Synchronized Position, Hold, Engage, and Reorient
Experimental Satellites
(SPHERES)
Test Equipment Data Package
1.0 Points of Contact

Prof. David Miller
Massachusetts Institute of Technology
617 253 3288
millerd@mit.edu

Prof. Dava Newman
Massachusetts Institute of Technology
617 258-8799
dnewman@mit.edu

Dr. Javier de Luis
Payload Systems Inc.
617 868 8086 x13
deluis@payload.com
## 2.0 Table of Contents

1.0 Points of Contact  
2.0 Table of Contents  
3.0 List of Figures  
4.0 Synopsis  
   4.1 Objectives/Goals  
   4.2 Motivation  
5.0 Specific Test Objectives for KC-135 Flight  
6.0 Specific Test Description  
7.0 SPHERES Project Payload Description  
   7.1 SPHERES Mechanical Configuration  
   7.2 SPHERES Configuration During KC-135 Testing  
8.0 SPHERES Test Equipment Description (KC-135)  
   8.1 Propulsion  
   8.2 Power  
   8.3 Avionics  
   8.4 Communications & Software  
   8.5 Metrology  
   8.6 Structures  
9.0 Structural Load Analysis  
10.0 Electrical Load Analysis  
11.0 Pressure vessel certification  
12.0 In-flight Test Procedures  
13.0 Parabola Requirements, Number and Sequencing  
14.0 Test Support Requirements, Ground and Flight  
15.0 Data Acquisition System  
16.0 Test Operating Limits / Restrictions  
17.0 Proposed Manifest for Each Flight  
18.0 Photographic / Video Requirements  
19.0 Hazard Analysis  

Appendix I: Structural Load Analysis  
Appendix II: Pressure Vessel Certification  
Appendix III: Hazard Reports
3.0 List of Figures

Figure 1: Computer rendering of SPHERES ................................................................. 5
Figure 2: SPHERES in the Shuttle Middeck ............................................................... 5
Figure 3: Air Force Techsat21 Space Based Radar ....................................................... 6
Figure 4: NASA ST3 Separated S/C Interferometer ...................................................... 6
Figure 5: NASA Terrestrial Planet Finder Mission ....................................................... 6
Figure 6: Picture of a thruster pair ................................................................................. 11
Figure 7: Picture of CO₂ tank inside SPHERES ........................................................... 11
Figure 8: Propulsion Subsystem Schematic ................................................................. 12
Figure 9: The Alkaline Battery Pack ............................................................................ 13
Figure 10: ASTEC COTS Regulator ............................................................................. 13
Figure 11: C-40 Microprocessor .................................................................................. 14
Figure 12: Tattletale Microprocessor .......................................................................... 14
Figure 13: Schematic of the Communications Subsystem .......................................... 17
Figure 14: 3-D View of the aluminum frame of SPHERES .......................................... 19
Figure 15: Pro Engineer drawing of structural strut ..................................................... 20
Figure 16: 3-D SPHERES drawing with lexan facets attached .................................... 20
4.0 Synopsis: Executive Summary of the SPHERES program

4.1 Objective/Goals:

SPHERES (Synchronized Position Hold Engage Re-orient Experimental Satellites) is a spacecraft formation flying testbed being developed by the Space Systems Laboratory and Department of Aeronautics and Astronautics at MIT. The objective is to develop a testbed for the validation of metrology, formation flying, and autonomy algorithms to coordinate the motion of multiple satellites in a micro-gravity environment. SPHERES is currently undergoing 1-g air table testing to be followed by a KC-135 flight in April 2000. Eventually, SPHERES will transition to an International Space Station (ISS) facility for reducing risk in missions of interest to the Air Force and NASA.

The SPHERES design includes the following:
1. A compressed CO₂ propulsion subsystem to provide the necessary thrust for maneuvering in micro-gravity,
2. A communications subsystem for inter-satellite and satellite/laptop data transfer,
3. A metrology subsystem for maintaining the system in a given position or changing it to a new one,
4. An avionics subsystem to provide the necessary computational power, and
5. A power subsystem for supplying electrical power to all components which require it.

Figure 1: Computer rendering of SPHERES

Figure 2: SPHERES in the Shuttle Middeck
4.2 Motivation

Demand is increasing for spacecraft to perform autonomous formation flying missions. Current test-beds do not allow full modeling of formation flying dynamics. Several characteristics of multiple satellite systems make them better for some applications than a single satellite. Smaller satellites reduce manufacturing and launch costs and are cheaper and easier to replace in case of in-orbit failure. Simpler systems reduce individual spacecraft complexity and ease operations and implementation. Multiple satellite systems can execute missions that would otherwise be too expensive with a single large spacecraft. An example of this is a separated spacecraft interferometer. A development of such a testbed would allow greater ease in developing systems for such purposes since testing could be carried out prior to actual launch into space.

