provide over 10Mbps of bandwidth utilizing standard COTS equipment and publicized protocols; but such a system requires that the software be controlled, since the 802.11b network is part of the ISS controlled environment. Therefore, the SPHERES team required that the communications system utilize an uncontrolled frequency range. At the time of development of the SPHERES testbed, the simplest integration was through the use of 916MHz technologies. This required substantial effort in the development of a custom communications protocol and limited the bandwidth to at best 56.6kbps. But, the use of the custom system allowed the software sub-system to remain decoupled from any safety requirements.

6.2.5 Design Framework Assessment Summary

Having been designed to exhibit the features of the MIT SSL Laboratory Design Philosophy, SPHERES closely follows the principles which derived directly from the philosophy. The principles of *Enabling a Field of Study* and *Iterative Research* have been successfully implemented in SPHERES. The Guest Scientist Program enables research by multiple scientists by providing the necessary tools for scientists to conduct research in their home locations (simulation, data analysis) and at remote facilities, with option to be present at several testing facilities (MIT SSL, NASA RGA, MSFC Flat Floor). The laboratory facilitates iterative research by allowing the necessary reconfiguration of algorithms, minimizing overhead time to repeat experiments and upload new algorithms, and providing scientists with flexible operations plans. The SPHERES laboratory exhibits the major traits called for in the principle of *Focused Modularity*. While modularity did not play a major role in the design of the individual satellite sub-systems, it did guide the overall design: the satellites represent a standard satellite bus. Further, the software exhibits modularity throughout.

The principles of *Optimized Utilization* and *Remote Operations and Usability* derive from the need to operate aboard the ISS, a task inherent in the design of the SPHERES laboratory. SPHERES makes an acceptable use of the resources aboard the ISS, although several resources were not utilized correctly due to the inability to fulfill all existent NASA requirements with the resources available. SPHERES accounts for all the considerations raised in the principle of *Remote Operations and Usability*, providing both the operators and scientists with the tools to conduct remote research. These include the ability of the operator to control the experiment, preview expected results, and provide feedback to the scientist. The scientist has tools to predict results, analyze the data, and compare results. The correct use of ISS resources enable real-time communications between the operator and the scientist if necessary.

SPHERES provides the ability for scientists to test metrology, control, and autonomy algorithms in a representative environment, achieving TRL 5 or TRL 6 in most cases, and TRL 7 in a selected few. This ability allows SPHERES to meet the principle of *Incremental Technology Maturation* because the cost of SPHERES is minimal compared to the full cost of an operational mission. By providing a representative environment at low costs, where the technologies can be demonstrated and the risks reduced, SPHERES can allow the total cost and risk of an operational mission to be reduced.

The principle of *Requirements Balance* originated from the observation that the two guidelines behind the development of SPHERES did not specifically account for the limited resources available for a mission. The successful development of the SPHERES laboratory indicates that enough requirements balance took place to create the design. But review of the implementation demonstrates that further requirements balance could have occurred to prevent incosistencies in the effort and resources put into the development of a few sub-systems (e.g., metrology), while others (e.g., power, expansion port) could have used further resources to provide important benefits.

6.3 Evaluation Framework

An ISS NGO evaluator would be provided with a proposal that describes the design of a mission with enough details to address all of the microgravity laboratory design principles. The review by the NGO addresses the following points:

- Correct utilization of ISS resources
- Technology advancement
- Mission scope

In the case of SPHERES an ISS NGO would receive information similar to that presented in the SPHERES Critical Design Reviews (Technical: [SSL, 2002] and Science: [SSL, 2002a]) and the Safety Data Packages [SPHERES, 2001]. This information is now used to asses SPHERES using the evaluation framework presented in Section 5.11.

Principle of Iterative Research

The stated science objectives of SPHERES (develop metrology, control, and autonomy algorithms for distributed satellite systems) clearly indicate the need for iterations. To demonstrate the maturation of algorithms requires running multiple tests and evaluating the results until the desired performance is met. The ISS evaluator must asses the ability of SPHERES to support iterative research based on the evaluation framework:

1. *Does the experiment collect the data necessary to support or refute the hypothesis?*

   It is not the job of the ISS NGO evaluator to guarantee that the proposed facilities collect all the data necessary for mission success, but it is in the best interest of the ISS program to determine if a project has the ability to collect relevant data through either custom hardware or systems available aboard the ISS. In reviewing SPHERES, the evaluator can see the existence of two measurement systems (inertial and global metrology systems), the use of the communications system to download data to an ISS SSC, and the use of the ISS telemetry system to download the data to ground.

