Ground-Based Investigation of Near-Earth Space Plasma Processes in the NRL Space Physics Simulation Chamber

W.E. Amatucci,[1] D.D. Blackwell,[1] G.R. Gatling,[1]
E.M. Tejero,[1] C.D. Cothran,[2] D.N. Walker,[2] and
E.D. Gillman[3]
[1]*Plasma Physics Division*
[2]*Sotera Defense Solutions, Inc.*
[3]*National Research Council Postdoctoral Fellow*

Introduction: The NRL Space Physics Simulation Chamber Laboratory conducts a broad-based research program addressing near-Earth space plasma physics. The unique Space Chamber device (shown in operation in Fig. 1) produces large-volume, steady-state, space-like plasmas with conditions scaled to match various ionospheric and magnetospheric regions of interest. The program includes basic research illuminating the underlying physics driving key space plasma processes and applied research for understanding plasma effects on spacecraft systems, testing spacecraft hardware, and development of innovative plasma sensors.

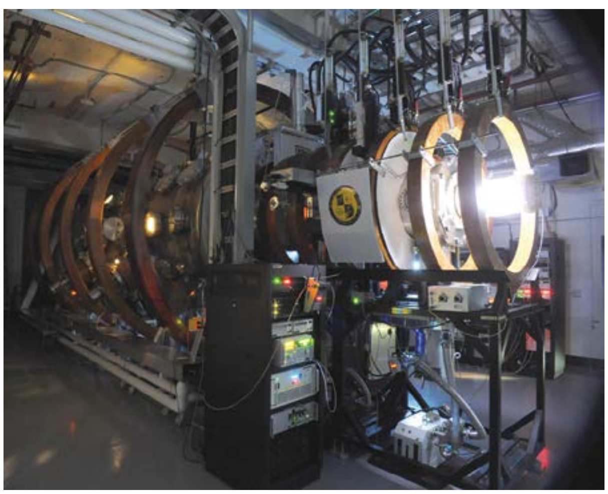

FIGURE 1
The NRL Space Physics Simulation Chamber with the helicon plasma source in operation. The main chamber is 2 m in diameter and 5 m long, allowing for the creation of large-scale plasmas and accommodation of spacecraft hardware. The source chamber is 0.55 m in diameter and adds 2 m to the chamber length.

Simulating High-Altitude Space Physics: Recent Space Chamber investigations have addressed issues involving dynamic particle interactions in the radiation belts and the effects of discharges between rendezvousing spacecraft at geosynchronous orbit. The radiation belts are regions of space where high-energy particles remain trapped by the Earth's magnetic field, posing a serious threat to the lifetime of orbiting satellites. In the natural environment, electromagnetic plasma whistler waves limit the number of high-energy particles by scattering them from their trapped orbits. NRL theorists have proposed techniques building on nature's example to protect space assets by generating whistler waves that enhance the scattering process.

Important aspects of these techniques are being tested in the Space Chamber. For example, under certain conditions, the radiation belt electron populations themselves can be used to amplify whistler waves, leading to accelerated loss of the dangerous particles. This depends upon having wave–particle interaction times sufficient for amplification to occur. However, the required interaction times are difficult to achieve in laboratory-scale devices, which cannot match the vast spatial and temporal scales of space. This limitation has been overcome in the Space Chamber by creation of high-Q standing whistler wave patterns.[1] By repeated reflection of antenna-driven whistler waves from controlled boundaries, long interaction times between a whistler wave and injected energetic electrons can be achieved, allowing for detailed comparisons with theory and simulation results.

The ability of the large-volume Space Chamber to precisely control conditions while being able to manipulate realistic spacecraft hardware was exploited recently in a joint NRL-NASA-DARPA project to investigate the effects of high-voltage discharges between rendezvousing spacecraft at geosynchronous orbital altitudes. Figure 2 shows examples of grippers from robotic arms being developed for the NRL SUMO/FREND program approaching target spacecraft hardware, which could be charged up to 10,000 V. The experiments demonstrated the current profile that can be expected in such discharges and the effects of repeated discharging, and tested possible mitigation methods.