![Air Force Techsat21 Space Based Radar](image1.png)

![NASA ST3 Separated S/C Interferometer](image2.png)

![NASA Terrestrial Planet Finder Mission](image3.png)

SPHERES will allow testing of (1) relative attitude control and station-keeping between satellites, (2) re-targeting and image plane filling maneuvers, (3) collision avoidance and fuel balancing algorithms, and (4) array geometry estimators necessary for missions such as the Air Force’s Techsat 21 and NASA’s ST3 and Terrestrial Planet Finder missions. While the dynamics and precision of SPHERES do not necessarily match those required of these
missions, it does allow the designers of these missions to validate the algorithm design, initialization, de-bugging, and refinement process.

The SPHERES testbed consists of three 0.25 meter diameter, 3.0 kilogram, self-contained satellites with on-board propulsion, processing, RF communication and metrology. In addition, the testbed has four metrology transmitters and a laptop which acts as a “ground station” and provides experiment control. On ISS, new algorithms can be uplinked and data downlinked via the Ku-Band system and astronaut laptops.

The propulsion sub-system consists of twelve solenoid-actuated valves which expel carbon dioxide through micro-machined nozzles. The thrusters are grouped in six opposing pairs to provide attitude and station-keeping control. The propellant is stored in DOT approved steel tanks which hold 74 grams of liquid CO2 at 860 psig. A regulator drops this pressure to 70 psig prior to distribution via a manifold. The tanks are replaceable and provide about 3 minutes of operations.

The metrology sub-system has global and local elements. The global metrology measures the time of flight of 40 kHz ultrasonic pulses emitted by the four metrology transmitters. Infrared transmitters provide precise synchronization pulses. Eight ultrasonic microphones distributed on the surface of the SPHERES are used to derive a total of thirty-two propagation delays used to derive six degrees of freedom. Each SPHERES has a local, internal, inertial measuring unit (IMU) consisting of 3 accelerometers and 3 rate gyros.

The power and avionics sub-systems consist of replaceable battery packs as well as a TI C40 DSP, a Motorola TattleTale computer, a solenoid firing circuit board, a metrology board, power distribution, a UART internal digital communication board, and two external RF communications circuits. The custom boards were designed using ORCAD and procured from professional board manufacturers. Each SPHERES consumes 12 to 14 Watts under nominal operation.

The software and communication sub-systems are multi-rate and multi-channel, respectively. The real-time software executes a 1.0 kHz interrupt to actuate the thrusters via pulse width and pulse frequency modulation. The control algorithms are updated using a 50 Hz interrupt. Global metrology, inter-SPHERES communication as well as SPHERES-to-laptop communication is updated at one to ten hertz rates. Communication uses token ring architecture for both the SPHERES-to-laptop as well as the inter-SPHERES communication. SPHERES-to-laptop communication is used to archive measured data and operate the testbed.

SPHERES is being developed through a unique educational experiment where undergraduate aerospace engineering students are exposed to the full lifecycle of an aerospace product through the conception, design, implementation and operation of a world-class facility for validating technologies crucial to the operation of formation flying satellites. Students not only learn about design, teamwork and communication but also interact with potential customers from government and industry, appreciate the constraints of integrating to a carrier, exercise professional computer-aided design tools, and struggle with the iterative process of design improvement and system-wide integration. SPHERES is an innovative blend of research, education and collaboration for furthering the United States’ capabilities in space.
5.0 Specific Test Objectives for KC-135 Flight

The primary objective of KC-135 experimentation is to test the functionality of SPHERES hardware in a micro-gravity environment, in an effort to demonstrate subsystem compatibility and isolate potential problems. Specifically, the KC-135 flights are intended to test the following characteristics of the flight hardware:

- Accuracy of global metrology system and data collection
- Efficiency of 3-axis IMU reduction damping system
- Human interaction with flight hardware under testing conditions

6.0 Specific Test Description

The specific test objectives will be achieved in the following manner:

