Planar Ion Probe for Low-Latitude Ionosphere/Thermosphere Enhancements in Density (LLITED) CubeSat Mission

Liam Gunter (gunterl@erau.edu)
Embry-Riddle Aeronautical University

Aroh Barjatya (aroh.barjatya@erau.edu)
Embry-Riddle Aeronautical University

Rebecca Bishop (rebecca.l.bishop@aero.org)
The Aerospace Corporation

Abstract

The Low-Latitude Ionosphere/Thermosphere Enhancements in Density (LLITED) CubeSat mission provides simultaneous Ionosphere/Thermosphere (IT) measurements in order to fill the gap present in current Equatorial Temperature and Wind Anomaly (ETWA) data. In-situ ion density measurements are provided by Embry-Riddle's Planar Ion Probe (PIP). PIP is an ultra low Size, Weight, and Power (SWaP) electrometer equipped with a planar Langmuir probe. Its simple fixed-bias system enables low-noise measurements of in-situ ion density without the side effects associated with a sweeping probe. Here we present the LLITED mission overview, PIP design and preliminary noise results.

Introduction

Coupling between Earth's IT regions has recently been observed to be more complex than previously expected. IT interactions in the low-latitude dusk-side manifest through two dominant phenomena: the Equatorial Ionization Anomaly (EIA) and the ETWA, shown in figure 1 and 2 below. The EIA has been extensively observed and modeled, while the ETWA is relatively unknown.

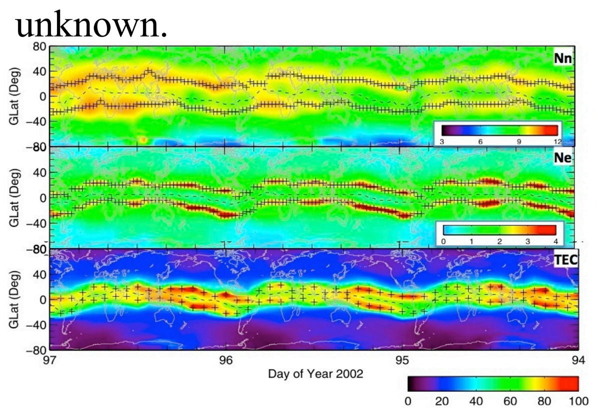

Figure 1: Data from the CHAMP accelerometer (top panel; 10^{-12} kg/m^3), planar Langmuir probe (middle panel; 10^{12} m^{-3}), GPS RO sensor (bottom panel; TECU). Crosses & dashes mark the location of crests & trough, respectively. [adapted from Figures 1, 3, 6 of Lei et al. [2010].

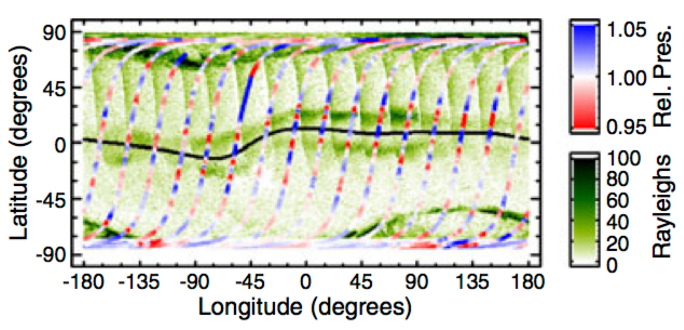

Figure 2: One day (14 October 2005) of measurements of IGS data from STREAK mission superposed on data from the GUVI imager on the TIMED spacecraft [from Clemmons et al., 2013].

The lack of data on the ETWA is due mainly to poor coverage of the region with properly instrumented spacecraft. Specifically, proper ETWA observation should nominally involve both neutral (thermosphere) and plasma (ionosphere) measurements. LLITED intends to be the first mission to collect coincident data pertinent to IT interactions at lower altitudes, expanding the knowledge base regarding the ETWA. The mission will collect neutral density, ion density, and total electron content profiles of the low-latitude IT region.