The SPHERES CDR clearly indicates that the sensors of the satellites provide the necessary measurements to perform tests of the different algorithms; the evaluator need not question the proposal unless there is an obvious question on the ability to collect the data. In the case of SPHERES there is no obvious failure to collect the data, and the resources aboard the ISS have been used correctly to this purpose.

2. *Do the operational plans of the facility provide sufficient flexibility for efficient iterations?*

The SPHERES operational plans clearly include wide flexibility, but the ISS NGO should notice that a lot of this flexibility depends on periodic operations aboard the ISS. The ground-based tests prior to ISS deployment are outside of the control of the ISS program, and allow scientists substantial research time to analyze data and come up with new algorithms. But the plan for operations aboard the ISS depends on having test sessions every two weeks, at which point the ISS staff will play a critical role in the effectiveness of iterations. Therefore, the ISS NGO staff must, at least, make note that the ability of this facility to perform iterations requires allocation of resources by the ISS program. In the case of SPHERES the resources are not mission critical; that is, if one or two sessions are missed, the program will not fail. Therefore, it is possible to allocate the resources without undue stress on the ISS program.

3a. *Can the facility perform multiple experiment runs with repeatability and reliability?*

The facilities of SPHERES have been designed specifically to allow for repetitions of tests aboard the ISS, as well as multiple other locations. The operator can start tests with minimal setup time; the interface provides simple controls to start and stop tests. Further, the reliability of SPHERES has been demonstrated in ground-based facilities. But the project does have a major limitation in its ability to support repetition: depletable propellant and batteries. The ISS NGO needs to evaluate the ability of SPHERES to perform repetitions over an extended period of time, and get assurances that the consumables can be resupplied to the ISS for continued operation. SPHERES has limited launch capabilities for consumables; currently they account for up to six months of operation. This is a reasonable time frame, although the ISS NGO should make note of this limitation in the review of SPHERES.

3b. *Can the facility be reconfigured while in the ISS in such a way to provide new meaningful results and/or reflect changes in the hypothesis?*

The primary scientific objective of SPHERES is to develop algorithms for distributed satellite systems. The SPHERES facilities aboard the ISS allow reconfiguration of the algorithms being tested via wireless links between the satellites and the ISS SSC. Therefore, SPHERES allows reconfiguration of both individual algorithms and of high-level hypothesis.

The proposed expansion port of SPHERES allows further reconfiguration, including the change of hardware. But because these changes require launch of further hardware to the ISS, an ISS NGO evaluator must first see that the program has the resources available to deliver these items to the ISS. Because SPHERES has not yet demonstrated this capability, the evaluator should only consider software reconfiguration under this question.

Based on these reviews, an ISS NGO evaluator can see that the SPHERES laboratory enables iterative research at all the levels presented in Figure 5.1 for software-based research. While several reservations exist on the ability of the laboratory to support iterative research in the long-term, the proposed initial mission should be successful.

Principle of Enabling a Field of Study

Review of the Science CDR [SSL, 2002a] immediately identifies the field of study covered by the SPHERES laboratory: metrology, control, and autonomy algorithms for distributed satellite systems. The development of these algorithms is essential for several upcoming missions; their maturity through demonstration in a space environment can greatly reduce the risk of the operational missions. The same presentation contains an overview of the Guest Scientist Program, which provides the capabilities to support multiple scientists:

- *Efficient data paths* - Data transfer to and from the ISS includes the use of the ISS data system to minimize the delay in delivery to the SPHERES program. The ISS NGO evaluator wants to ensure that if the ISS systems are used, the program does not create undue delays for the data to reach the scientists, countering efficient use of ISS resources. The SPHERES team does not create any further delays in the delivery of data, which is immediately forwarded to the scientists.
- *Data analysis tools* - The evaluator can determine from the Science CDR that guest investigators have a simulation to predict results at their home facilities. Further, the GSP clearly defines all standard SPHERES data packets and allows scientists to define their own structures.

