Multipoint In-Situ Radiation and Plasma Sensing System (MIRPSS)

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ABSTRACT

To ensure the safety of human explorers as well as the health and productivity of robotic systems both in Earth orbit and beyond, it is important to understand and predict the space plasma and radiation-belt particle dynamics in the Earth’s ionosphere and magnetosphere. Increased scientific understanding of how the Earth’s ionosphere and magnetosphere respond to changes due to solar variability will enhance our ability to provide forecasts and “nowcasts” of space weather. To this end, TUI and Penn State are developing a nanosatellite mission concept that utilizes a constellation of CubeSat-class satellites containing in situ radiation, plasma, and magnetic field sensors to produce simultaneous multi-point measurements of the radiation and space plasma environment. Each spacecraft will contain a hybrid plasma probe (comprised of a combination of a Langmuir and plasma frequency probe), total radiation dose and dose rate dosimeters covering a range of populations, and a magnetometer. Real-time measurements from a constellation of these nanosatellites in the regions of interest would allow simultaneous, system-wide measurements that would help resolve space–time ambiguities in existing radiation and space plasma data sets.

INTRODUCTION

In October 2005, a workshop was held on the solar system radiation environment and how it impacts NASA’s Vision for Space Exploration. Among the findings of the workshop was the following:

“Astronauts and spacecraft participating in the [Vision for Space Exploration] will be exposed to a hazardous radiation environment, made up of galactic cosmic radiation and driven by solar energetic particle events and ‘space weather’ changes. Accurate and timely information about this environment is required in order to plan, design, and execute human exploration missions. The information required consists of estimates or measurements of the time of occurrence, duration, and spatial distribution of the radiation, as well as the type, maximum intensity, and maximum energy of the constituent particles. Unfortunately, the prediction and forecasting of solar activity and space weather are severely hampered by a lack of understanding of how the Sun affects the heliosphere and planetary environments of Earth, the Moon, and Mars. Scientific progress in this field, leading to accurate long-term and short-term predictions of the space radiation environment, is required if solar and space physics scientists are to make the significant contribution required of them by human exploration missions.”

It is clear that, in order to ensure the safety of human explorers as well as the health and productivity of robotic systems both in Earth orbit and beyond, it is important to measure and monitor the space plasma and radiation-belt particle dynamics in the Earth’s ionosphere and magnetosphere. Increased scientific understanding of how the Earth’s ionosphere and magnetosphere respond to changes due to solar variability will enhance our ability to provide forecasts and “nowcasts” of space weather.

To this end, Tethers Unlimited, Inc. (TUI) and The Pennsylvania State University (Penn State) are developing a nanosatellite mission concept that utilizes a constellation of CubeSat-class satellites containing in-situ radiation, plasma, and magnetic field sensors to produce simultaneous multi-point measurements of the radiation and space plasma environment. Each nanosatellite will contain a hybrid plasma probe (comprised of a combination of a Langmuir and plasma frequency probe), total radiation dose and dose rate dosimeters covering a range of populations, and a magnetometer. Real-time measurements from a
constellation of these nanosatellites—the Multipoint In-situ Radiation and Plasma Sensing System (MIRPSS)—in the regions of interest would allow simultaneous, system-wide measurements that would help resolve existing space–time ambiguities in existing radiation and space plasma data sets.

Recently, the U.S. National Science Foundation (NSF) held a workshop to explore the use of small satellites for space weather and atmospheric research. This workshop was in response to a key recommendation in the recent report by the Assessment Committee for the National Space Weather Program (NSWP), which was for NSWP agencies to investigate immediately the feasibility of using micro-satellites with miniaturized sensors to provide cost-effective science and operational data sources for space weather applications. In response, NSF’s Division of Atmospheric Sciences organized the workshop to explore the possibilities and benefits of utilizing small satellite missions to provide essential measurements for space weather and atmospheric research. What was clear from the workshop was the small satellite missions indeed can provide this important data.

