The Precision Expandable Radar Calibration Sphere (PERCS) With Applications for Laser Imaging and Ranging

Paul A. Bernhardt[1], Andy Nicholas[2], Linda Thomas[3], Mark Davis[3]

[1] *Plasma Physics Division,* [2] *Space Science Division,* [3] *Space Systems Development Department, Naval Research Laboratory,* Washington, DC, Paul.Bernhardt@nrl.navy.mil

Chuck Hoberman, Matt Davis

Hoberman Associates, New York, NY

ABSTRACT

The Naval Research Laboratory will provide an orbiting calibration sphere to be used with ground-based laser imaging telescopes and HF radio systems. The Precision Expandable Radar Calibration Sphere (PERCS) is a practical, reliable, high-performance HF calibration sphere and laser imaging target to orbit at about 600 km altitude. The sphere will be made of a spherical wire frame with aspect independent radar cross section in the 3 to 35 MHz frequency range. The necessary launch vehicle to place the PERCS in orbit will be provided by the Department of Defense Space Test Program. The expandable calibration target has a stowed diameter of 1 meter and a fully deployed diameter of 10.2 meters. A separate deployment mechanism is provided for the sphere. After deployment, the Precision Expandable Radar Calibration Sphere (PERCS) with 180 vertices will be in a high inclination orbit to scatter radio pulses from a number of ground systems, including (1) over-the-horizon (OTH) radars operated by the United States and Australia; (2) high power HF facilities such as HAARP in Alaska, EISCAT in Norway, and Arecibo in Puerto Rico; (3) the chain of high latitude SuperDARN radars used for auroral region mapping; and (4) HF direction finding for Navy ships. With the PERCS satellite, the accuracy of HF radars can be periodically checked for range, elevation, and azimuth errors. In addition, each of the 360 vertices on the PERCS sphere will support an optical retro-reflector for operations with ground laser facilities used to track satellites. The ground laser systems will be used to measure the precise location of the sphere within one cm accuracy and will provide the spatial orientation of the sphere as well as the rotation rate. The Department of Defense facilities that can use the corner-cube reflectors on the PERCS include (1) the Air Force Maui Optical Site (AMOS), (2) the Starfire Optical Range (SOR), and (3) the NRL Optical Test Facility (OTF).

1. Introduction

A practical, reliable, high-performance satellite made up of a spherical polyhedron with 180 vertices, 92 faces, and 270 edges will be launched into low-earth-orbit. The polyhedron structure is illustrated in Figure 1 showing the 80 hexagon faces and 12 pentagon faces around the sphere. The PERCS satellite will have the shape of the sphere in Figure 1 with the pentagon and hexagon surfaces removed so that only a wire frame structure is in orbit. This opening of the faces provides a large, 10-meter-diameter sphere with very low atmospheric drag.

There are three major objectives for the PERCS instrument program. The first of these is to provide an *HF Radar Calibration Target* using a spherical wire frame whose primary purpose is operational validation of the calibration for antenna patterns of ground-based HF radars. For this, the plan is to construct a model for monostatic RCS testing in an anechoic chamber, then to construct a spaceflight version and launch it into low-earth orbit and, finally, validate the PERCS concept using ground over-the-horizon (*OTH)* and *space weather* radars. The second objective is to validate the *HF direction finding* accuracy for ship, shore, and airborne systems. The primary use would be to scatter ground HF transmitter signals for Navy HF DF systems. For this application, the program would both model and measure the Bistatic radar cross section of PERCS. To test PERCS with HF DF arrays, ground HF transmitters such as the Navy relocatable over the horizon radar (ROTHR) and the Air Force/Navy HAARP system would be employed. The third application is for PERCS to provide an optical calibrator for *Laser Satellite Imaging* with an array of corner reflectors. This would verify the calibration of laser imaging systems that provide space situational awareness to the Department of Defense. By adding corner cube reflectors to each vertex of the wire frame, a calibration target would be available to support operational laser ranging, tracking, and imaging systems.