- *Flexible operations* - As with iterative research, the SPHERES plans do provide substantial flexibility, but require the allocation of resources by the ISS program. This allocation of resources is within the capabilities of the ISS, although it may have to be reviewed in the long term.
- *Reconfiguration* - As before, demonstrated reconfiguration of the SPHERES facilities aboard the ISS is limited to software changes. SPHERES does allow multiple scientists to utilize the ISS facilities as long as their tests require only software. To allow hardware reconfiguration, the SPHERES program will need to demonstrate the capability to deliver new hardware to the ISS.

From the ISS program point of view, the SPHERES laboratory has been correctly designed to allow research on a substantial field of study (algorithms for distributed satellite systems) and has created the necessary programs and facilities to support multiple scientists. These programs do utilize ISS resources, but not beyond the capabilities of the ISS program. Therefore, the ISS NGO would have no recommendations to change any aspect of SPHERES with respect to the principle of *Enabling a Field of Study.*

Principle of Optimized Utilization

An ISS NGO evaluator must determine if a project makes proper use of the special resources available at the ISS. The design of SPHERES demonstrates utilization of many resources available at the space station. Further, the presented trades between operational environments indicate that the program would not have the resources to operate as a standalone space mission; that it does not have the need for such operations; and most importantly, that it would loose many of the benefits obtained by operating in the controlled environment of the station with human interaction (i.e., would no longer create a risk-tolerant environment for algorithm research) if it were a free flyer program. Next, the evaluator should asses whether the utilized resources of the ISS are used correctly and if other resources exist to benefit the program and at the same time make better use of the station:

- *Crew* - SPHERES is programmed to utilize approximately six hours of crew time each month, accounting for half an hour of setup, two hours of tests, and half an hour of breakdown. In terms of the absolute amount of time, this is an acceptable amount, towards the lower side of expected crew use.

The importance of the crew involvement as an integral part of the science conducted with SPHERES stands out. SPHERES requires the astronaut to truly become an extension of the researcher, requiring the astronaut to understand some of the science aspects and make decisions based on their own observations. From the ISS NGO perspective, this is both an asset and a concern. It is an asset because astronauts will be researchers in space, directly in line with the main objective of the station. It is a concern because the astronaut may be responsible for the scientific success of the mission. Therefore, the ISS NGO evaluator will need to put extra emphasis on the need to satisfy the principle of *Remote Operation and Usability.*

- *Power* - The SPHERES facilities aboard the ISS utilize minimal amount (50W) of power compared to that available for experiments. But SPHERES requires the delivery of custom batteries to the station, rather than using existing power resources. For the ISS program this means the use of both launch, storage, and disposal resources for a resource widely available at the station. Upon review with the SPHERES team, the evaluator would learn about the lack of resources to develop a recharging station and put it through the necessary safety review processes. The evaluator should then present the problem to the ISS NGO leaders, who have the responsibility to review the processes required to allow better utilization in the future. Upon review of the procedures, the ISS NGO staff should continue in contact with the SPHERES team to encourage them to better utilize the power resources.
- *Telemetry / communications* - SPHERES utilizes a small amount of telemetry during normal operations; its real-time communications are limited to pre-specified operating sessions. The use of the existing SSC, which communicates directly with the ISS network, simplifies integration of the project with existing resources. Therefore, SPHERES successfully utilizes the telemetry and communications resources of the ISS.
- *Long term experimentation* - The expected mission life of six months to one year presented in the critical design review is a valid utilization of the ISS. But this longevity depends strongly on the availability of the two consumables used in SPHERES: batteries and propellant. The ISS NGO evaluator should be interested in knowing the capabilities of the facilities in case each of the resources run out, therefore should ask the SPHERES team to present contingency plans in case consumables run out.

  Note that utilizing rechargeable batteries would better ensure long-term experimentation, reinforcing the need for the SPHERES team to reconsider the use of disposable batteries.
- *Benign environment / atmosphere* - The presented design for the SPHERES facilities aboard the ISS require a pressurized atmosphere; the project takes advantage of this resource to greatly reduce its costs and development time.

> Further, SPHERES makes use of the controlled environment of the station to reduce the risk involved in developing new algorithms.