Simulating Low-Altitude Space Plasmas: In an effort to understand space weather phenomena in the auroral ionosphere, Space Chamber research has produced the first observations of electromagnetic ion cyclotron (EMIC) waves driven by nonuniform, or sheared, plasma flows.[2] The origin of EMIC waves in the ionosphere is not known, but they can influence space weather through energy transport, ion heating, and outflow. In the Space Chamber, sheared plasma flows are driven by localized electric fields designed to match electric fields associated with EMIC waves in space. The threshold plasma conditions necessary for EMIC wave excitation in the presence of sheared flow and frequency and wave vector spectra have been identified in the laboratory. The discovery of a localized source of EMIC waves impacts the energy balance of space weather models since the waves can effectively

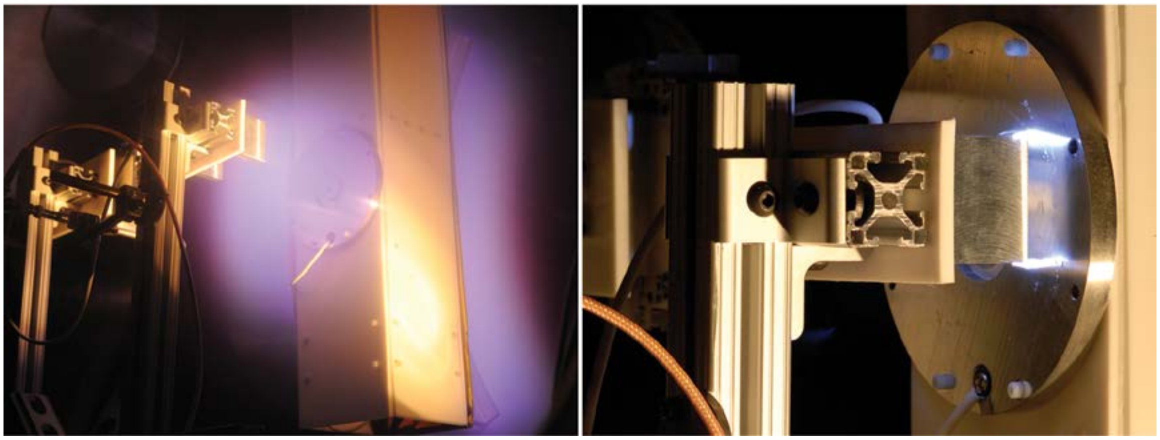

FIGURE 2
Photographs showing high-voltage discharges between simulated components of spacecraft rendezvousing at geosynchronous orbit. The photo on the left shows the dc glow discharge plasma that forms around the charged components when neutral gas is added to simulate the firing of thrusters. The photo on the right shows the arc discharge that occurs when the target and simulated gripper are brought within close proximity.

reflect back a portion of incident energy to the magnetosphere, while locally heating heavy ions and initiating bulk plasma transport.

Space Sensor Development: An innovative plasma impedance probe under development in the Space Chamber Laboratory shows promise for outperforming standard plasma parameter diagnostics.[3,4] In laboratory testing, the NRL impedance probe has provided more accurate plasma density measurements than standard probe techniques, as well as accurate determination of plasma potential and electron temperature. Characterization of these basic plasma parameters is integral to nearly all laboratory plasma experiments and near-Earth space weather investigations. The laboratory investigations have also illustrated that the NRL impedance probe can yield useful data in operational regimes where other techniques are not feasible, opening up many new possibilities for making measurements in industrial processing plasmas and in atmospheric pressure discharge experiments. Additionally, in the space environment, there presently are no simple, dedicated sensors to monitor spacecraft charging, which can pose a serious threat to satellite operations. The sensitivity of the NRL plasma impedance probe response to slight changes in the sheath surrounding a charged object provides unique opportunities for early detection of the onset of hazardous levels of spacecraft charging.

A version of the probe that will focus on tracking plasma electron density will undergo its first space test flight aboard the NRL Tether Electrodynamics Propulsion CubeSat Experiment (TEPCE). The density measurements provided by the Space PlasmA Diagnostic suitE (SPADE) will aid in the determination of TEPCE's efficiency for collection of ionospheric electrons and provide a key initial test of this emerging technology.

[Sponsored by the NRL Base Program (CNR funded), DTRA, NASA, and AFOSR]

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Artificial Ionospheric Plasma Clouds Using HAARP

P.A. Bernhardt,[1] C.L. Siefring,[1] S.-M. Han,[1] D.L. Byers,[1] A. Fliflet,[1] S.C. Briczinski,[2] M. Wilkens,[3] and E.G. Kendall[4]

[1]*Plasma Physics Division*
[2]*National Research Council Postdoctoral Fellow*
[3]*Sotera Defense Solutions*
[4]*SRI International*

Introduction: Artificial balls of plasma have been produced in the upper atmosphere (160 to 200 km altitude) using the 3.6 MW high frequency (HF) transmitter facility known as HAARP (High frequency Active Auroral Research Program). These glow plasma discharges were generated in November 2012 as a part of the Basic Research on Ionospheric Characteristics and Effects (BRIOCHE) campaign in Alaska. The plasma balls (or electron density enhancements) are being studied for use as artificial mirrors at altitudes 50 km below the natural ionosphere to be used for reflection of HF radar and communications signals. The density of these plasma clouds is proportional to the square of the transmission frequency, which is an integer harmonic of the electron cyclotron frequency.