The data generated from a constellation of nanosatellites with plasma and energetic-particle sensors will allow scientists to incorporate simultaneous multi-point measurements and improve existing radiation and space plasma models and forecasting tools. The radiation environment imposes constraints on all proposed human and robotic Exploration Missions, and unknowns in the current and future radiation environment and its effects lead to increased risk as well as reduction of mission capability as overly conservative approaches are implemented. Improved fundamental knowledge of the space environment and its effects will allow scientists and engineers to reduce the risk to astronauts and spacecraft through hardware design and mission operation constraints, and maximize the return from planned Exploration Missions. This mission concept will measure the current state of the environments with high temporal and spatial resolution, leading to improved models and forecasts.

In addition, measurements from such missions would feed into models that would generate space weather forecasts beneficial to users of GPS signals for positioning and targeting, and users of high frequency (HF) communication equipment.

BACKGROUND

In addition to the needs of the Vision for Space Exploration, NASA’s Sun–Earth Connection (SEC) Division has on its roadmap a requirement of new “miniaturized in situ instrumentation technologies,” characterized by reduced “mass, power, and volume consistent with achieving science goals while enabling deployment on nanosatellite constellations or microsatellites.” The SEC program further states the need for “…miniaturized in situ instruments for making measurements of particles and fields in the immediate vicinity of the spacecraft.”

Large, monolithic scientific satellites, such as the Earth Orbiting Satellite (EOS), are very expensive to build, launch, and maintain. In addition, the deployment of these complex systems is risky, because if something fails on the satellite, it has the potential of halting or ending the entire mission. Of course, this potential for failure can be overcome by extensive testing and redundancy, which increases the overall cost of the program. On the other side of this complexity scale lie distributed sensor systems whose elements are nanosatellites and nanosatellite clusters. Along with inherent redundancy, an array of sensors can collect data from a much larger area than a single, monolithic satellite. Unfortunately, the current state of the nanosatellite industry is such that there are very few off-the-shelf components ready for use. There is a need for novel, small, lightweight, low-power in situ plasma and radiation diagnostic instruments. In addition, deployment of satellite “constellations” necessitates that each satellite also be inexpensive, lightweight, and small, since many will need to be released from a single launch vehicle for the mission to be cost-effective.

CubeSat Form Factor

The development of satellites, spacecraft subsystems, and components is still dominated by the launch problem—the availability of frequent, low-cost launch opportunities. Often, spacecraft developers target secondary launch opportunities for their experiments and technology demonstrators, and a number of nanosatellite payload standards have evolved. One of the most popular and prevalent platforms is that of the CubeSat, a 10×10×10 cm spacecraft with mass of no more than 1 kilogram (Figure 1). This standard is quite interesting in that there is at least one launch opportunity per year for CubeSats as coordinated by California Polytechnic University at San Luis Obispo at a current cost of around US$40,000 per CubeSat. While this is not cost competitive with other launch vehicles on a per kilogram basis, the charge includes integration, licensing, and launch costs.

Market surveys performed by TUI have shown that the availability of component subsystems for this size class of satellite is very limited and, more often than not, requires custom hardware development. Literature surveys and discussions with other CubeSat developers have led us to conclude that this is a problem faced by
many nanosatellite developers. Nevertheless, if one does develop a CubeSat, it can currently be launched within a year of its completion, with launch availability increasing as additional launch vehicles support integration of CubeSat deployers. The low cost of launch and readily available launches make the CubeSat form factor desirable as a nanosatellite constellation platform.

**Operationally Responsive Space**

In recent years, interest in the idea of “responsive space” has grown as it becomes clear that mission needs are not always known years in advance. Classically, space technologies and satellites require long development times and deployment cycles. By developing general and flexible technologies that can be used with little or no modification in a multitude of different applications, the time required to execute space missions can be drastically reduced.