SPHERES successfully utilizes four of the five ISS resources identified for special consideration. The crew is involved directly with the science, beyond mechanical or repetitive activity. The ISS telemetry data system is well integrated to the facilities. Assuming no unexpected problems with delivery of consumables, the longevity of the project is appropriate. The project utilizes the benign environment to reduce both its costs and risks. While the power consumption is minimal in terms of available ISS power, SPHERES requires its own power source (disposable batteries). The project must be reviewed to correct this problem, which would not only reduce delivery costs to the station, but also help ensure the longevity of the mission.

Principle of Focused Modularity

To review the modularity of SPHERES, the ISS NGO considers the three main elements of the facilities delivered to the ISS:

- *Satellites* - The satellites do not exhibit any modularity of their sub-systems. The structure does not allow separation of the sub-systems, therefore it is not possible to utilize any specific part of the satellites in other projects. A review of the sub-systems would identify the usefulness of some modularity in the satellites. The communications system could be modular, providing a simple wireless communications interface to other projects. If the batteries were rechargeable, they could provide power to new facilities. While in some cases the microprocessor could be made modular, the selected SPHERES processor is too specific to the application, therefore there is no need to make it modular from the ISS perspective.

  The satellites do provide the ability for reconfiguration via their expansion port (requires hardware delivery) and the update of the software and user interfaces (via the ISS communications channels). Therefore, the satellites can be used for as yet unforeseen projects.

- *Metrology beacons* - The metrology beacons are identical and can be reconfigured easily. While they require specific signals to operate, there are no limitations which restrict their use with other projects beyond the SPHERES facilities. Therefore, these beacons could become a tool available for other project which needs a ranging system and can accommodate the signal timing requirements.

- *Communications* - The transceiver provided by SPHERES operates with any module that has an RS232 serial interface (UART). This allows the module to be used with a wide range of projects beyond SPHERES. But it requires that each new project utilize exactly the same communications hardware, with its custom firmware, greatly reducing the ability to consider the communications transceiver a modular entity. Like with the satellites, the SPHERES communications transceiver could be reviewed to allow for better modularity.

From the ISS perspective, SPHERES offers little modularity. The satellites provide substantial reconfiguration capabilities, allowing their use in future projects. But this depends on the ability to launch hardware and develop new software. Further, these new uses depend on the SPHERES team cooperating with new scientists, and does not directly provide new capabilities for the station. Therefore, the satellites do not provide any substantial modularity to the station. The communications system, while modular on the ability to operate with any RS232 serial line, requires the use of special hardware and firmware, limiting its usefulness. The metrology beacons do provide a new system which could be made available to new users. A clear interface exists and there are no physical limitations to their use by other projects.

Principle of Remote Operations and Usability

This principle calls for the reviewer to determine if the proposed program has clearly identified the data and information requirements to provide scientists with sufficient data and operators with the necessary information to conduct science. The SPHERES program clearly identify the data paths, allows scientists to create custom data, and provides methods to test the selected data through actual experiment runs prior to deployment to the ISS. Therefore, the ISS program has reasonable assurances that the data collected aboard the station will be sufficient for the scientist. The requested real-time communications are not intended for the scientists directly, but rather for the SPHERES team to support the operator during the first two operating sessions. Thereafter, the operator is expected to use the facility independently, so the ISS NGO must ensure that the operator has enough information to perform the required tests in the future.

The principle provides the following guidelines to evaluate the capability of an operator to successfully run tests:

- *The operator has the necessary interfaces to control the facilities aboard the ISS in an efficient and safe manner.*

  The SPHERES interface provides the operator with a clear procedure to load programs, select tests, and start experiments. Starting an experiment is contingent on the astronaut enabling the necessary satellites, which implies the astronaut has control of them. The interface ensures that whenever a test is in progress, the stop command is always available to the astronaut. Therefore, the operator does have the necessary controls to conduct tests in an efficient and safe manner.

- *The operator is presented the information necessary to successfully evaluate experiments.*

  The SPHERES documentation indicates that the operator is to be presented with a preview (written explanation with optional images and/or animations) of the experiment before a test is started. The description of each test will provide the astronaut with a clear idea of the expected results. A result code will allow the astronaut to compare their observations with the determination of the algorithm, providing further information to determine if the test was successful. Using this information, the operator can make the decision to repeat a test or move on with the program.