LLITED is a twin 1.5U CubeSat mission and is expected to be launched in a polar 350 – 450 km orbit in 2019 or 2020. This orbit provides global coverage of low-latitude ETWA regions. Observations of the low-latitude regions necessitate instruments only operate 25 - 45% of the orbital period. The dual satellites travel with 1/4 - 1/2 orbital separation, which allows for temporal observations of ETWA evolution.

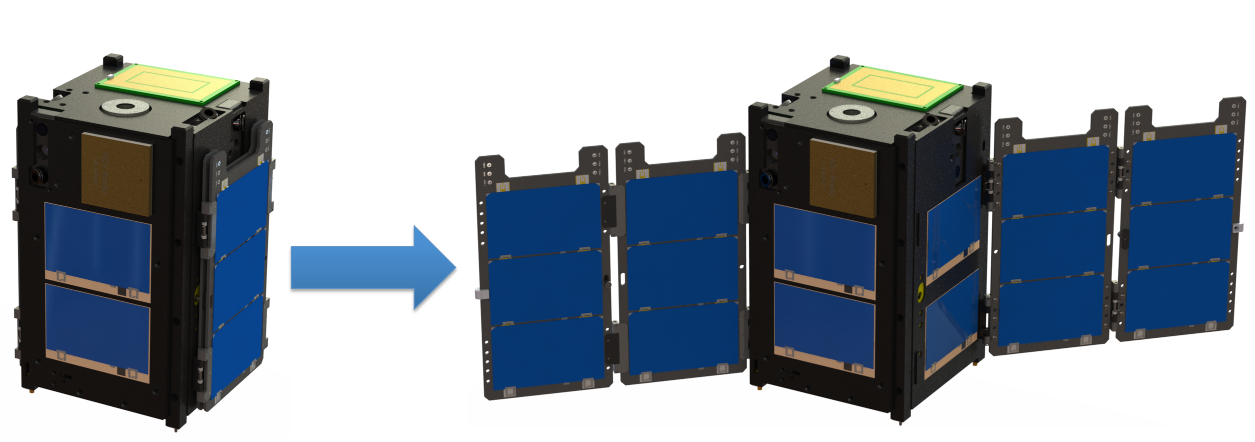

Figure 3. Stowed (left) and deployed (right) configuration of LLITED CubeSat

LLITED Mission

LLITED directly addresses a key science goal from the Heliophysics Decadal Survey: "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." LLITED will characterize and improve our understanding of the ETWA, provide insight into the coupling physics between the ETWA and the EIA, and increase our knowledge of the dusk-side dynamics that may influence space weather. LLITED will make progress towards answering three questions:

1. What is the mesoscale variability of the ETWA as a function of season, and longitude/latitude as well as its relationship to EIA heating?
2. What is the relationship between neutral wind (i.e. tides) and the EIA zonal structure?
3. Are the small-scale wave fluctuation in neutral atmosphere quantities, such as those observed by earlier missions exhibited in the ionospheric density?

LLITED addresses these questions through its suite of three payloads: neutral density measuring ionization gauge sensor MIGSI, total electron content measuring radio occultation sensor CTECS, and ion density measuring PIP. The LLITED CubeSats, MIGSI and CTECS are being built by the Aerospace Corporation, whereas PIP is being provided by Embry-Riddle.

LLITED Traceability Matrix

General Observational Approach	Science Measurement Requirements	Instrument Performance	Limiting Space Systems Requirements
Observations in the 15:00 to 01:00 LT (dusk) sector and over -40° to 55° latitude	In-situ neutral pressure: 15 km resolution 2×10^{-7} to 1×10^{-6} torr	MIGSI: Ionization Gauge: 100 Hz sampling (~80 m res.) 2×10^{-8} to 1×10^{-2} torr	Orbit: Polar, 350-450km, Circular (preferably 400km) Attitude: 3-axis stabilized,
LLITED Product: Background ionosphere density measurements	Plasma Density Profiles: TEC from 100 to 400 km	CTECS-A: GPS RO TEC from 100 to s/c alt.	MIGSI and PIP on ram pointing surface
LLITED Product: Coincident neutral pressure/plasma density	Plasma Density in-track 200 km resolution 10^{12} to 6×10^{12} m^{-3}	PIP: Planar Ion Probe 100 Hz sampling (~80 m res.) 2×10^{9} to 2×10^{13} m^{-3} Resolution: 2×10^{8} m^{-3}	Control: 1° Knowledge: 0.1°
Measurements range: 350– 450 km			On-board Data Storage: >128 MB for 3 sensors