- The accuracy of the global metrology system will be characterized by the analysis of data collected during open loop thruster firings in all 6 degrees of freedom. Initial experiments will include manual movement of the SPHERE to determine data collection functionality. In additional tests, collected data will be compared to prescribed directions, distances, and movements pre-set by test conductors.
- The efficiency of the 3-axis IMU reduction damping system will be tested through the use of close-loop control coupling between the IMU units and thruster pairs to determine the capability of the SPHERE to counteract manual disturbances. When disturbed, the IMU will detect the change in attitude and correct the satellite using thruster pair firings.
- Human interaction (i.e. handling of the SPHERES, experiment configuration, and data collection) will be analyzed to find the safest and most efficient use of test conductors in later test flights.
7.0 **SPHERES Project Payload Description**

To demonstrate the dynamics associated with formation flying, the Synchronized Position, Hold, Engage, and Reorient Experimental Satellites (SPHERES) project is being developed by MIT for use in the Space Shuttle and the International Space Station. Three SPHERES units will accept software control algorithms via data up-link from a laptop computer. Each satellite will possess internal propulsion, power, avionics, software, communications, and metrology subsystems and will be capable of maintaining a given orientation relative to the other units. Infrared/ultrasound transmitters placed inside the mid-deck will transmit reference data to the SPHERES units to be used for guidance and navigation. During the mission, expendable batteries and CO$_2$ fuel tanks will be swapped as needed. A data down-link to the laptop will provide information on the status of the system throughout the duration of the experiment.

The SPHERES design includes the following:
1. A compressed CO$_2$ propulsion subsystem to provide the necessary thrust for maneuvering in micro-gravity,
2. A communications subsystem for inter-satellite and satellite/laptop data transfer,
3. A metrology subsystem for maintaining the system in a given position or changing it to a new one,
4. An avionics subsystem to provide the necessary computational power, and
5. A power subsystem for supplying electrical power to all components which require it.

Operation of SPHERES requires a fair amount of human intervention. After launch and ascent on the Shuttle, the SPHERES units are removed from standard mid-deck lockers and powered up. Self-diagnostics reveal through external indicators the health status of the internal subsystems. A laptop computer uploads a formation flying control algorithm into the satellites, after which they are allowed to float freely and autonomously in the mid-deck. The satellites then maneuver into prescribed positions and hold that position until an electronic command is issued to reorient into a new one. Data are continually sent from the satellites to the laptop to report the status of the system. This process may then be repeated for different formation flying control algorithms. Throughout the experiments, batteries and CO$_2$ fuel tanks are changed out as necessary.

The crew will have access to the interior of the SPHERES units via hinged access hatches. These allow for the replacement of expendable batteries and fuel tanks. The majority of the crew time required for the experiment will be in replacing these consumables and issuing the commands to up-link new control algorithms. Data transfer from the SPHERES to the laptop will be automatic, and the satellites will fly autonomously.
7.1 SPHERES Mechanical Configuration

Each SPHERES satellite consists of a 26-sided roughly symmetrical polyhedron. The cross-section through any of the three principal orthogonal planes is a regular octagon, of which the apothem is approximately 4 inches. Therefore the “radius” of one satellite is roughly 8 inches, with the greatest dimension in any given direction barely topping 9 inches. An internal aluminum truss supports external skin panels made of LEXAN polycarbonate, on which are mounted pairs of opposing gas thrusters to allow for linear translation and angular rotation. Externally mounted infrared/ultrasound receivers detect pulses from transmitters positioned in the mid-deck to determine position, attitude, and orientation.

Beneath the external skin lies the bulk of the hardware. The internal frame consists of twelve interlocking aluminum bars to which are mounted the major components of the subsystems. The pressurized CO₂ tank is positioned in the center of the satellite and is connected to the internal frame via a mounting bracket. The tank connects to a pressure relief valve by way of a pressure regulator. The relief valve connects to a manifold, which divides the gas among six smaller manifolds, each of which controls flow into two valves representing one gas thruster pair. These valves are controlled electronically by the avionics subsystem and when opened allow a thruster to fire.

Dual batteries lie on either side of the tank and are also connected via mounting brackets. The batteries provide power to all electrical components within the satellite.

Lying in directions orthogonal to the batteries are the card cages. These contain the C40 and Tattletale microprocessors along with the integrated circuit cards. External ports on the surfaces of the cages provide connections for power and data flow in and out of the cages.

7.2 SPHERES Configuration During KC-135 Testing

During launch and landing, SPHERES fits into carry-on containers that will be secured to the aircraft floor. During testing, all materials will be secured that are not being used. Two SPHERES will be brought on-board the KC-135 to ensure that testing may continue despite the failure of one.