Recent Accomplishments: NRL scientists in the Plasma Physics Division succeeded in producing artificial plasma clouds with densities exceeding 9×10^5 electrons per cm^3 using HAARP transmission at the 6th harmonic of the electron cyclotron frequency at 8.58 MHz. In previous work, lower density plasma density clouds at lower frequencies had lifetimes of only 10 minutes or less.[1] This higher density plasma density ball was maintained for over one hour by the HAARP transmissions and could have been sustained indefinitely by the ground HF radio transmissions. The NRL team is working on this project with collaborators at the Air Force Research Laboratory, SRI International, the University of Alaska in Fairbanks, the University of Florida, and BAE Systems.

The glow of artificial plasma clouds is directly detected with low light level cameras.[2] The optical images of the artificial plasma balls show that they are turbulent with dynamically changing density structures (Fig. 3). Electrostatic waves generated by the HAARP radio transmissions are thought to be responsible for accelerating electrons to high enough energy to produce the glow discharge in the neutral atmosphere. Radio diagnostics of the artificial plasma clouds are (1) ground-based radio soundings and (2) reception of stimulated electromagnetic emissions (SEE).[2] Figure 4 illustrates the signature of an artificial plasma cloud near the 4th gyro harmonic resonance in the ionosphere. When the electromagnetic pump wave is tuned to the resonance, the electrostatic waves are generated by the parametric decay instability. These waves are converted to electromagnetic emissions to be detected on the ground as downshifted spectral features. These same electrostatic waves accelerate electrons to high enough energy for collisional ionization of the ambient neutral gas forming the plasma cloud. The ionospheric sounder detects this cloud as an apparent layer below the ambient ionosphere.

Theory and Modeling: The parametric interactions theory is being developed into a comprehensive model of the plasma cloud generation. High-power electromagnetic fields are propagated to the ionosphere using multidimensional magnetionic theory in both the ambient and modified plasma. At plasma resonance points in the atmosphere, different modes are excited including electron Bernstein, upper hybrid, and whistler waves. The waves with phase velocities that match the speeds of electrons transfer energy to the background electrons. Electrons with energies above the ionization potential of the ambient neutrals cause breakdown of these neutrals. The avalanche process that yields dense clouds of plasma is being investigated with a suprathermal electron source introduced into the NRL SAMI3 plasma transport model. The goal of the theoretical efforts is to develop techniques for the production of denser and more stable electron density clouds.

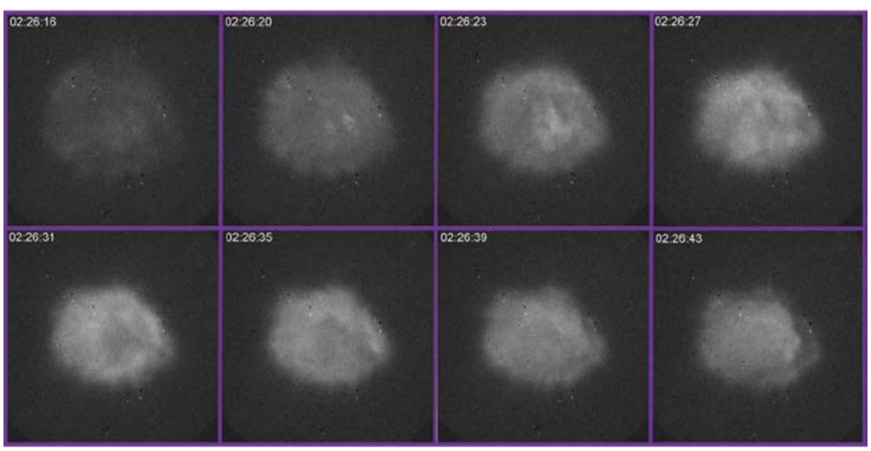

FIGURE 3
Sequence of images of the glow plasma discharge produced with transmissions at the 3rd electron gyro harmonic using the HAARP HF transmitter in Alaska. The 3rd harmonic artificial glow plasma clouds were obtained with HAARP using transmissions at 4.34 MHz. The resonant frequency yielded green line (557.7 nm) emission with HF on 12 November 2012 between the times of 02:26:15 and 02:26:45 GMT. (Images provided by Elizabeth Kendall of SRI International)