Langmuir Probe Background

Traditionally, in-situ plasma density is determined through the use of sweeping Langmuir probes. Sweeping a voltage bias on an electrode immersed in plasma and measuring the resultant current yields an IV curve from which one can determine electron and ion density, and electron temperature. The IV curve characteristics are dependent on probe geometry, wherein current collected by cylindrical and spherical probes increases with applied potential, and the current collected by planar probes remains flat.

Sweeping Langmuir probes require a ratio of vehicle surface area to probe area of greater than 10,000 to avoid charging the spacecraft with every sweep. Thus, fixed bias probes are much preferred for small spacecraft such as a CubeSat.

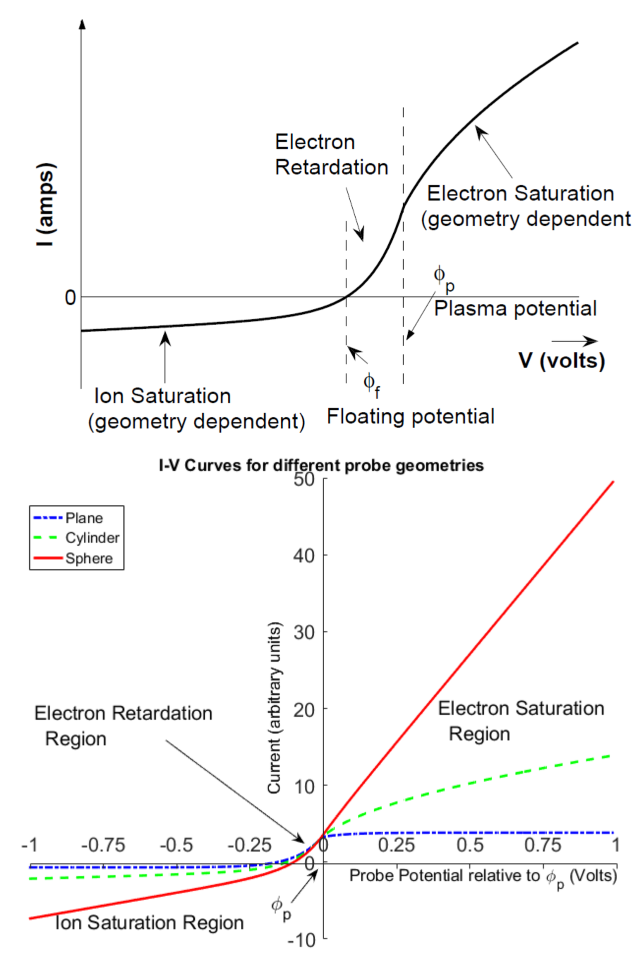

Figure 4. Langmuir probe IV curves, from Barjatya 2007

While probes fixed biased in electron saturation region have the benefit of high signal to noise ratio, they do result in negatively charging the spacecraft. Thus, for a Langmuir probe to be used on a CubeSat form-factor spacecraft, a fixed-bias probe in ion saturation region is a more effective arrangement. Using a flat plate probe has an additional benefit of being immune to variation in spacecraft charging potential because as long as the probe operates in ion saturation region the current response is flat, as well as the benefit of not being a deployable.