8.0 SPHERES Test Equipment Description (KC-135)

The following is a summary of the equipment required for the proposed tests:

- Two SPHERES
- Laptop computer (data storage, algorithm control) plus mounting bracket for RF antennae
- Replacement tanks and batteries
- Video camera equipment for monitoring
- Two issued test stands
• Four metrology transceivers plus mounting equipment

Mounting for the laptop computer will be provided by a bracket that has already flown on the KC-135 during a previous test. The video equipment will be secured to the test stands as per standard mounting procedure. Three of the four metrology transceivers will be affixed to the test stands in the same way that the video cameras are mounted. These three transceiver boxes will be outfitted with a bottom-plate in order to be compatible with the standard tripod mounting on the test stands. The fourth transceiver box will be mounted to the floor of the aircraft with velcro.

Below is a detailed description of the SPHERES subsystem hardware:

8.1 Propulsion

The propulsion system for the SPHERES testbed is comprised of cold gas thrusters that use the pressure driven expulsion and expansion of liquid carbon dioxide (CO\textsubscript{2}) to create propulsive force. The propulsion system is relatively simple. CO\textsubscript{2} from a liquid CO\textsubscript{2} tank is passed through tubing to a regulator that lowers the pressure from the vapor pressure of CO\textsubscript{2} (850 psi) to 75 psi. From the regulator the lower pressure CO\textsubscript{2} is fed through more tubing to a central manifold which feeds into 6 individual thruster pairs of diametrically opposed thrusters. These thrusters (photo upper left) fire to expel the cold CO\textsubscript{2} gas and create thrust. Depending on which individual thrusters fire, the SPHERES testbed can be translated and rotated to any desirable position and orientation, providing that the CO\textsubscript{2} tank does not exhaust its supply of CO\textsubscript{2} first. The Propulsion system is modeled in the diagram below.
Carbon dioxide is an ideal propellant for a compressed gas system because it can exist as a liquid at room temperature, unlike N₂/Air. A liquid state is crucial for SPHERES applications because it allows a greater amount of gas to be stored than if the propellant was stored in a gaseous state. The only concern with CO₂ was toxicity. Originally the concern was that CO₂ would violate the non-toxic byproducts requirement for shuttle, but this has been disproved through initial calculations. By assuming instant mixing and performing a quick analysis we were able to determine the following:

- Mid-deck volume is 65 m³ → 2.6 kmol
- Canister of CO₂ is 74g → 1.7 mol
- Burst canister raises mole fraction of CO₂ by 0.065%
- NASA safe limit set to 15 mmHg, or 2.0% mole fraction

From this analysis we determined that under the instantaneous mixing assumption, 31 simultaneous canister bursts would be necessary to exceed the safety limit imposed by the Shuttle requirements. Furthering the analysis we determined:

- Crew of 7 produce ~ 210-360 grams CO₂ per hour
- This would exceed the safe limit in 5 – 8.7 hrs assuming no scrubbing
- Scrubbing at max rate removes 1 canister of CO₂ in one hour in addition to cleansing CO₂ production from seven crewmembers.
- This means that 24 + h CO₂ tanks can be used without exceeding safe limits (where h is the number of hours the experiment will be conducted)
Although the above assumption will be reviewed, it is believed that these numbers show that the toxicity of CO$_2$ is not as large of a concern as originally thought.

8.2 Power

The power subsystem is designed to provide adequate voltage and current to all other SPHERES subsystems in the individual SPHERES satellites. Hardware selection was based on prior trade-off and analysis. The battery was chosen based on optimizing mass, volume, voltage, and capacity (leads to lifetime). DC voltage regulator selection was based on required voltage outputs, maximum power, mass, and volume. The power source is 12 AA (1.5V) COTS alkaline batteries connected in series, providing a total of 18V. Following the present requirements, the subsystem will be able to provide power for approximately 90 minutes. The 12 AA batteries are contained in two battery packs (six batteries in each pack) as shown in Figure 9.

![Figure 9: The Alkaline Battery Pack](image)

When placed in series, the batteries provide 18 V that are distributed to each subsystem within the satellite. The voltage will be regulated to 3.3V, 5V, 9V, and 22V in order to satisfy voltage requirements. Commercial-Off-The-Shelf (COTS) voltage regulators (ASTEC AA10B-012L-050S, AA05A-024L-050S) will supply the 5V and 12V.

![Figure 10: ASTEC COTS Regulator](image)

The 3.3V is obtained through linear voltage regulating circuitry drawing from the 5V source. A custom step-up circuit will regulate the 22V. The regulated voltages are then distributed to the appropriate subsystems.