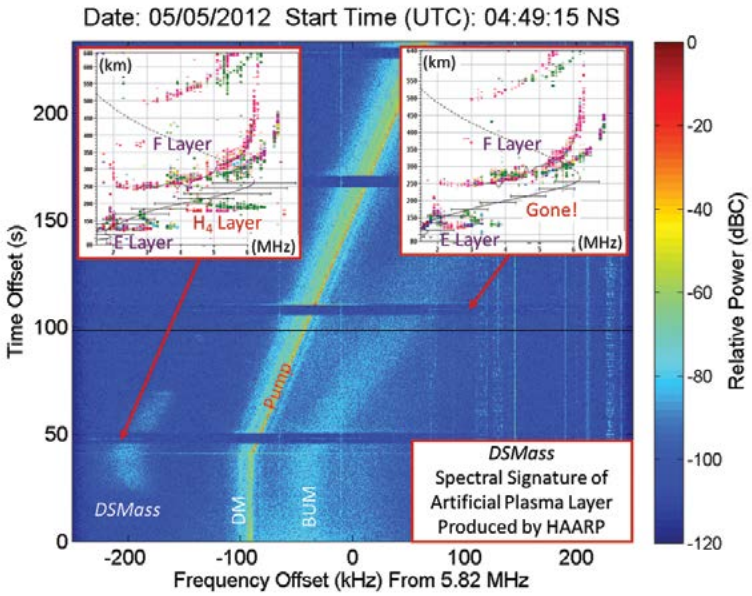

FIGURE 4
Radio frequency spectrograph showing the stimulated electromagnetic emissions from the ionosphere during times of artificial plasma cloud generation. The inset figures are ionosonde records of the ionosphere with (left) and without (right) a signature of an artificial plasma cloud. The H_4 layer is labeled to indicate the plasma cloud produced with an HF pump wave near the 4th gyro harmonic. This ionosonde feature is preceded by the DSMass spectral emissions centered 110 kHz below the transmitter frequency. Tuning the pump frequency away from the 4th harmonic resonance eliminates both the DSMass and the H_4 layer plasma cloud. (DSMass = downshifted mass; DM = downshifted maximum; BUM = broad upshifted maximum)

Laboratory Experiments: The HAARP experiments are being complemented with a series of laboratory studies using high-power electromagnetic waves to produce glow plasma discharges (Fig. 5). A microwave signal at 2.45 GHz is amplified using a porous spherical cavity resonator developed in the Plasma Physics Division to break down the neutral gas inside the resonator.[3] A low-pressure chamber developed for microwave processing has been modified for these demonstrations of plasma ball creation. The microwave-driven plasma laboratory is being used as a surrogate for HAARP to study the role of initial plasma seeds for creation and maintenance of artificial plasma clouds. These experiments have shown that it is difficult to produce electron clouds with densities greater than the critical frequency for reflection of the incident electromagnetic wave. Also, slow venting of neutral gases into the chamber has been used to study the effect of composition changes and neutral winds on the formation of the artificial plasma glow discharges.

FIGURE 5
Plasma ball generated inside a polyhedral cavity resonator with an external microwave field. The dynamics of the laboratory-generated glow plasma discharge are similar to those generated below the ionosphere by HAARP high-frequency transmissions.

Summary: By successfully making stable plasma clouds in both the upper atmosphere and the laboratory, NRL scientists are closer to producing artificial ionospheric mirrors with high-power radio waves. Breakthroughs in plasma cloud formation are accomplished by integrating HAARP upper atmospheric experiments, computer modeling with nonlinear plasma theory, and laboratory breakdown experiments.

Acknowledgments: Operations of the HAARP Ionospheric Research Instrument were provided by Marsh Creek LLC under support from the Air Force Research Laboratory.

[Sponsored by DARPA and the NRL Base Program (CNR funded)]

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Maritime Detection of Radiological/ Nuclear Threats

B. Phlips, E. Wulf, L. Mitchell, A. Hutcheson, and W.N. Johnson
Space Science Division

Introduction: Improved detection of weapons of mass destruction is one of the seven critical capabilities identified in the most recent Quadrennial Defense Review (QDR). It is therefore also one of the science and technology (S&T) priorities of the Secretary of Defense for fiscal years 2013 to 2017. Unfortunately, the remote detection of special nuclear materials (fissile materials that can be used to make a nuclear weapon) is difficult because the materials are not very radioactive, and because the radiation signature decreases rapidly with distance. An additional problem is that there are many sources of naturally occurring and manmade radioactive materials that can cause confusion when looking for a faint source of radiation.