  Therefore, upon review of the existing documentation, the SPHERES program appears to provide the necessary information for astronauts to evaluate experiments. Still, the ISS NGO must clearly establish that this depends on the SPHERES team providing the information continuously. Further, because astronauts conduct a wide range of experiments on many areas, they should not be held responsible for any misinterpretations of the presented previews.

- *The operator can provide feedback to the research scientists from their observations in the operational environment.*

  The SPHERES project accounts for the ability of the operator to provide feedback in two manners: the use of a survey at the end of each experiment, with questions directly related to the science; and the ability of the operator to provide open feedback after the survey. This information is stored together with the data collected during the experiment, and transferred at the same time. Therefore, the scientist can always correlate the collected data with astronaut feedback to better evaluate the success of an experiment.

From the ISS NGO perspective, it appears that the SPHERES team has accounted for all the necessary tools to allow successful remote operations of the SPHERES facilities, even without real-time communications between the scientists and the operator. The design does depend on the correct interpretation of the descriptions, images, and movies provided in the previews and result codes presented after each test. Therefore, the possibility for operator error exists, but it has been reduced by the providing the astronaut information both before and after each test.

Principle of Incremental Technology Maturation

By correctly utilizing the environment of the ISS, SPHERES provides scientists with a relevant environment to test new metrology, control, and autonomy algorithms aboard the space station. The ability to run multiple tests, change operating conditions, and reconfigure the software covers the necessary operating points to demonstrate the technology. The fact that scientists can present previews demonstrates the ability of SPHERE to enable predictions of performance; the data collection allows comparison of these predictions with actual results. Therefore, SPHERES satisfies the requirements to advance technologies to TRL 5.

SPHERES can achieve TRL 6 and TRL 7 only for those programs where the hardware represents either operational models of the sub-systems (TRL 6), or full scale prototypes of the operational system (TRL 7). Therefore, the ability of SPHERES to advance technologies beyond TRL 5 depends on the specific mission being considered. The ISS NGO evaluator can consider that TRL 6 may be achieved for a limited set of missions; the evaluation should not consider the capability of SPHERES to mature technologies to TRL 7 unless specifically addressed by the SPHERES documentation. Therefore, SPHERES is considered a laboratory which allows technology maturation to TRL 5 and TRL 6.

6.3.1 ISS NGO Evaluation Summary

Overall the SPHERES laboratory successfully implements the features called for in the design principles. The deployment of the SPHERES facilities to the ISS present a unique opportunity to expand the science conducted aboard the ISS for more than a single research program. A clearly established Guest Scientist Program opens up research aboard the ISS to multiple scientists conducing research on distributed satellite systems metrology, control, and autonomy algorithms. The laboratory clearly accounts for the need to facilitate iterative research through its capabilities to repeat tests with minor overhead and the ability to reconfigure the software to enable modifications of algorithms and hypothesis. Utilizing SPHERES, these algorithm technologies can be matured to TRL 5 or TRL 6 in most cases.

SPHERES makes correct utilization of the facilities aboard the ISS. The crew, telemetry, long-term experimentation, and benign environment resources are used appropriately. While SPHERES minimizes its power consumption, to levels almost negligible to the availability of power aboard the ISS, it requires the launch of power sources (batteries) which have mass and volume not negligible to the ISS. Therefore, an ISS NGO would strongly urge the SPHERES project to upgrade their facilities to make use of the power sources available in the ISS. Further, the use of consumable CO_2 as propellant creates important concerns about the ability of the facilities to operate over the long-term; while the ISS NGO cannot provide a reasonable substitute, the SPHERES team should provide the evaluator with contingency plans on how to obtain partial use of the SPHERES facilities aboard the ISS in the case where the propellant is not available.

The facilities provided to the astronauts aboard the ISS provide substantial tools to make the operator an extension of the scientist. Not only does the operator start and stop tests, they also evaluate the experiments to determine, without real-time scientist interaction, whether a test was successful or not and when to repeat tests or move on with a program. The interface provides operators with substantial information to make these decisions. Further, they allow the astronaut to provide feedback to the scientist, effectively creating an electronic laboratory notebook where the astronaut can make annotations about each test.