THE HYBIRD PLASMA PROBE: A UNIQUE COMBINATION FOR PLASMA PROBES FOR *IN SITU* SPACE ENVIRONMENT CHARACTERIZATION

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ABSTRACT

The Hybrid Plasma Probe (HPP), currently under development at Penn State, is a combination of a Fixed-Bias Langmuir Probe (FBLP), Swept-Bias Langmuir Probe (SBLP), Plasma Frequency Probe (PFP), and Fast Temperature Probe (FTP). The HPP implementation allows the four instruments to share common resources, thereby optimizing power, mass, and volume resources. Another rationale for the HPP instrument is that these four instrumental modes are capable of making different and complementary *in situ* plasma measurements and with tradeoffs in accuracy and spatial/temporal resolution. The SBLP mode provides several plasma characteristics with high accuracy but with lower temporal resolution. In contrast, the FBLP and PFP modes can provide very fast measurements of only density, but with less accuracy. Thus, the various instrument modes can be employed to allow the instrument to perform a range of missions. Furthermore, the inclusion of HPPs on multiple, coordinated small satellite missions (e.g., CubeSats) would provide an efficient method for understanding temporal and spatial variations in the ionosphere. The capability of collaboration with ground-based measurements further enhances the science return from the HPP and our understanding of the effects of space weather.

1. INTRODUCTION

Penn State's Student Space Programs Laboratory (SSPL) is developing a CubeSat- based instrument for the study of the Earth's ionosphere. The instrument, called a Hybrid Plasma Probe (HPP), is baselined as the primary instrument for the OSIRIS mission concept, discussed in Section 5 below.

The development of the HPP is a direct response to the growing interest in and need for more detailed data on space weather and the effects of space weather on the Earth's ionosphere. Space weather can affect many systems on which society relies including communications, the Global Positioning System (GPS), and power grids. These effects drive the interest in understanding the relationship between solar activity and the response of the ionosphere.

To better understand these interactions, it is necessary to gather data from many points and a large variety of data on the local plasma environment. Many sampling points are required to distinguish if structures seen in the data are spatial or temporal in nature, and the variety of data provides a trade off between spatial and temporal resolutions. This has driven the design of the HPP, a combination of four plasma probes:

- Fixed-Bias Langmuir Probe (FBLP)
- Swept-Bias Langmuir Probe (SBLP)
- Plasma Frequency Probe (PFP)
- Fast Temperature Probe (FTP)

Combining these probes provides a unique benefit to mission designers and the scientific community, as discussed below.

If flown individually, each instrument would require redundant hardware components. **Error! Reference source not found.** shows that elements such as the controller and physical probe are duplicated in all instruments, whereas the voltage source is present in the FBLP, SBLP, and FTP; frequency sources in the FPF and FTP; and current sensors in both Langmuir probes.

If the instruments are combined into a single package, these common components can be shared. Sharing components ultimately saves valuable spacecraft resources such as power, mass, and volume

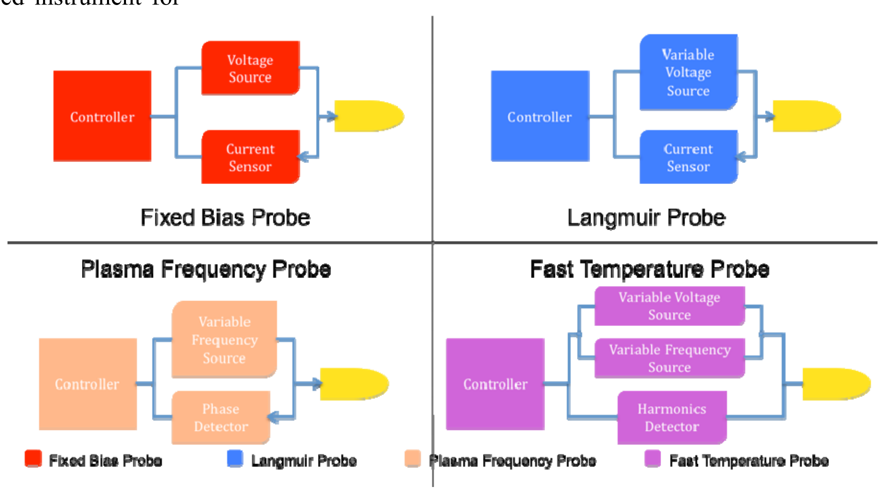

Figure 1: Individual Probe Architectures

Proc. '19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Bad Reichenhall, Germany, 7–11 June 2009 (ESA SP-671, September 2009)