The Radiation Detection Section of NRL's High Energy Space Environment Branch has been developing gamma-ray detection instruments for ground-based and space-based applications for years. One such system, MISTI (Mobile Imaging and Spectroscopic Threat Identification), was developed for the Domestic Nuclear Detection Office (DNDO) of the Department of Homeland Security (DHS). The MISTI instrument[1] was mounted in a 20 ft box truck and was delivered to DHS in October 2009.

SuperMISTI: SuperMISTI[2,3] is a follow-on instrument to the MISTI instrument and is designed for standoff detection in a maritime environment. It was developed as part of the Office of Naval Research (ONR) Maritime Weapons of Mass Destruction Detection program. The instrument consists of two standard refrigerated containers, each with its own power, communications, optical cameras, and GPS systems.

One container holds an array of high-purity germanium (HPGe) detectors (see Fig. 6). These cryogenic detectors can measure the energy of gamma rays with a high degree of accuracy, i.e., fine energy resolution. This accuracy helps solve the detection problem in two ways. First, the precise measurement of the energy provides unambiguous determination of the isotope emitting the gamma rays and allows the differentiation between isotopes of interest and other natural or manmade radioactive isotopes. The second advantage of the high energy resolution is that very little natural radiation background is exactly within the narrow energy band relevant for the isotopes of interest. The effective background is therefore quite low and the sensitivity of the system much improved.

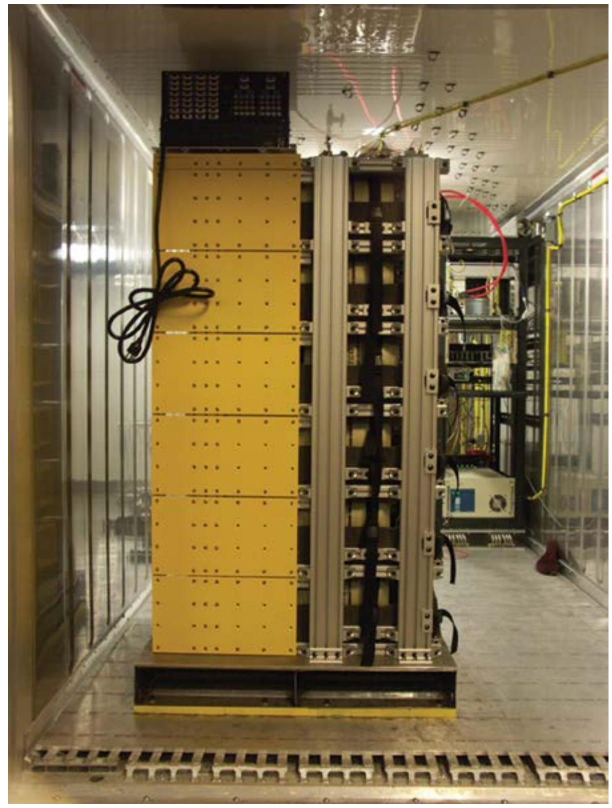

FIGURE 6
Photograph of the pallet containing high-purity germanium (HPGe) detectors.

The second container holds a gamma-ray imaging camera based on a two-dimensional array of sodium iodide detectors and a coded aperture camera. The sodium iodide detectors image the gamma rays that pass through the coded aperture. The coded aperture consists of a pattern of lead blocks that create a shadow on the detector array. The position of the shadow allows the position of the gamma-ray source to be reconstructed. The gamma-ray camera provides images but has a relatively poor energy measurement capability. The camera is therefore cued by the high-purity germanium array and together, the systems allow for sensitive detection, isotope identification, and three-dimensional localization of a source of gamma rays.

The MANTA Campaign: In July 2012, the SuperMISTI instrument was deployed at Norfolk Naval Station for the MANTA test campaign. The MANTA test campaign was organized by ONR to determine the on-water performance of different radiation detection systems. The deployed systems were tasked with detecting sources hidden in different types of vessels that were either docked at a pier or moored in open water. The two SuperMISTI containers were deployed on a 60 ft barge as shown in Fig. 7. The large cylindrical containers seen on the right-hand side of the photograph were ballast tanks to keep the barge level. During the MANTA campaign, the barge was pushed by a tug at different speeds and standoff distances from vessels of interest. Some vessels contained radioactive sources. The task for SuperMISTI was to detect the sources, identify the isotopes, and localize the source on the vessel remotely.

FIGURE 7
Photograph of the two refrigerated containers on a barge at Norfolk Naval Station.