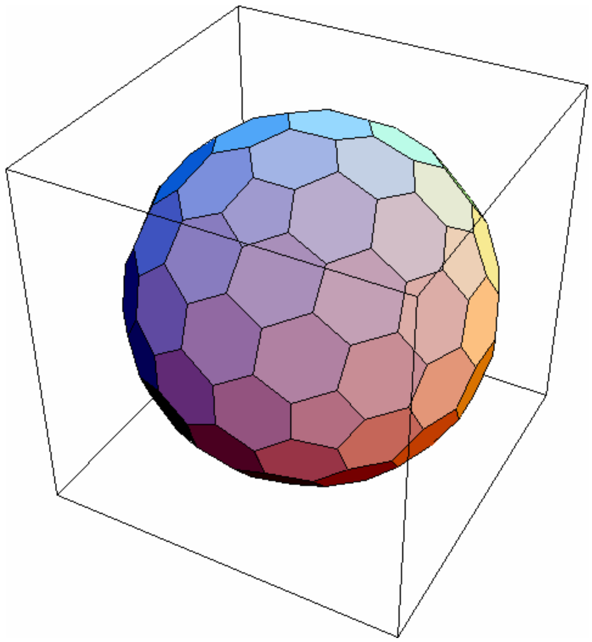

Figure 1. Spherical polyhedron with 180 vertices.

2. HF Radar and Radio Transmitter Calibration Applications

An application of the PERCS for validating the calibration of OTH radars is illustrated in Figure 2. When the sphere passes though the HF radar beam, the signals will be backscattered to the OTHR receiver antenna array. If the system calibration is done at night with frequencies that are much larger than the critical frequency of the ionosphere, the HF ray paths will be nearly straight lines. The strength of the radar echoes will be given by the radar equation

$$P_R = \frac{\sigma_0 P_T G_T G_R \lambda^2}{(4\pi)^3 R^4 B_n} \tag{1}$$

where G_T and G_R are transmitter and receiver gain, P_T is transmitter power, R is range to PERCS, B_n is receiver bandwidth, and σ_0 is the PERCS radar cross section. Measurements of the receiver power P_R over the PERCS trajectory provides a system calibration of the OTHR system sensitivity. This technique is an improvement over current techniques for calibration such as measuring the ratio of radar signal to ocean clutter or measuring the scatter from irregular shaped satellites such as the International Space Station or the Space Shuttle. In fact, the concept of using a 10-meter-diameter sphere for comparative calibration of OTH radar systems came from the head of the over-the-horizon radar systems at DSTO in Australia.

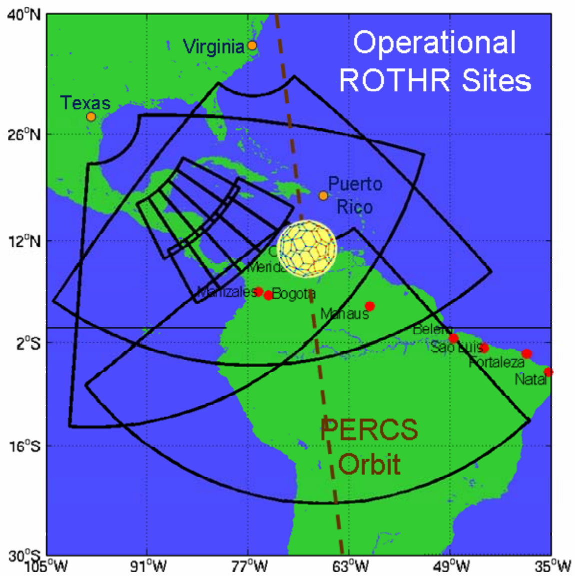

Figure 2. Flight path of the PERCS orbit over the footprint of ground OTH radars. The calibration sphere flies along a precise orbit illustrated by the dashed line.

Another application is to scatter HF waves from PERCS for calibration of high power HF facilities (Figure 3). DoD research in the areas of ionospheric modification, or HF interactions, is currently quite active, including support for the High Frequency Active Auroral Research Program (HAARP) Facility in Alaska and the newly renovated Arecibo heater in Puerto Rico. The antenna pattern gain for ionospheric modification facilities and the total power fed to the transmitter determines the effective radiated power (ERP) for the systems. This ERP is dependent on frequency, ground conductivity, and the physical condition of the HF transmitting array. With PERCS, periodic checks may be made for the absolute radiation efficiency of facilities like HAARP in Alaska, the Arecibo heater in Puerto Rico, and the EISCAT heater in Norway.