Table 1: Summary of Projected HPP Capabilities by Mode

	SBLP	FBLP	PFP	FTP
Temporal Resolution	4 Hz	5 kHz	5 kHz	10 Hz
Absolute N_e	1×10^9–5×10^{12}m^{-3}		1×10^9–1×10^{13}m^{-3}	—
Abs. N_e Accuracy	15%	—	1.50%	—
$\Delta N_e/N_e$	—	0.60%	—	—
Electron Temp.	—	—	—	300–5000 K

with the added benefit that the combined HPP can be switched between the different instrument modes offering the flexibility to take targeted measurements.

2. INSTRUMENTATION OVERVIEW

Langmuir probes (LPs) have flown more than 50 times on sounding rocket missions developed by Penn State faculty in the Communications and Space Systems Laboratory (CSSL) and students within SSPL. The LPs developed at Penn State fall into two categories: (1) fixed-bias (FBLP) and (2) swept-bias (SBLP). Both probes operate similarly in that a bias voltage is applied to a probe submerged in a plasma environment and the return current is measured. With the FBLP, this bias voltage is fixed, whereas with the SBLP, the probe is swept through a range of voltages. The addition of a swept bias allows direct measurement of the spacecraft potential by identifying the inflection point in the returned data as seen in Figure 2 [1].

The PFP is an impedance probe that operates by measuring the change in the impedance of a probe immersed in the local plasma environment when an RF signal is applied. This probe can operate in two manners: (1) a sweeping mode in which the PFP sweeps the entire frequency spectrum or block of frequencies

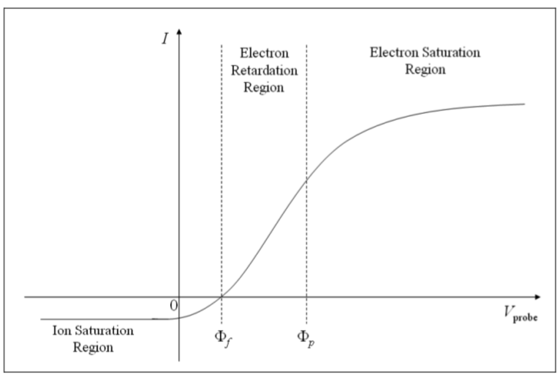

Figure 2: Example Current–Voltage Relationship

and (2) a resonant frequency–tracking mode, in which the instrument tracks the point where the energy supplied to the probe is maximally absorbed by the environment [3].

The FTP is an instrument that applies a small sinusoidal signal to an LP biased in the electron retardation region, i.e., the region between the plasma potential and the instrument floating potential, as shown in Figure 2. Sampling and analysis of the return signal give the electron temperature by calculating the ratio between the first and second signal harmonics [2].

The projected capabilities of the HPP in these instrument modes are presented in Table 1***: Summary of Projected HPP Capabilities by Mode***.

3. PLASMA MODEL

To understand the HPP's interaction with the local plasma environment, a model of the probe–plasma system is being developed. By modeling conditions likely to be seen on an instrument during flight, such a model gives both instrument and mission designers the ability to make trade studies on performance and functionality, as well as to interpret returned data.

Given the nature of the HPP and its individual instrument modes, it is appropriate to model each instrument mode individually. The early work, shown here, has focused on the PFP model. The additional modes will be included as the model matures.