Two circuit breakers are included in the power subsystem design to prevent the battery from being damaged in the case of immediate over-discharge or shorting. Each battery, as well as each individual cell, will also be inspected before integration into the subsystem to
ensure proper ventilation and functioning. The battery will only be operated in a shirtsleeve environment and will be placed away from all heat sources and sinks inside the sphere. The battery pack casing is designed to ensure no physical way for the positive and negative terminals of the battery to touch, and therefore short, on the way into or out of the sphere.

8.3 Avionics

The Avionics subsystem provides all circuitry and processors needed in the SPHERES satellites. The subsystem currently consists of two microprocessors and four circuit boards. The C-40 DSP will provide the computational power and storage for all the subsystems with the exception of metrology.

![Figure 11: C-40 Microprocessor](image)

The metrology subsystem will use a separate Tattletale microprocessor.

![Figure 12: Tattletale Microprocessor](image)

There will also be a circuit board for metrology, as well as for propulsion, power, and the UARTs. The metrology circuit card contains the metrology receiving, transmitting, and filtering circuits. The propulsion circuit board contains the propulsion firing circuitry that operates the solenoids. The power circuit board contains the voltage regulating circuitry and components, as well as the circuit breakers. The UART board contains all UART and communications circuits. The boards will be placed around the central cube of the structure of the SPHERES, leaving two faces open. The C-40 and UART board are stacked and placed on one face, leaving enough room to add another C-40, if the extra processing power is eventually desired. The next face will contain the propulsion board, in the same section as
one of the battery packs. The adjoining face will contain the metrology card and Tattletale microprocessor, also stacked. The last face will contain the power card in the same section as the second battery pack. The cards interlock, and therefore connect through hardware at the interfaces of each face. This design reduces the number of wires needed to connect the boards, although some wire connections are still required. The current necessary wires are two lines from the metrology board to the C-40 and twelve lines from the DSP to the propulsion board (a corner connection).

### Table 1: Functions of the various avionics boards

<table>
<thead>
<tr>
<th>BOARD</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Board</td>
<td>Regulates and distributes power at the needed voltages</td>
</tr>
<tr>
<td>Metrology Board</td>
<td>Provides a mounting base for the Tattletale. Houses the Ultrasound and IR receiver circuitry</td>
</tr>
<tr>
<td>Propulsion Board</td>
<td>Contains all firing circuits. Also contains the spike and hold circuitry which provides the needed 22 V to open solenoid valves</td>
</tr>
<tr>
<td>UART board</td>
<td>Contains needed circuitry for communication between the Tattletale and DSP. Also functions as a mounting base for the DSP and communication boards</td>
</tr>
<tr>
<td>Communication Boards</td>
<td>Contains antenna and needed circuitry for STG and STS communication</td>
</tr>
<tr>
<td>DSP Board</td>
<td>Digital signal processor board where control systems will be run</td>
</tr>
<tr>
<td>Tattletale</td>
<td>Microprocessor dedicated to the acquisition of metrology sensor input and calculation of SPHERES location</td>
</tr>
</tbody>
</table>
8.4 Communications & Software

The Communications and Software sub-system (subsequently noted as Comm-Soft) is responsible for the movement and processing of data between the satellites and the ground station. It incorporates all necessary communicative software and hardware necessary to provide for this transmission and receipt of data to and from the various sources, as well as the operating system software that controls the actions of the satellites individually.

The Comm-Soft hardware is built around the DR1012-DK Virtual Wire Development Kit and includes all the associated wiring, antennae, and chipsets needed to process and handle out-going and in-coming message data. Its transmission/receipt operating frequency falls in the range of 860-870 MHz, which does not interfere with shuttle systems. The Comm-Soft hardware runs at app. 3.0 V and 20 mA, supplied by the avionics subsystem section.