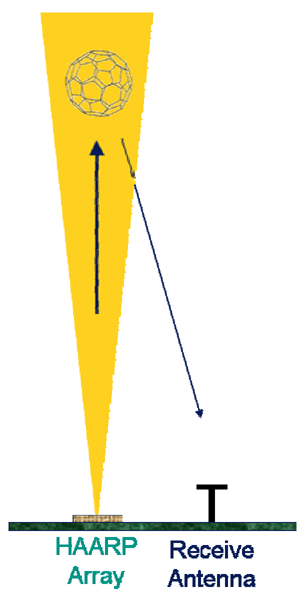

Figure 3. Scattering of HF waves from the HAARP transmitter for measurements of the HAARP antenna pattern.

3. HF Direction Finding and Communications by Scatter from the PERCS Satellite

The PERCS satellite is large enough to provide a strong reflected signal for both HF direction finding and PERCS scatter communications. When an HF wave from a ground transmitter reflects from the PERCS, it can be received at another location on the ground (Figure 6). A new communications mode can be studied with this scatter. In addition, a known angle of arrival at HF frequencies is provided to the ground receiver.

The final HF application for the PERCS sphere will be to validate the direction finding (DF) accuracy for ground, ship, and airborne antenna arrays. To locate the source on an HF signal, both the azimuth and elevation of the incoming ray path is measured with HF/DF antennas. Calibration of these antennas is difficult and usually scale models of ships and other systems are constructed for measurements in anechoic chambers. Validation of this calibration for Navy ships and other DF measurements systems is an essential application of PERCS.

The concept for this mode of operation is illustrated in Figure 4. The HF frequency should be at least two or three times the F-layer critical frequency to minimize the bending of the ray paths after reflection from the PERCS satellite.

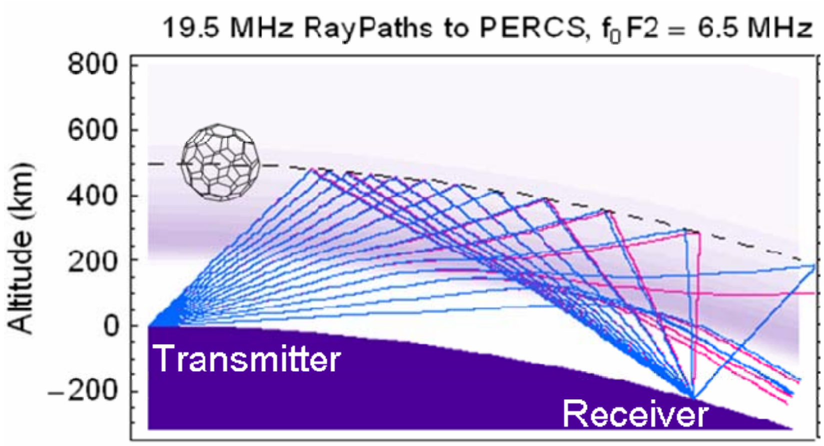

Figure 4. Scatter of HF waves from PERCS to ground receiver for angle arrival calibration.

4. Laser Satellite Tracking Applications and PERCS Drag

Each vertex of the V180 PERCS will provide mechanical support for a laser retro-reflector. High quality fused silica glass will be used for retro-reflections added to each vertex (Figure 5). Ground laser beams can illuminate the PERCS to provide detectable light signals that provide both the position and rotation rate of the sphere in orbit. This provides a unique target for ground laser systems to test their tracking capabilities. With the vertexes separated by as much as one PERCS diameter (10-meters), a laser imaging system coupled with a telescope may be able to resolve this dimension in the orbiting sphere. In addition, the retro-reflectors provide precise position and rotation data on the sphere. The laser position data is valuable for comparison with location data obtained with ground radars.