Results: The typical results for a pass of SuperMISTI by a vessel in open water are shown in Fig. 8. The photograph shows an optical photograph of the vessel being passed, and overlaid on it a gamma-ray image (blue rectangle) of the position of the radioactive source. While the position resolution of the gamma-ray

FIGURE 8
Photograph of the LCU-2000 target ship with the reconstructed radiation source position overlaid as the dark blue rectangle.

camera is quite coarse, it is sufficient to localize the position of the source on the vessel and to guide any potential boarding party. Not shown in the photograph is the spectroscopic data that allowed unambiguous identification of the isotope prior to the image reconstruction. During the MANTA test campaign, SuperMISTI correctly detected, identified, and localized all sources it was exposed to from the standoff distances where detection was expected. SuperMISTI demonstrated the passive standoff detection of special nuclear materials in a maritime environment at operationally relevant distances.

[Sponsored by the Office of Naval Research Maritime Weapons of Mass Destruction Detection program]

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RAIDER-M: Transitioning Space System Knowledge to Terrestrial Remote Sensing

M. Haffner and C. Huffine
Space Systems Development Department

Overview: Terrestrial remote sensing systems and space-based systems face some of the same challenges. Both system classes require high reliability, autonomous operation, and remote management capability. The Advanced Systems Technology Branch of NRL's Space Systems Development Department has transitioned space system knowledge to a shipboard remote sensing platform, the RAIDER-M system. High-reliability design principles and rigorous component testing have allowed RAIDER-M to achieve continuous operation and reliable sensing and data reporting since deployment in the harsh environment at sea. Remote management principles used in space-based systems have been applied to the RAIDER-M design and have allowed the NRL team to push software updates improving the remote sensing capabilities without the need to have physical access to the fielded units.

Design for Reliability: The RAIDER-M project consists of a number of remote sensing nodes that relay data through the Iridium satellite network. Reliability was a prime consideration in designing the system, as a significant percentage of the lifecycle costs could be servicing of the deployed sensor units. Most units are deployed on ships at sea and we have only short windows of opportunity to gain access to them once installed. With some vessels based outside the continental United States (OCONUS), servicing the units can be expensive. Also, RAIDER-M sensing units endure environmental extremes — arctic to Saharan temperatures, hurricanes, inches of ice accumulation, and the ever-present corrosive marine environment. Figure 9 shows an installed unit.

FIGURE 9
An installed RAIDER-M unit.

RAIDER-M units are constructed of all commercial off-the-shelf (COTS) components with a single-board ARM computer running Linux at the heart. To maintain operation in the field, the system is designed with a power-reset capability for all sensor and communication interfaces. The processor monitors data flow through the system and, if a problem is detected, has the ability to cycle power to any of the components. A watchdog timer capable of initiating a system reset in the event of a processor lockup also supervises the processor. Finally, there is a scheduled reboot of the system every 24 hours.

The Linux operating system running on an ARM processor provided a well-maintained and stable base upon which we were able to quickly build a remote sensing platform. The system boots into a read-only file system stored on a secure digital (SD) card. A secondary copy of the file system is stored in on-board flash. If the primary file system is not bootable for any reason, the processor automatically boots from the secondary copy.

Components were selected based on their temperature range and power consumption specifications. Some components, most notably the Iridium modems, had limited options available that met our basic performance requirements. Many critical components underwent environmental testing to ensure they would operate over the range of extremes we expected to encounter.

All components are mounted in a watertight box constructed of marine grade stainless steel, and penetrations are limited to only environmentally sealed connectors or indicators. Penetrations are on the bottom of the unit to lessen the chance of water infiltration assisted by gravity. The units themselves are mounted to “marine board,” a noncorroding, nonrotting polymer that comes in sheets similar to plywood. A lesson learned after the initial deployment was that the relatively low reflectance of the stainless steel led to high temperatures inside the unit in warm locations, so an aluminum sunshade was designed for the enclosure to help maintain an acceptable internal temperature.

The resulting RAIDER-M units have low recurring engineering (RE) cost, with the Iridium modem being about 25% of the per-unit cost. Typical power consumption is approximately 10 W.

Software and Remote Management: While the RAIDER-M units operate autonomously in the field, they employ a remote management interface similar to that developed for satellite and aviation payloads. The RAIDER-M software is based around a Linux kernel running on the embedded single-board computer. We continued the UNIX development paradigm of implementing system functionality as small, single-purpose utility programs. We connect these small programs into a complete system through scripts written in bash shell. Embedded Linux systems with functionality built around shell scripting and these small utilities have been implemented in several other programs such as TacSat, GLADIS, Copperfield-2, and SRP.

The modular architecture provided by the bash script approach has several advantages. One advantage is the ability to easily apply the utilities to multiple portions of the overall system. If a program is written to send and receive data over a network socket, any portion of the system needing to access network sockets can use the same executable. In fact, we are able to use many of the same simple utilities developed in previous programs by simply compiling them for RAIDER-M’s

ARM architecture with no changes required in the underlying code.