The PFP model can be broken into three main portions: plasma, probe, and stimulation and detection that are modeled using MATLAB Simulink. Simulink provides toolboxes and predefined functions, making models easier to create and easier to verify. This, coupled with its ability to handle inputs from external sources like electron density and magnetic field models, makes Simulink an ideal environment to create a model of the instrument's operating environment.

The first step is to model the plasma by representing it in terms of the upper hybrid frequency, ω_{uh} which itself is comprised of the electron collision and cyclotron frequencies, ω_{pe} and ω_{ce}, respectively, via the relationship

$$\omega_{uh} = \sqrt{\omega_{pe}^2 + \omega_{ce}^2}\,. \tag{1}$$

The electron plasma frequency itself is a function of the electron density via the relationship

$$\omega_{pe}^2 = \frac{n_0 q^2}{\varepsilon_0 m_e}, \tag{2}$$

where n_0 is the plasma density, q is the elementary charge magnitude, ε_0 is the permittivity of free space, and m_e is the mass of an electron. Finally, the electron cyclotron frequency is related to the magnetic field strength, B, via

$$\omega_{ce} = \frac{qB}{m_e}. \tag{3}$$

With the relationship now in terms of plasma density and the magnetic field strength, the model can take into account changes in both and predict the response of the PFP.

Similar work has been done for the Langmuir probe with models developed for the swept and fixed bias modes as part of a recent SSPL M.S. thesis [1].

4. DESIGN CONSIDERATIONS

A driving factor in the development of the HPP is the ability to take measurements at very high spatial, and hence temporal, resolutions. Since the target is a satellite platform, the instrument must be capable of sampling upwards of 5 kHz to provide 1.5-m resolution. To ensure that this is met, the time constant must be calculated for each of the instrument modes. The simplest analysis is the Langmuir probe mode, which is presented below.

By calculating the LP's time constant, the maximum theoretical temporal resolution can be determined. This is important to show that the instrument is limited by the electronic back-end rather than probe dynamics. Should data be taken at intervals faster than the rise time of the probe response, the data would be more difficult to process on board the instrument.

The first step is to find the system's time constant. Given that $\tau = RC$ and $V = IR$, we derive the following equation:

$$\tau = V\frac{C}{I}, \tag{4}$$

where τ is the time constant, V is the probe bias voltage, C is the capacitance of the probe itself, and I is the current supplied from the environment. Next, we must solve for the current that will be collected by the Langmuir probe, which is designed to operate in the orbital-motion-limited regime. This is done with the following equation that provides a relationship between the probe area, the electron density, and the probe bias voltage:

$$I_e = An_eq\frac{2}{\sqrt{\pi}}\sqrt{\frac{qV}{2\pi m_e}}, \tag{5}$$

where I_e is the LP current, A the probe area, and V is the probe bias. Finally, substituting I_e in for I in Eqn. 4, the time constant τ is derived. This results in an expression for the time constant that is a function of the collection area, electron density, and probe bias voltage.

Trade studies can now be conducted to determine the optimal characteristics such as probe area, cable length, etc., throughout the development cycle of the instrument itself. Performing these calculations for the HPP shows that the HPP's spatial resolution is limited by the capabilities of the instrument measurement hardware and not the probe geometry itself.

Similar work is being completed for the other instrument modes.

5. INSTRUMENT USAGE EXAMPLE

CubeSats are currently one of the most employed spacecraft buses for student-built satellite projects. The CubeSat spacecraft bus standard was developed by the California Polytechnic State University to be launched as secondary payloads using a deployer they also developed called the P-POD. A CubeSat is a satellite that is 10 × 10 × 10 cm in volume (or multiples thereof). The proliferation of CubeSats has come from their ability to be launched as secondary payloads on just about any mission, enabling a much lower cost access to space, on the order of US$50,000 for a single CubeSat.

This reduction in satellite launch cost can be attributed to the development of the P-POD, a device for both containment and deployment, which provides the interfaces between the launch vehicle and the CubeSat bus. It is this defined interface that is the cornerstone for the success of CubeSat missions. The predefined requirements give launch vehicle providers the confidence necessary to ensure mission success for the launcher's primary mission while still providing the opportunity for CubeSats to be launched.