With precise laser tracking, PERCS is valuable for scientific research into the mechanical forces of the satellite. The trajectory of PERCS will be changed by the electrodynamic interactions of conducting structures with the geomagnetic field. While moving in low-earth orbit, as the PERCS satellite crosses magnetic field line, currents will be induced in the conducting edges. The forces associated with the magnetic field interactions with these currents will change the orbit and rotation of the sphere. In addition, solar illumination of PERCS will cause photo-detachment of electrons on the sphere so that it may become positively charged. Electrostatic forces on the charged sphere will also change its orbit (Figure 6).

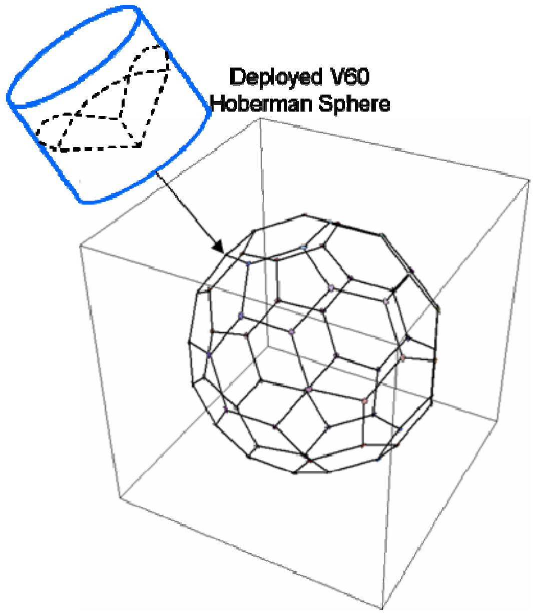

Figure 5. The addition of corner-cube reflectors at each PERCS vertex provides calibration for laser satellite imaging and tracking systems. Ground laser beam illumination of retro-reflections for each vertex of PERCS will provide isolated points of light.

The PERCS in orbit will be viewable from the ground by city light scattering from the array of retro reflectors around the sphere. In addition at twilight, sunlight scatter from the gold struts of PERCS will provide a visible display of the satellite motion from the ground. The viewing and tracking of PERCS will provide calibration opportunities for passive optical tracking systems.

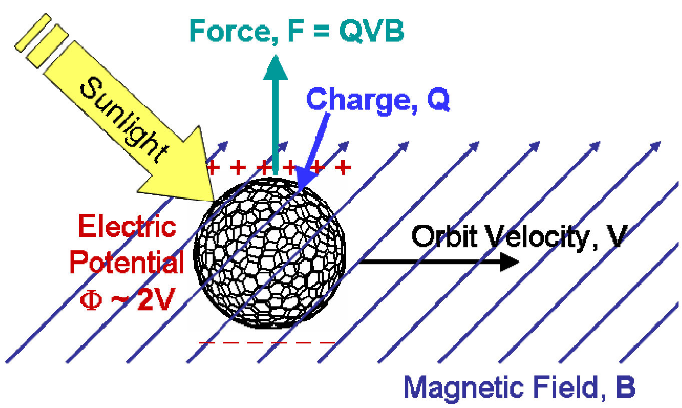

Figure 6. Electrodynamics of an orbiting wire frame.

Previous spherical satellites have had solid surfaces so that their orbital motion has been dominated by collision drag. The PERCS satellite has a drag area of only 2 m^2 whereas the geometric projection of a 10-meter sphere is 200 m^2. The PERCS sphere has 100 times less drag for a similar sized satellite in low-earth orbit. By measuring the position of PERCS to 1 cm accuracy using the laser retro-reflections, the electrostatic deflection of PERCS will be measured for comparison to the electrodynamic interaction and collisional drag theories developed at the Naval Research Laboratory.

The proposed PERCS instrumentation will have a useful life of more than ten years. With an open frame design, the HF radar calibration sphere will have the cross sectional area of only 2 square meters with a radio frequency scatter cross section of over 200 square meters up to 35 MHz frequency. The mass of the PERCS sphere will be over 200 kg. The drag deceleration of a satellite is dependent on the area over mass ratio. For PERCS above 600 km, the orbit lifetime limit from atmospheric drag will be over ten years. A simulation of the drag effects for a 40 kg sphere with both solid-surface and open-frame surfaces as well as aluminum and stainless steel construction is given in Figure 7. A 10-meter solid sphere stays in orbit for a few days whereas PERCS will be in orbit for years.