Each satellite will contain two separate antennae that correspond to satellite-to-satellite (STS) transmission/receipt and satellite-to-ground (STG) transmission/receipt. This means that the satellites will be able to talk normally between themselves while uploading algorithmic data from the ground or downloading data received through the course of the experiment. Because of the nature of the antennae and the time required for them to change modes between transmission and reception of data, a form of token ring network protocol was developed to keep track of which satellite has the authority to talk at a given time. This allows for a more orderly tracking of messages and metrology information and avoids the issue of data collision that occurs when two or more satellites send information at the same time. It also allows for a form of error correction to avoid incorrect satellite commands during testing. Hardware was chosen to make the conversation between the satellites and the ground as succinct as possible without sacrificing a loss of data or a compression of needed information. The result is a system that can completely cycle through all communications (talk to all satellites and the ground) at a frequency of 10 Hz. In addition, this token ring style protocol allows for the ability of the system to still function on an experimental if, for some reason, one of the satellites completely fails during testing. This system thus provides for a minimum data rate of 960 bps (STS) and 212 bps (STG). Typical baud rates lie in the area of 18000 bps, limited by the antenna and its half-duplex nature (cannot send and receive at the same time).
In addition to communications equipment, the SPHERES also use several microprocessors to make decisions concerning metrology data as well as general housekeeping requirements. The Texas Instruments TattleTale8 processor is responsible for the general control of all systems on the individual satellites, as well as the initiation of communicative messages. Its efficiency relies on the software design of the background, shell, and operation system to use minimal microprocessor time. More importantly, as the re-configurable portion of the satellite system, the shell software allows for the various algorithms to be uploaded from different controllers.

Software for the Comm-Soft subsystem was programmed using C, a general-purpose language that is both very powerful and relatively easy to code. It also provides for the greatest adaptability to the various programming styles for others. As our project entails the creation of a test bed for various uploaded algorithms, this was felt to be an important point in language selection.
8.5 Metrology

The metrology subsystem provides real-time position and attitude information for the individual components of the SPHERES testbed. It utilizes two independent position and attitude determination systems: an inertial measurement system and an Infrared/Ultrasound (IR/US) ranging system. Raw data from the inertial system and from the IR/US system are processed in a standard Tattletale processor before being passed to the main SPHERES control processor.

Each satellite component of the SPHERES testbed carries an inertial measurement system. The system consists of a 3-axis accelerometer to provide accelerations and three rate gyros to provide rotational rates. These data are integrated in real-time to yield position, velocity, and angular velocity. The IR/US position and attitude information is used to correct errors in the inertial measurement system.

The Infrared/Ultrasound system uses a series of IR and ultrasound transmitters at known locations to create a local GPS-like environment for receivers on board each SPHERES. The eight IR/US receiver pairs on each SPHERES are used to calculate the range from each transmitter pair to each receiver pair by timing the difference in arrival times of the simultaneously generated IR and ultrasound pulses. Since the IR light arrives virtually instantaneously when compared to the ultrasound, range is calculated by multiplying the speed of sound by the time of flight difference.

Four IR/US transmitter boxes create the local positioning environment, each containing a battery and Tattletale processor. The battery in each box is identical to the batteries used on board each SPHERES (battery safety issues are discussed in the Power Subsystem Description).
8.6 Structures

The structure subsystem serves to physically integrate all subsystems into a complete unit. The primary structure consists of a 12-member aluminum framework to which 26 LEXAN panels are affixed. The framework provides attachment points for the internal mounting of components, and the LEXAN panels provide attachment points for the external mounting of these.

The aluminum framework is composed of 12 aluminum bars, all 8 inches long, with a square cross-section 0.25 inches on a side. All bars are identical in every respect. These bars fit together like Lincoln Logs in a three-dimensional grid fashion such that the projection of the framework onto a plane normal to a principal axis looks like a tic-tac-toe grid. Each joint is secured by one screw passing through an aligned pair of holes, one of which is a countersunk through hole, the other of which is a #4-40 UNC-2B threaded hole. The holes used for joining bars are sunk into notches that are cut out where joints are to occur. Along the length of each bar is an alternating threaded hole pattern, consisting of #4-40 UNC-2B threads. These holes are spaced every 0.5-inch along orthogonal faces, the patterns themselves staggered by 0.25 inches with respect to each other. In this sense, every 0.25 inch along a bar there is a threaded hole oriented 90-degrees with respect to the holes on either side of it. Additionally, threaded holes are placed on the end faces of the bars to facilitate the mounting of square LEXAN panels.
Aluminum brackets are attached to the ends of the bars. These serve as mounting points for the rectangular and triangular LEXAN panels. There are three unique brackets, each designed to offset the internal asymmetry of the bars in such a way that the external panels attach in a symmetrical fashion. Although the three brackets are slightly different, the basic premise is common to all of them. Two faces are oriented 45-degrees with respect to the orthogonal faces of the brackets for attaching the rectangular LEXAN panels. A third facet links the two 45-degree faces, providing a face to which the triangular LEXAN panels can be attached.

The 26 LEXAN panels fall into four distinct styles. Square panels fill six orthogonal faces and exist in two flavors, the only difference lying in the placement of the countersunk mounting holes to account for the internal asymmetry of the aluminum frame. Twelve rectangular panels mount 45-degrees with respect to the square panels, and with the square panels, the rectangles describe octagons about each of the three principal axes of the SPHERES. The remaining eight panels are equilateral triangles and fill out the remaining gaps in the structure.