The Secretary of Defense’s Office of Force Transformation (OFT) has begun to push the concept of “Operationally Responsive Space,” which starts with the operational need, e.g., reconstitution of space capabilities, or the ability to gain space situational awareness over a theater. The payload is then pulled off a shelf, designed, and/or built to meet the need and launched into an orbit for maximum theater capability within operational planning time constraints. In other words, the mission may not always be known a priori, yet a spacecraft or constellation must be launched to meet an operational need within the timeframe of the need. This means that standard hardware must be available and quickly configured to meet that specific need. Table 1 provides a listing of standardized hardware that would fit together as decks within a CubeSat. Satellites to support new missions could be quickly configured and flown to meet operational needs.

**PROPOSED TECHNOLOGY**

We are developing a nanosatellite concept with a suite of plasma and radiation diagnostic sensors produced as “decks” for CubeSats or other nanosatellites that are extremely capable, yet small, lightweight, and low power. While not constraining this system to work exclusively with CubeSats, the CubeSat architecture currently offers a standardized platform with not only a launch history, but also a schedule of future launches for the foreseeable future. In addition, CubeSats are packaged in such a way that a technology demonstrator mission of three CubeSats could be accomplished at relatively modest cost (see Figure 1 left) due to their ability to be launched from a P-POD. The MIRPSS sensor package will miniaturize and integrate a Langmuir probe with a plasma frequency probe to create a Hybrid Plasma Probe (HPP), and combine that with a radiation environment sensor to form a small, low cost, standardized sensor package that can be integrated into multiple nanosatellites to enable real-time monitoring of the global space environment.

**Langmuir Probe**

The standard *in situ* instrument for measuring the plasma environment is the Langmuir probe (LP), which has flown many times over the years in various configurations on both satellites and sounding rocket payloads. A complete LP instrument consists of a probe immersed in plasma, a voltage source that sweeps the voltage over a bipolar range, and a current sensor that measures the current as a function of applied voltage. By analyzing the resulting current-vs.-voltage profile, a measurement of electron density, electron temperature, ion density, plasma potential and spacecraft floating potential can be made. The MIRPSS LP instrument would utilize a cylindrical

<table>
<thead>
<tr>
<th>Component and Function</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Power Supply/Conditioning</td>
<td>Including solar cells, which would mount on sides of CubeSat</td>
</tr>
<tr>
<td>Command and Data Handling</td>
<td>FPGA or microprocessor based</td>
</tr>
<tr>
<td>Communications</td>
<td>2.4-GHz ISM band packet modems have been flight proven on CubeSats</td>
</tr>
<tr>
<td>GPS</td>
<td>Position updates</td>
</tr>
<tr>
<td>Housekeeping Sensors</td>
<td>Flexible in configuration depending on mission needs and other decks configured</td>
</tr>
<tr>
<td>Measurement/Science</td>
<td>MIRPSS would include HPP, Radiation, and Magnetometer in single deck</td>
</tr>
<tr>
<td>Tether Module</td>
<td>For connecting multiple nanosats, 100s–1000s of meters</td>
</tr>
<tr>
<td>Expansion Decks</td>
<td>To meet new and evolving mission needs</td>
</tr>
</tbody>
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**Figure 1:** Deployer That Holds 3 CubeSats (Left), And a Representative CubeSat (Right)
probe mounted at the end of an equipotential triaxial boom that is used to minimize the field discontinuities near the probe’s end. To maximize the accuracy of the electron temperature measurement, the probe needs to have a very uniform work function. Rhenium deposited by a chemical vapor deposition (CVD) process exhibits a very high degree of crystal orientation and work function uniformity. The electronics package for this instrument would consist of a digitally controlled voltage source and a floating electrometer with sensitivities in the picoampere range. The components of the LP and, in particular, the probe tip and boom arrangement would be adapted to suit the small scale of CubeSat spacecraft.