Also, the use of a scripting environment allows reconfiguration of system functionality through a simple and reliable procedure. The RAIDER-M communication protocol allows us to upload and execute a script remotely. Since much of the functionality of RAIDER-M is implemented in scripts rather than large binary files, we are able to change system performance or apply bug fixes by sending small text files with new command logic. This is especially important in systems where high reliability is required and the data link bandwidth is low. The Iridium data link provides a link rate of 2.4 kbps data transfer; realistically, after protocols and packaging overhead, a 1 kbps rate is more typical.

A key to managing the "network" of the sensors is having a way to understand the health and status of individual units and the entire constellation at a single glance. A "dashboard" was developed to collect telemetry information and display it to the engineers (Fig. 10). Coupling that information with other tools such as Google Earth, LaTeX, and Gnuplot allows for instantaneous situational awareness and daily production reports. The constellation operates nearly 24/7 "lights-out" from a command and control and operations perspective.

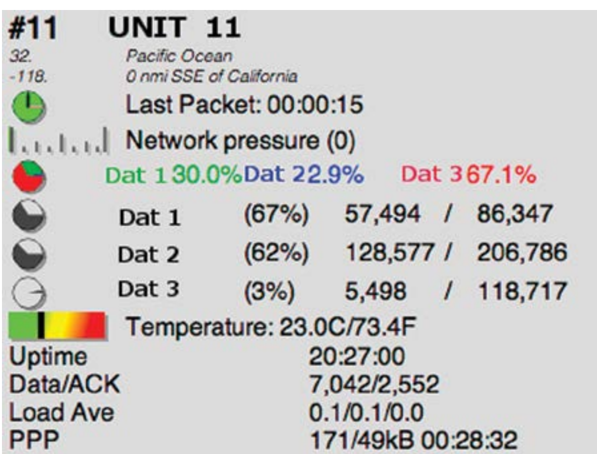

FIGURE 10
Unit dashboard display.

Summary: We have deployed approximately 16 RAIDER-M units across the globe. Several units have been operating autonomously for months and we have been able to apply software updates to fielded units remotely. The application of technology developed for high-reliability, reconfigurable space platforms has allowed us to rapidly create a reliable and reconfigurable terrestrial remote sensing system.

Acknowledgments: The authors would like to acknowledge RAIDER-M development team members Craig Wilson for layout and construction of the sensing units, Linda Summers for building all our RF cables, Brian Micek, consultant, for his work on the software system and communications protocols, and Dan Lizotte, consultant, for his help with installations.

[Sponsored by Navy TENCAP]

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Morphing Satellite Reflector Antennas Using Tensegrity Structures

A. McKenna
Spacecraft Engineering Department

Introduction and Motivation: With the arrival of new communications and antenna technologies in the past few decades, requirements for antennas on Department of Defense satellites have increased in both complexity and scope. Modern military satellites may have extended lifetimes and require flexibility to fulfill ever-changing mission needs. A mechanically reconfigurable reflector would provide advanced beam forming and steering capabilities, which can increase or extend the usefulness of a satellite throughout its lifetime, as well as allow a single satellite design to be launched at different orbital locations. The design of the morphing reflector described here makes use of a unique lightweight structural configuration called tensegrity.[1]

Tensegrity Structures Background: Tensegrity provides a unique approach to reducing weight. A tensegrity structure arranges the members in a specific geometric configuration to eliminate many typically found structural forces and to ensure that specific members remain in tension throughout a well-defined set of loading conditions. Replacing these tensional components ("strings") with wires or cables greatly reduces weight.

One type of tensegrity unit that lends itself well to larger structure construction is the tensegrity prism, a three-bar example of which is shown in Fig. 11. Composed of three struts along with top and bottom polygons that are connected by strings, the tensegrity prism is one of the most stable units of tensegrity. Additionally, it can be modified to overcome one of tensegrity's weakest elements, torsional force. The left image of Fig. 11 shows a minimal tensegrity prism, with the fewest number of strings needed for stability. The right image shows a nonminimal prism, with three extra strings for