Planar Ion Probe (PIP)

PIP is a flat-plate, fixed-bias Langmuir probe designed to remain in the ion saturation region, where negative voltage repels electrons, and current collected is effectively due to ions only. Typically, Langmuir probes biased in ion saturation region measure only thermal ion current, but at orbital velocities ion ram current is an order or magnitude larger than thermal current for planar geometry. Ion ram current is given by the following expression:

$$I_{probe} = (n_i)(q_i)(V)(A_{probe})$$

Where n_i is ion density, q_i is ion charge, V is spacecraft velocity, and A_{probe} is the ram cross section area. With the precise knowledge of the velocity, angle of the planar surface to the ram direction, and assumption of singly charged ions, one can directly derive absolute ion density from the current measurements.

PIP is constructed of two integral components, the planar Langmuir probe sensor and the electronics processing board. Planar probe provides large-area ion collection. The guard strip around the probe provides an infinite planar field geometry from the probe's perspective. Both the probe and guard are hard gold-plated to prevent atomic oxygen corrosion and to provide a uniform work function across the surface.

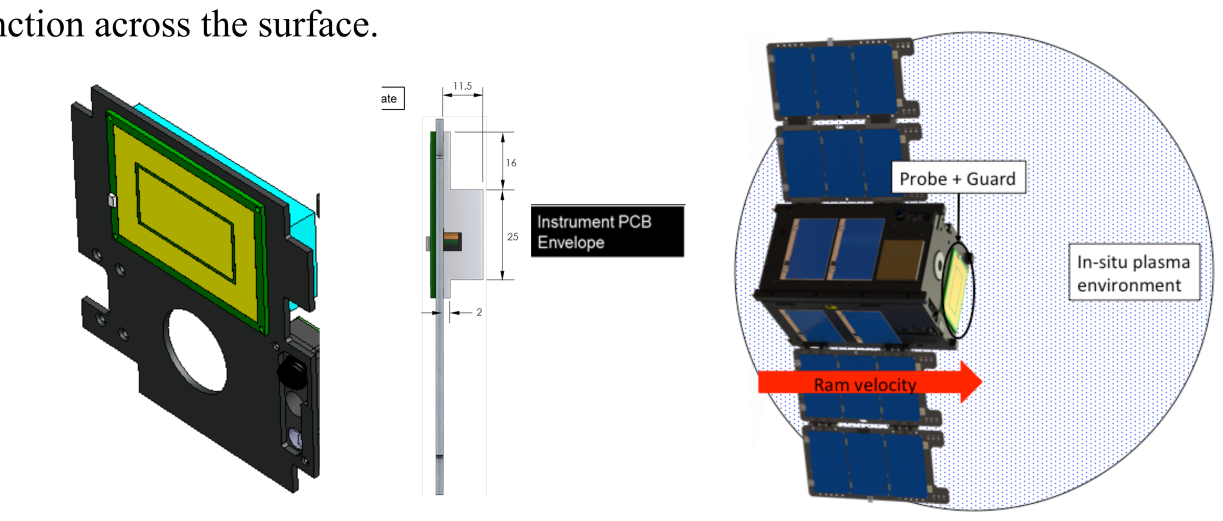

Figure 5. Planar Ion Probe Mechanical Design and placement in CubeSat structure

SWaP is an important concern for severely constrained CubeSat designs. PIP's electronics board is very space-efficient and is approximately a fifth of a typical CubeSat stack PCB. PIP is provided +/-15V and +5V regulated supplies by the spacecraft power system. While it does not regulate these supplies, the buses are decoupled at the external connector as well as every IC power pin. Only the digital components' 3.3V line is produced on the instrument itself.

PIP is designed for a 2×10^9 to 2×10^{13} m^{-3} dynamic range measurement. To accomplish this, dual 16-bit channels with gains of 1 and 100 cover the dynamic range. 10% minimum resolution yields a physical 2×10^8 m^{-3} resolution. At its designed 1kHz sample rate, 8m spatial resolution is possible. There is a -7V probe bias relative to CubeSat chassis ground in order to place the probe assuredly in the ion saturation region and avoid any positive spacecraft charging affecting the ion measurements.