Recognizing the value of CubeSats, SSPL is developing a mission called the Orbital System for Investigating the Response of the Ionosphere to Stimulation and Space Weather (OSIRIS). This is a mission consisting of a system of satellites that will (1) provide *in situ* measurements of the stimulated (heated) ionosphere produced by ground-based heaters; (2) assist in correlating *in situ* heated ionosphere measurements with ground-based measurements including incoherent scatter radars and ionosondes; and (3) investigate spatial and temporal characteristics of the heated ionosphere by

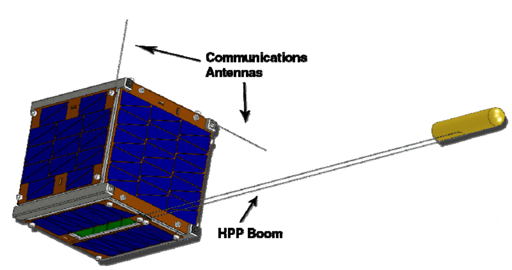

Figure 3. CubeSat Satellite Concept

measuring plasma properties as the satellites gradually separate.

The use of a ground-based heater to artificially simulate the ionosphere provides many advantages over observing only natural phenomena. One of the biggest advantages is that the mission no longer depends on the solar cycle and unpredictable activity to produce measureable events. With the use of a heater, the mission can artificially create a disturbance over a region and measure the ionosphere's response to that disturbance. Another advantage to using an ionospheric heater is that simply varying the output power of the ground transmitter can alter the magnitude of the events. Once again, this releases the mission from reliance on the solar activity alone.

Using multiple probes to make measurements through a region of interest has been used successfully before. The *Cluster* mission uses data gathered data from four satellites flying in a tetrahedral formation at an altitude of 600 km. In this set of data, shown in ***Figure 4***, four satellites register a change in electron density at different times on large scale feature in the magnetosphere. When tracked and plotted on a map, it was found that the times coincided with the satellites reaching a certain location. Therefore, the data describes a spatial, not temporal, feature. This type of measurement is not possible with single satellite because it would be impossible to distinguish between the feature's time and space characteristics: multi-point measurements are the only method to mitigate this ambiguity. OSIRIS will use a slowly separating constellation of three satellites to study similar ionospheric structure.

6. FUTURE WORK

In the coming months, the HPP development effort will continue with bench-top testing and calibration. Models from the individual instruments will also be combined and adapted to the architecture of the HPP.

Pending availability of a sounding rocket opportunity, we are targeting to fly the HPP in late 2010 or early 2011, although the launch opportunity has yet to be identified. Following a successful sounding rocket flight, the HPP will be included in the OSIRIS satellite constellation.

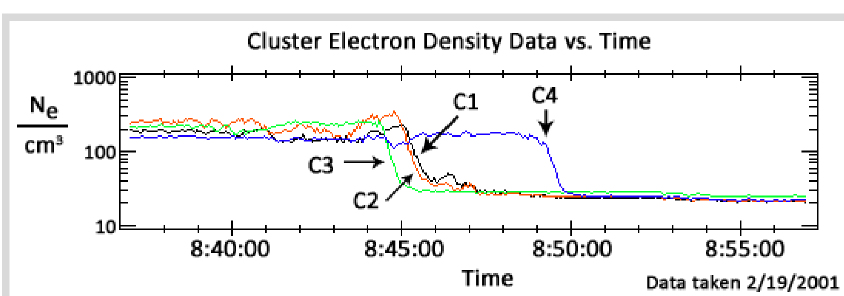

Figure 4. Cluster Electron Density Data [source: A. Fazakerley at MSSL and CSDS].

7. CONCLUSION

The HPP instrument has been under development at Penn State and is maturing in design. Faculty and students at Penn State are looking forward to successful calibration using the resources at SSPL and leading up to a sounding rocket test flight. Future CubeSat-based science opportunities are promising, providing many opportunities for the SSPL-developed HPP.

8. REFERENCES

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