While the LP can measure ion and electron densities, as well as electron temperature, the technique is limited in accuracy as well as temporal (and hence spatial) resolution on a moving platform due to finite (> 10–100s of milliseconds) sweep times. Although not used as much as the LP, the plasma frequency probe (PFP) is a technique that can provide fast (and hence high spatial resolution) measurements of the absolute electron density of plasma.

**Plasma Frequency Probe**

The plasma frequency probe is a newer and less commonly used instrument that uses radio frequencies, usually in the low megahertz range, to excite the plasma and then measure the response. This instrument fundamentally measures the impedance of a sensor head immersed in plasma, which exhibits a strong resonance at the plasma’s upper hybrid plasma frequency. By tracking the phase difference between the applied RF voltage and the current returning from the plasma, a precise measurement of the upper hybrid frequency can be obtained. As long as the magnitude of the ambient magnetic field is known, a measurement of the electron density with an accuracy of 1–2% can be readily obtained as compared to the swept LP technique, which has accuracy typically in the 10–20% range. This type of instrument has been built and tested at Penn State for a number of years and has been involved in a number of ground-based projects and sounding rocket campaigns. To maximize the accuracy of the plasma resonance probe, a magnetometer will also be integrated into the spacecraft.

**MIRPSS Hybrid Plasma Probe**

MIRPSS will use a hybrid plasma probe (HPP) comprising a combination Langmuir (LP) and plasma frequency probe (PFP). In addition, the circuit topology developed will allow the HPP also to be used as a biased probe (BP) and as a fast temperature probe (FTP). There are two primary motivations behind the development of the hybrid plasma probe. The first is that, as enumerated below, there are many interesting unanswered science questions that this new instrument could help to answer if included as part of future nanosatellite constellation missions. The second motivation is that technology has advanced to the point that we can capitalize on many of the recent advances in semiconductors and RF communication systems to develop such a probe within the constraints of inexpensive, small size, low power, and low mass.

A prototype hybrid plasma probe design is currently under development at Penn State. A prototype of the HPP has been developed that is an integration of PFP and LP systems. These systems were designed with the intent of sharing components such as the microcontroller, electrometer, and sensor head. The sensor head that was constructed to work with the PFP system for the LionSat® nanosatellite mission (30 kg, 18.5×18.5 in total envelope) could be optimized for the CubeSat footprint, which will require some type of boom deployment mechanism. The electronics will also need to continue to be shrunk in size and power (currently approx. 4×8 in.), but the goal of ~100 g, ~1 W is realistic because the HPP can achieve minimum power draw, mass, and volume due to the sharing of many components.

![Figure 2: Temporal and Spatial Scale of Ionospheric Phenomena](image)

One of the driving forces behind the development of the new generation HPP is the recognition that many of the physical processes that are occurring in ionosphere, thermosphere, and mesosphere (ITM) regions operate on very small spatial and time scales. Remote sensing techniques such as radiowave scintillation and radar sounding can provide only indirect evidence of the presence of such small-scale variations. Hence, in situ measurements are the only way to determine the fine
structure that fully defines the underlying physics. Unfortunately, in situ techniques dictate that these regions be sampled from very rapidly moving platforms. A probe, such as the HPP that can be placed in different modes, would allow a broad range of investigations of geophysical conditions that occur on very short time/spatial scales that are still not well understood (Figure 2).

**Radiation Environment Sensor**

To monitor the radiation environment, we are investigating a dosimetry technique that offers significant mass, volume, and cost advantages over more sophisticated dosimeters. This approach utilizes multiple solid-state p–i–n silicon photodiodes with guard rings mounted behind aluminum shields of varying thickness that act as energy level filters. For example, the CEASE instrument package had two independent total radiation dose and dose rate sensors that had 0.20 cm and 0.63 cm aluminum planar shields, which corresponded to an energy threshold of 20 and 35 MeV for protons, and 1 and 2.5 MeV for electrons. When an energetic charged particle passes through the shielding and through the intrinsic silicon volume, an electron–hole pair is generated for every 3.6 eV of deposited kinetic energy. The photodiode is biased in such a way as to collect the holes and electrons, causing a small current to flow. The integrated measurement of this current, therefore, is proportional to the total energy deposited by particles, from which total dose and dose rate can be computed. A measurement technique used successfully on previous space missions that allows differentiation between proton and electron flux could also be used with MIRPSS. The miniature dosimeter based on this approach would require selecting an appropriate number and thicknesses of aluminum shields, which would provide a total dose and dose rate dosimeter in the energy bands of interest.