PIP's salient features:

- Total 17cm^2 electronics board
- 4 x 6 cm sensor plate with 1 cm wide guard electrode
- Total mass less than 150 g
- Total power requirement less than 200 mW
- Current measurement range from 2.05 nA to 20.5 µA corresponding to density measurement range of 2×10^9 m^{-3} to 2×10^{13} m^{-3}
- Current resolution of 306 pA (low gain) / 3.03 pA (high gain) corresponding to density resolution of 3.13×10^8 m^{-3} (low gain) / 3.10×10^6 m^{-3} (high gain), giving much better than 10% precision through the four decades of measurement.

PIP Design

The PIP circuit board is divided between analog and digital planes, with separate ground planes and guarding to mitigate parasitic coupling in the sensitive components. The analog side converts measured ion current into voltage (transimpedance amplifier), removes the bias and splits channels (instrumentation amplifier), removes noise (Anti Aliasing filter), and protects the Analog to Digital Converter (Schottky diodes). The ADC chip then digitizes this signal and communicates to the microcontroller via SPI protocol. The conceptual layout and the corresponding PCB are shown in figure 6.

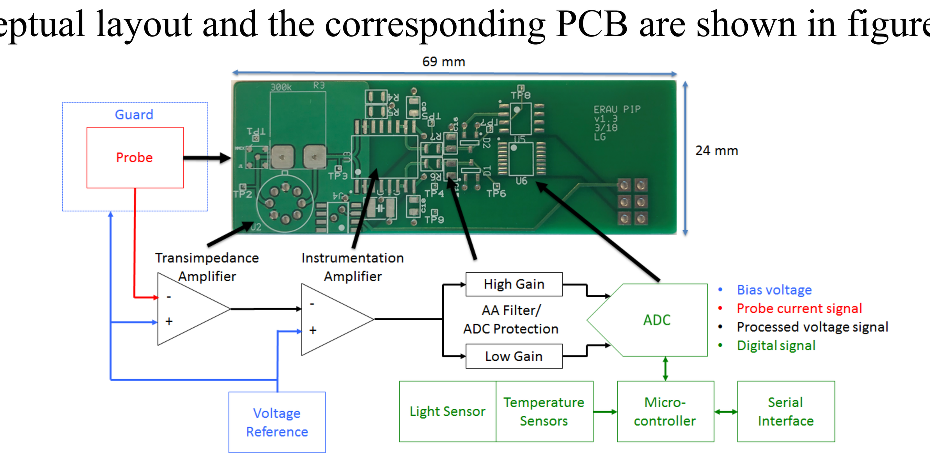

Figure 6. Planar Ion Probe board layout

For housekeeping, PIP monitors its three power supplies, two temperatures, and incident light. Temperature readings (0.5°C resolution) near the transimpedance amplifier and Analog to Digital Converter (ADC) help calibrate the instrument w.r.t. temperature. Light detected on the probe helps determine whether photoelectrons need to considered during data analysis.

A 115.2kbps serial UART connection connects PIP to the command and data handling board. A trigger word initiates a 32x oversampling science measurement. Flight data packets include 32 bits for the two channels of science data and 16 bits for instrument state and cycling housekeeping data.

PIP Analysis

$$I_{probe} = (V_{bias})/(R_{block})$$

Testing is conducted using a specialized resistor array block which houses 0.1% precision resistors housed in in a large aluminum mass for temperature stability. Connecting probe input and instrument ground across a resistor with a low noise cable supplies the instrument with a known current that is then used to check instrument performance and calibration.