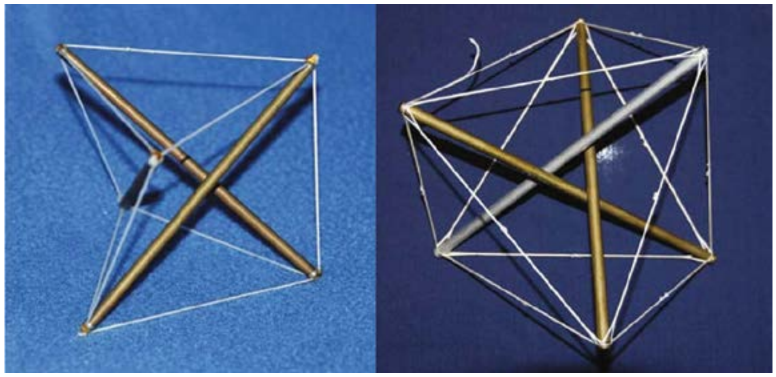

FIGURE 11
An example of three-bar tensegrity prisms. The left image is a three-bar minimal tensegrity prism with only nine strings, while the right has three additional strings to increase both tensional/compressive and torsional stiffness. Both structures are stable.

added stiffness. Increasing the prestress in the members will also increase the stiffness and the load capacity.

Tensegrity can be lightweight while still maintaining high strength. Also, morphing can take place by actuating the structure itself — the strings. Finally, tensegrity is a self-stabilizing structure, i.e., the structure will self-adjust its framework given a change in stress or length in one of the members. As long as the forces on the structure itself allow for a proper redistribution of internal forces so that all strings remain in tension, the structure will be stable.

Circular Multi-Cellular Tensegrity Antenna: The proposed concept of the morphing reflector makes use of six-bar tensegrity prisms arranged in concentric rings outward from a central point. This arrangement of cells is termed Circular Multi-Cellular Tensegrity (CMCT). A CMCT reflector antenna has several advantages. First, it is easily scalable, both by increasing string and strut lengths and by adding another ring of cells. Second, since it is composed of tensegrity units, shape changes can be created merely by changing the string lengths, which is a tremendous advantage over traditional morphing mechanisms, as only a linear wire actuator is needed. Additional research will investigate the possibility of using smart materials as the strings, allowing the structure to self-actuate. The CMCT structure creates control points at the ends of the struts and along the strings. A reflective antenna mesh attaches to these control points, creating a reconfigurable surface for beam shaping and steering.

Feasibility Results: With the goal of investigating the feasibility of constructing such a CMCT antenna and having it morph, NRL developed a program to calculate possible geometries. The equilibrium condition of tensegrity structures is subject to a form-finding problem in which an achievable configuration is found. Using the properties of tensegrity prisms and the constraints of CMCT, the program searches for solutions of CMCT structures that could be suitable for reflector antennas.

The f/D ratio, which relates the focal length (f) to the antenna diameter (D), is an important variable in reflector antennas and plays a part in both design roles, such as focusing the antenna on a specific area of interest, and performance roles, such as increasing efficiency and decreasing polarization and sidelobes. The program was used to see if it was possible for a CMCT antenna to morph through a typical range of f/D values.

As Fig. 12 shows, stable and geometrically valid configurations for each ratio were found to be feasible. The conclusion is that mathematically, a tensegrity reflector antenna can morph through a series of stages to achieve a reasonable f/D range and fulfill multiple mission parameters. There are no morphing reflectors in orbit today, and none are being developed outside of NRL with this novel concept. Current usage of array-fed reflectors has disadvantages that could be eliminated or greatly reduced by the application of this morphing reflector.

[Sponsored by the NRL Base Program (CNR funded)]

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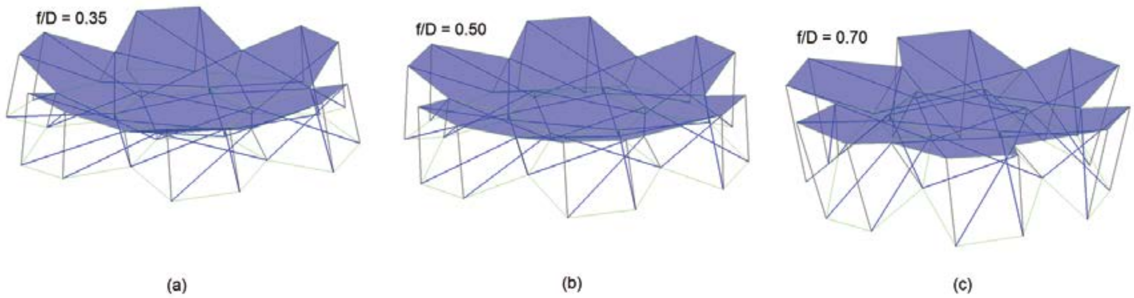

FIGURE 12
Morphing output over varying f/D ratios. Note that surfaces between control points are shown as planar, but in a finalized design would be a reflective, nonplanar mesh.

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