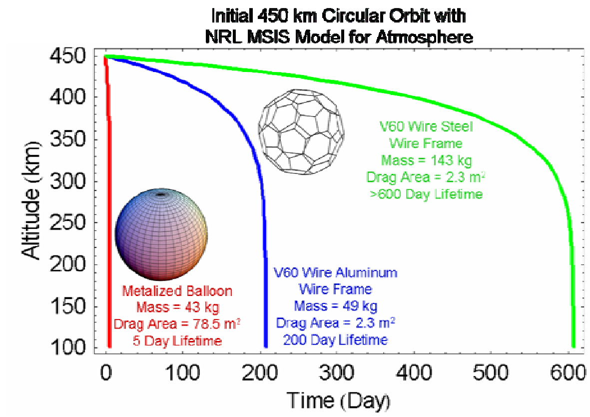

Figure 7. Calculated effects of atmospheric drag on orbiting 10-meter diameters spheres with (a) solid surface, (2) aluminum wire frame, and (3) stainless steal frame structures. The heavier wire frame PERCS stays in orbit the longest.

5. Placing PERCS in Orbit

To launch the sphere in space, it will be collapsed down to a 1-meter-diameter ball. This ball expands by a factor of 10 using Hoberman sphere technology, which is based on patents that has common applications as a toy[3,4]. A separate patent[2] for PERCS jointly with NRL, Hoberman Associates, and Cornell University is currently pending. The PERCS used for the space applications is being designed by Hoberman Associates in New York City, New York under contract with the Naval Research Laboratory.

The deployment of the PERCS sphere is illustrated in Figure 8. Torsion springs at each hinge in the Hoberman sphere are used to open the sphere after being ejected from the launch vehicle. The deployment mechanism for PERCS has been designed jointly by Hoberman Associates and the Space Engineering Department at the Naval Research Laboratory with funding by the Office of Naval Research.

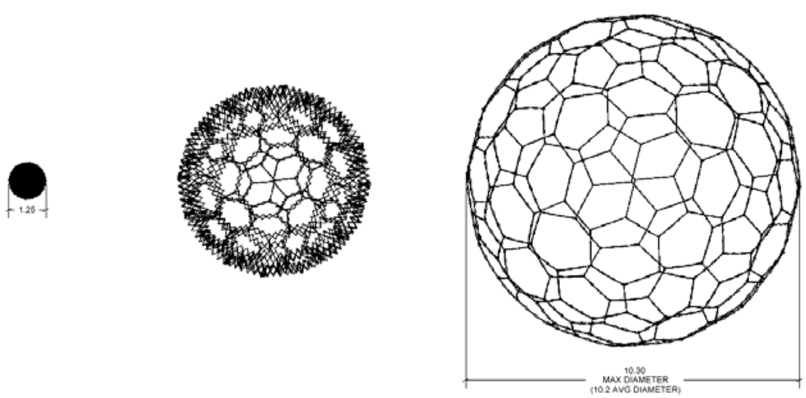

Figure 8. Deployed PERCS V180 wire frame in low-earth orbit provides a target for HF wave scatter and laser imaging.

3. Technical Description

For the first PERCS satellite, Hoberman Associates of New York City, New York will construct an 180-vertex sphere with a ten-meter diameter. This sphere will compress into a 1.2-meter diameter structure for launch and expand into its full 10.2-meter diameter after release from the launch vehicle.

The PERCS design presented here is based on the basic specifications provided in the paper by *Bernhardt et al*[1]. Each edge of the sphere is joined at a vertex. The expandable structure is composed of two interlocking spheres with 180 vertices on the inside and 180 vertices on the outside of the deployed sphere. The vertices are joined by a total of 1820 links in the form of scissors that allow the vertices to collapse toward the center of the sphere. Each scissor pair is forced toward a linear configuration by a torsion spring.

The mechanical configurations of the stowed, partially deployed, and deployed states are illustrated in Figure 8. Full deployment is achieved with torsion springs in each of 1620 scissor hinges (Figure 9). The distributed force at these hinge points provides for uniform deployment of the sphere. Each edge composed of three scissors is attached to pairs of hubs that move inward along a radius vector for stowage and outward at deployment. The scissors have been designed with straight and bent struts for this motion.