To the internal frame is mounted the secondary structure, which consists of all support structures for batteries, the tank, the integrated circuit cards, and all plumbing and wiring associated with said components. The external panels provide attachments for the gas thrusters, the metrology sensors, and the communication devices.
9.0 Structural Load Analysis

The SPHERES hardware is capable of withstanding greater than 2.5-g loading (see Appendix I). Other equipment such as laptop computers and camera/mounting devices have flown previously on the KC-135 and can also be shown to withstand the loading conditions.

10.0 Electrical Load Analysis

The SPHERES hardware, camera, and laptop use battery power only. No external power will be needed. The maximum current through the apparatus is not significant enough to pose any danger to any person aboard the KC-135. Hazard analysis included in Section 18.0 details power and current distribution.

11.0 Pressure Vessel Certification

See Appendix II

12.0 In-flight Test Procedures

Four series of tests, denoted S1-S4, will be conducted during the total flight time. The series are devoted to the following:

- **S1**  Environment acclimation, power-off hardware handling, and video capture
- **S2**  3-Axis rotation damping at different gains
- **S3**  Tests of global metrology system (Test I) without thruster usage
- **S4**  Tests of global metrology system (Test II) with open-loop thruster pair firing in 6 degrees of freedom

The following description of series tests assumes that all test equipment has been removed from take-off/landing storage, mounted video cameras have been turned on, data acquisition is functional, and acclimatization parabolas have passed.

**Series S1 Procedure:**
- a. Confirm that SPHERES power is OFF
- b. Free-float one SPHERES
- c. Observe power-off dynamics
- d. Capture SPHERES before 2-g pullout
- e. Repeat as per (a) for extent of S1 parabolas (see section 13.0)

**Series S2 Procedure:**
- a. Confirm that SPHERES power is ON
- b. Free-float one SPHERES
- c. Disturb SPHERES manually in prescribed direction
- d. Observe damping effects
- e. Capture SPHERES before 2-g pullout
f. Change gain if necessary  
g. Repeat as per (a) for extent of S2 parabolas (see section 13.0) to encompass all directional movement  

Series S3 Procedure:  
a. Confirm that SPHERES power is ON  
b. Place one SPHERES at preset location in test area  
c. Free-float SPHERES  
d. Manually direct SPHERES in prescribed direction  
h. Capture SPHERES before 2-g pullout  
e. Repeat as per (a) for extent of S3 parabolas (see section 13.0)  

Series S4 Procedure:  
a. Confirm that SPHERES power is ON  
b. Place one SPHERES at preset location in test area  
c. Free-float SPHERES  
d. Fire thruster pairs  
h. Capture SPHERES before 2-g pullout  
f. Repeat as per (a) for extent of S4 parabolas (see section 13.0) to encompass directional movement in all 6 degrees of freedom  

It is probable that the CO$_2$ compressed gas tanks will need to be changed out during the total flying time. While a practice tank-swapping maneuver will be conducted during the acclimatization phase of the flight, test conductors will only swap tanks during a set of parabolas if the wait until the next break is long enough to hinder the successful completion of one of the above tests. However, one tank lifetime is greater than the time of expected use of the system during a set of ten parabolas, so this situation is not expected to happen. Nominally, tanks will be swapped during each break. During a tank swap-out, the following procedure will be taken:  

a. Secure SPHERES  
b. Tank purge – computer command will open all valves simultaneously. 5-10 seconds (depending on amount of air left in tank) SPHERES will be restrained during this process  
c. SPHERES is turned off  
d. Tank regulator will be closed  
e. Tank removal – using a glove to protect test conductor, empty tank will be removed  
f. Empty tank will be secured in carry-on container to ensure it is safely out of the way  
g. New tank will be taken from another carry-on container  
h. New tank will be inserted into SPHERES, ensuring seal on tank is pierced  
i. Tank regulator will be opened  
j. SPHERES is turned on
The SPHERES tank swap-out can be performed in less than 30 seconds, in case swap-out must occur between parabolas.

Another concern is with the battery system on-board the SPHERE Satellite. With current power draw, the batteries are expected to last the extent of the flying mission. However, if the batteries must be replaced, the following procedure will be taken:

a. SPHERES is turned off
b. SPHERES door is opened
c. SPHERES battery pack is disconnected from the system
d. SPHERES battery pack is removed and is secured in a carry-on container
e. A new SPHERES battery pack is taken from the container
f. The new SPHERES battery pack is inserted into the SPHERES and connected to the system
g. SPHERES door is closed
h. SPHERES is turned on

The SPHERES battery-pack swap-out can also be performed in less than 30 seconds, in case swap-out must occur between parabolas.