**MISSION DESIGN**

A current emphasis in the NASA community is to think about a “sciencecraft,” where the science experiments and bus are fully integrated. Using this approach for nanosatellites makes the most efficient use of both the mechanical structure and the electrical systems. For the MIRPSS mission we must design the science goals so that they do not require three-axis stabilization of the platform, thereby avoiding much of the associated cost and complexity. As an example, the HPP boom and sensor can be configured in such a way as to allow the spacecraft to become gravity-gradient stabilized. Similarly, it is possible to have two dosimeter stack elements on opposite sides of the spacecraft to allow the dosimeters to have omnidirectional coverage.

For the mission design, one can consider both primary and secondary payload launch opportunities. If one were to target a primary launch opportunity, then many, many elements of a constellation can be launched simultaneously since a single P-POD with three CubeSats has a total mass of 5 kilograms. With this launch method, specific desired orbits can be obtained. Another mission design simply can rely on secondary payload opportunities, launching fewer satellites, to orbits chosen by the primary payload operators. In this fashion, it is possible to launch clusters of MIRPSS nanosatellites into more varied orbits.

**Figure 3: Affordable Nanosatellite Constellation for Simultaneous Multipoint Measurement Capability: Sampling Ionosphere and Radiation Belts**

To simultaneously measure both temporal and spatial features of the Earth’s ionosphere and magnetosphere, multiple spacecraft are required. The small size and relatively simple designs of the instruments and spacecraft make the system amenable to manufacturing and testing on a larger scale. In addition, by having a large constellation, the system is inherently redundant, which reduces the reliability requirements of each individual spacecraft, as fault tolerance is achieved not through redundant subsystems, but additional spacecraft. In Figure 3, we see a notional constellation of MIRPSS spacecraft placed into high inclination circular orbits allowing the system to sample much of the ionosphere and radiation belts. Based on the desired latitude and altitudes one would like to sample, the constellation’s design may utilize elliptical orbits to allow a range of altitudes to be scanned. In addition, multiple MIRPSS spacecraft may be tethered together (Figure 4) with tether lengths ranging from hundreds of meters to multiple kilometers, to permit in situ studies.
of localized plasma depletions (also known as plasma bubbles), a phenomenon known to cause satellite communication disruptions.

**Figure 4: Simultaneous Multipoint Measurement Capability: Tethered Nanosatellites**

**SUMMARY**

This paper is not meant to be an exhaustive description of the proposed MIRPSS system, but to indicate the type of missions and data products that would be enabled by MIRPSS and derivatives, i.e., using the proposed decks in new configurations to meet operational needs.

Nanosatellites need miniaturized in situ instrumentation technologies characterized by reduced mass, power, and volume consistent with achieving science goals while enabling deployment on constellations of nanosatellites. We have developed a mission concept that will employ state-of-the-art autonomous plasma and radiation sensors that have been miniaturized into a package for a nanosat platform to produce multipoint in situ measurements with high temporal and spatial resolution. This package will be one of a number of “decks” to be combined together to build up nanosatellites for constellation missions that can make multipoint measurements.

The instrument packages and spacecraft could be produced in an assembly line high volume (100s) fashion allowing for cost savings due to the economies of scale. With a high number of sampling nodes, reliability is achieved through redundancy, as compared to extensive and expensive component engineering, further keeping system costs in check.

**REFERENCES**

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