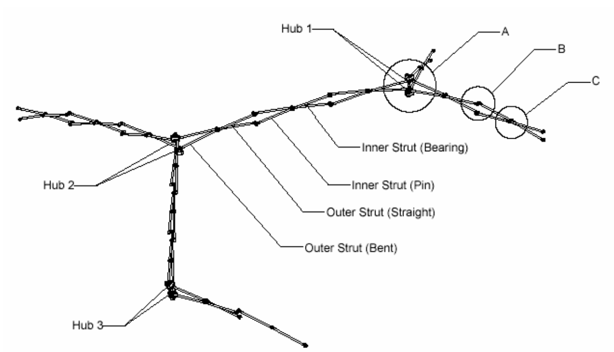

Figure 9. Edge of PERCS V180 composed of three scissors attached to a hinged hub.

When the PERCS V180 is stowed, the hubs merge into an inner sphere and an outer spherical comb. This structure is supported by a deployment structure for launch. At deployment (Figure 10), the hubs are locked in place with a mechanical link to provide precise dimensions for the target structure. Analysis has shown that the stresses in the fully deployed sphere under its own weight can survive deployment for testing under 1 g.

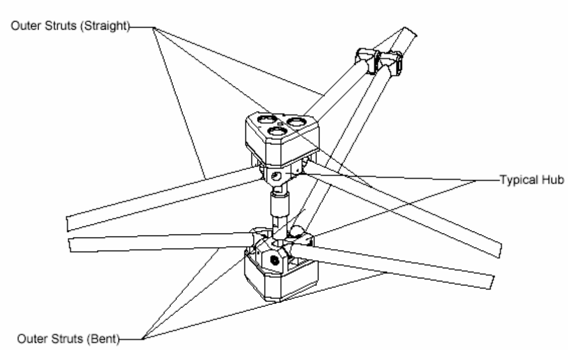

Figure 10. Hub detail showing strut connections below retro-reflector housings.

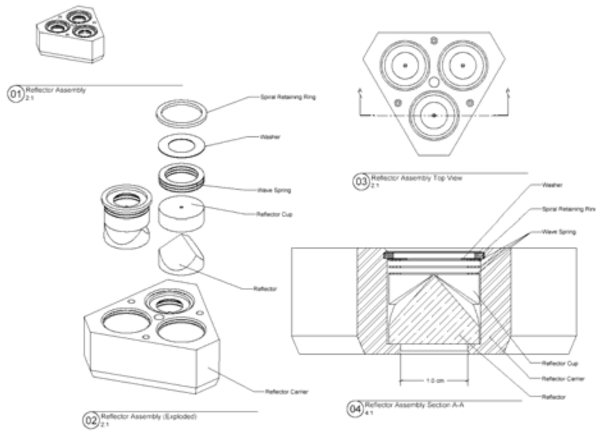

Figure 11. Housing for three 1-cm retro reflectors placed at 360 locations at the PERCS vertices inside and outside the polyhedral frame.

At the each vertex of the sphere will be a housing for laser retro reflectors (Figure 11). Three 1-cm diameter retro reflectors will be used to show the exact position and orientation of the sphere in orbit. The International Laser Ranging Service (ILRS) has agreed to make available their global network for tracking the position and orientation of the PERCS sphere. One-cm-diameter retro reflectors are used in triplets to spread the laser beam by diffraction to overcome velocity aberration from the satellite motion.

The 180 vertex sphere has 92 faces and 270 double edges. A total of 1620 struts, 810 torsion springs, 360 inside and outside hubs, and 1080 corner cube reflectors will be required for the completed PERCS. The total sphere has a mass of 250 kg.

The construction of the PERCS satellite will require (1) finalization of the PERCS design, (2) fabrication of the components of the PERCS sphere, (3) assembly of the PERCS sphere, (4) deployment testing of the PERCS sphere at 1 g gravitational force, (5) construction of the PERCS containment housing, (6) environmental testing in launch configuration, and (7) delivery for launch. A launch of 2011 is anticipated with the current schedule.

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