The final concern revolves around the test conductors themselves. The tests may continue as long as there are two members still capable of working in the environment. If three or more conductors become sick, the tests will be cancelled.

13.0 Parabola Requirements, Number and Sequencing

All parabolas flown for this experiment require a zero-g environment. The table below outlines the proposed test sequence for flights. Breaks between the flights will be used for tank swap-outs and logistical maneuvers. After each series of tests, the Test Director will determine if the objectives of the test have been met and if enough data has been gathered. He/she will determine whether or not to proceed with the next series of tests. Testing will continue unless three or more of the participants become ill.

<table>
<thead>
<tr>
<th>Parabola Number(s)</th>
<th>Test Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Acclimatization (get used to weightlessness)</td>
</tr>
<tr>
<td>3-5</td>
<td>Logistics Tests (video camera capture test, preliminary tank swap-out maneuver, human interactions testing)</td>
</tr>
<tr>
<td>6-10</td>
<td>S1: Power off handling tests (observe zero-g dynamics of SPHERES system – no damping)</td>
</tr>
<tr>
<td><em><strong>BREAK</strong></em></td>
<td>Turn on computers, swap tanks, prepare for S2 tests</td>
</tr>
<tr>
<td>11-20</td>
<td>S2: 3-axis rotation and damper tests at different gains (all 6 degrees of freedom tested plus combination maneuvers)</td>
</tr>
<tr>
<td><em><strong>BREAK</strong></em></td>
<td>Swap tanks, prepare for S3 tests</td>
</tr>
<tr>
<td>21-30</td>
<td>S3: Global Metrology Test I (manual movement of system)</td>
</tr>
<tr>
<td><em><strong>BREAK</strong></em></td>
<td>Swap tanks, make adjustments</td>
</tr>
</tbody>
</table>
14.0 **Test Support Requirements, Ground and Flight**

SPHERES testing requires only battery power. At least two team members out of the four-person team must be healthy to conduct productive experimentation. Data will be collected throughout the experiment to be studied following the flights. On the ground before and after flights, equipment will be tested for functionality, and detected problems will be fixed.

15.0 **Data Acquisition System**

A laptop computer will be brought on board to store data collected from the individual satellites undergoing testing. Data collection will occur at all times through an RF data-link between the SPHERES and the laptop.

16.0 **Test Operating Limits / Restrictions**

Limitations affecting data collection include equipment malfunction/failure or three sick test conductors. Global metrology and IMU damping will be tested on two separate SPHERES. Both will be brought on-board to ensure that, despite failure of one, testing on the other may continue.

17.0 **Proposed Manifest for Each Flight**

All flights of the KC-135 will follow a similar format. The first two parabolas of each flight will be used for acclimatization to the conditions of the KC-135. After these, 3 parabolas will be used to work out team logistics for data collection and experimentation. An emergency tank swap-out maneuver will be performed to ensure that it will be possible for team members to change a tank between parabolas if need be. The remaining five parabolas in the first set will be used to test the free-floating dynamics of the SPHERES in a zero-g environment. Team members will use this time to ensure that the experiment may continue safely with the SPHERES involved. Following the break, the next set of ten parabolas will be used for our S1 tests, demonstrating the ability of the SPHERES to control manual disturbances from an outside force – specifically an applied force from a team conductor. Following the second break, the global metrology system will be tested through the means of a two-stage process. First, the system will be manually tested, eliminating the variable of thruster firing to the system. Following five parabolas of this form of measurement, various thruster firings will be tested in addition to the metrology data acquisition for the remainder of the flight.

18.0 **Photographic / Video Requirements**

Video and photographic support is requested for all days of testing. Video footage will supplement the footage obtained from the still cameras as a check for the accuracy of the global metrology system. Photographs will be useful in conveying the testing environment to the rest of the team members and documenting the testing for future reference.
19.0 Hazard Analysis

The purpose of the hazard analysis is to identify the potential safety hazards associated with the Synchronized Position, Hold, Engage, and Reorient Experimental Satellites (SPHERES). It is also to identify the causes of those hazards, define the controls designed into the system to preclude the occurrence of unsafe conditions, and to identify the approach and methodology for compliance with the applicable safety requirements.

See Appendix III for all hazard reports.