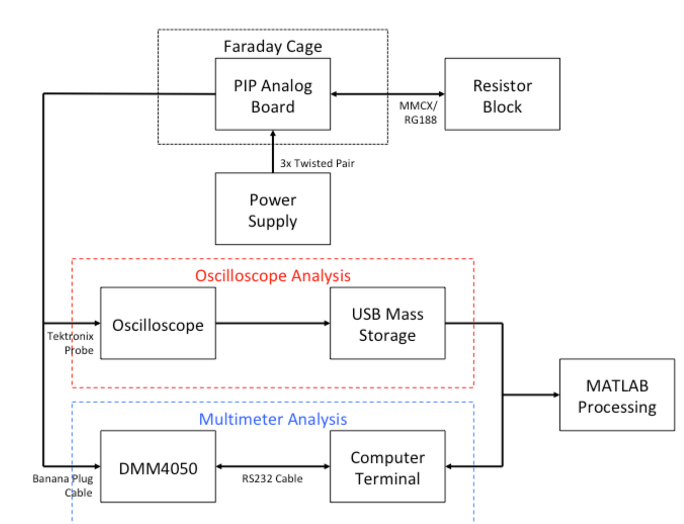

Figure 7. Planar Ion Probe analog noise characterization setup

Besides oscilloscope analysis (to ensure no power supply noise), a benchtop multimeter was operated remotely to determine DC/AC voltage, characterizing input response/noise RMS. Analysis with the design ADC and microcontroller is still ongoing, though flight instrument SPI protocol has been demonstrated.

Figure 8 (left) shows the DC output of the analog current response. The channels properly amplify and provide coverage of the intended dynamic range. Figure 8 (right) shows the channel noise levels. Low gain noise averages 0.783 counts, corresponding to ~2.45×10^8 m^{-3} resolution. High gain noise averages 26.2 counts, corresponding to ~ 8.12×10^7 m^{-3} resolution, both well within the instrument requirements.

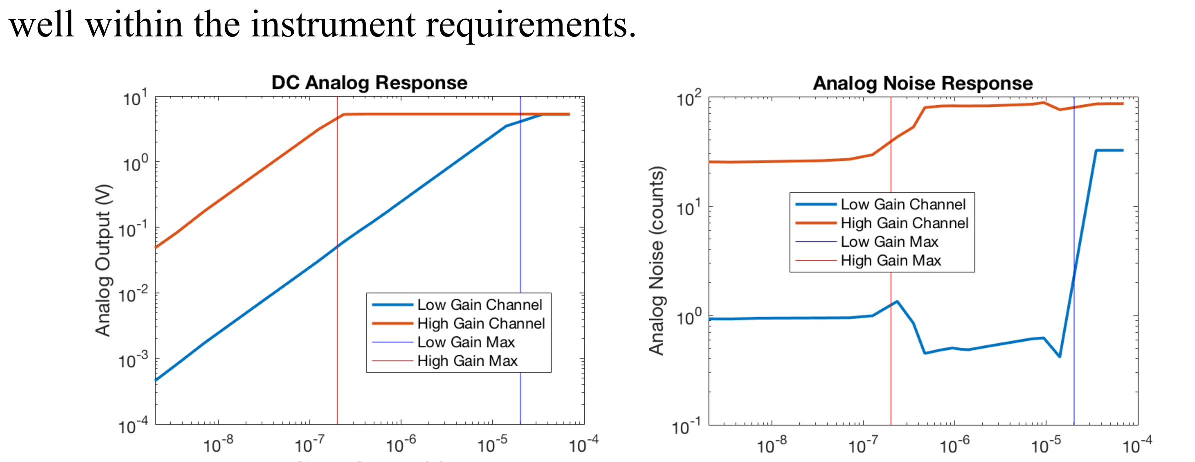

Figure 8. Planar Ion Probe analog testing results

Summary and future work:

PIP is an ultra low SWaP and low noise instrument to measure in-situ absolute ion density. This poster presents an introduction to LLITED mission and details the PIP mechanical and electrical design. The results presented here enumerate only developmental engineering test data. The second revision electronics are being finalized and will be tested in the near future in a relevant environment within the plasma chamber. Following validation of its design performance, the final calibration/flight boards will be manufactured for LLITED and delivered in October 2018.

The simple electronics and low SWaP make the PIP an excellent candidate for being applied as a patch to multitudes of spacecraft. Multiple identical instruments could be patched on to opposing spacecraft surface enabling absolute ion density measurements on spinning/tumbling spacecraft, as well as for mapping the plasma wake structure around the spacecraft.

References

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