Low SWaP Fixed Bias Langmuir probe instrument for orbital and sub-orbital platforms

EMBRY-RIDDLE Aeronautical University
DAYTONA BEACH, FLORIDA

SAIL
Space and Atmospheric Instrumentation Lab
sail.erau.edu

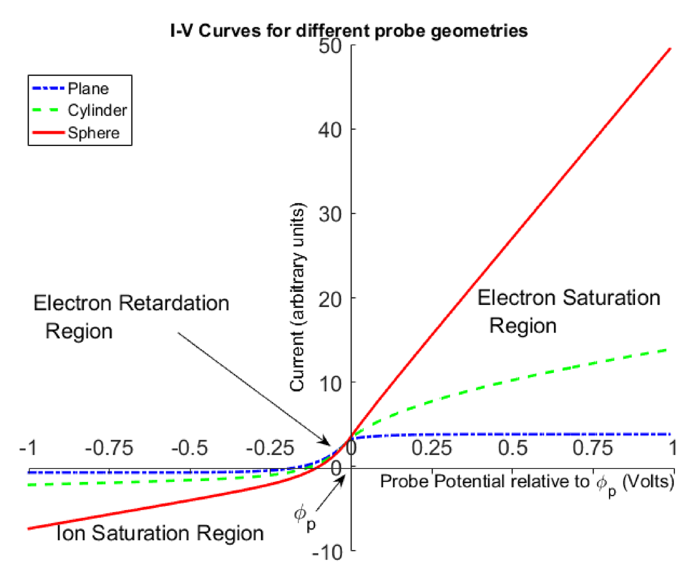
Aroh Barjatya[1] (barjatya@erau.edu), Robert Clayton[1], Shantanab Debchoudhury[1], Liam Gunter[1], Nathan Graves[1], Henry Valentine[1], Rachel Conway[1], Rebecca Bishop[2], James Clemmons[3]
[1] Embry-Riddle Aeronautical University, [2]Aerospace Corporation, [3]University of New Hampshire

Abstract

One of the crucial measurements for characterizing any space weather event is absolute plasma density and plasma density fluctuations, both spatially and temporally. Among the various methods to perform in-situ plasma density measurements is a simple fixed bias Langmuir probe. This poster discusses the various implementations of a Langmuir probe and why a Planar Ion Probe (PIP) is the easiest and best method to measure high cadence absolute ion density in planetary ionospheres. We present the performance of the instrument from the NASA LLITED dual CubeSat mission which included two 1.5U CubeSats. The same instrument has also flown as part of sounding rocket dropsondes enabling simultaneous multi-point measurements of various mesosphere-lower-thermosphere phenomenon. We present data from SpEED Demon sounding rocket mission that flew into a mid-latitude sporadic-E layer. Due to its intended CubeSat platform, the designed instrument has extremely low size, weight, and power requirements and is intended to be flown as an innocuous hosted instrument on constellations of 100+ satellites.

Langmuir Probe Background

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 (Fig 1a), while the current collected by planar probes remains essentially flat (Fig 1b).



Langmuir probe IV curves, from Barjatya 2007

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. While probes that are 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 CubeSat form-factor Langmuir probe, a fixed-bias probe in ion saturation region is a more effective arrangement. Using a flat plate probe has an additional benefit of being mostly immune to variation in spacecraft charging potential, given that the ion saturation region has a flat response, 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 thermal ion current, but at orbital velocities ion ram current is an order or magnitude larger than thermal current for planar geometry. Ion thermal and ram currents are given by the expression:

$$I_{thermal,j} = n_j q_j A_{probe}\sqrt{\frac{k_B T_j}{2\pi m_j}} \qquad I_{ram,i} = n_i q_i u A_{cross} = n_i q_i u \cos\theta A_{probe}$$

Where n is species density, q is species charge, T is species temperature, m is the species mass, u is spacecraft velocity, and A_{cross} is the ram cross section area, A_{probe} is actual probe surface area, and θ is the angle the probe surface makes with the ram direction. We can define η as the ratio of ram to thermal current:

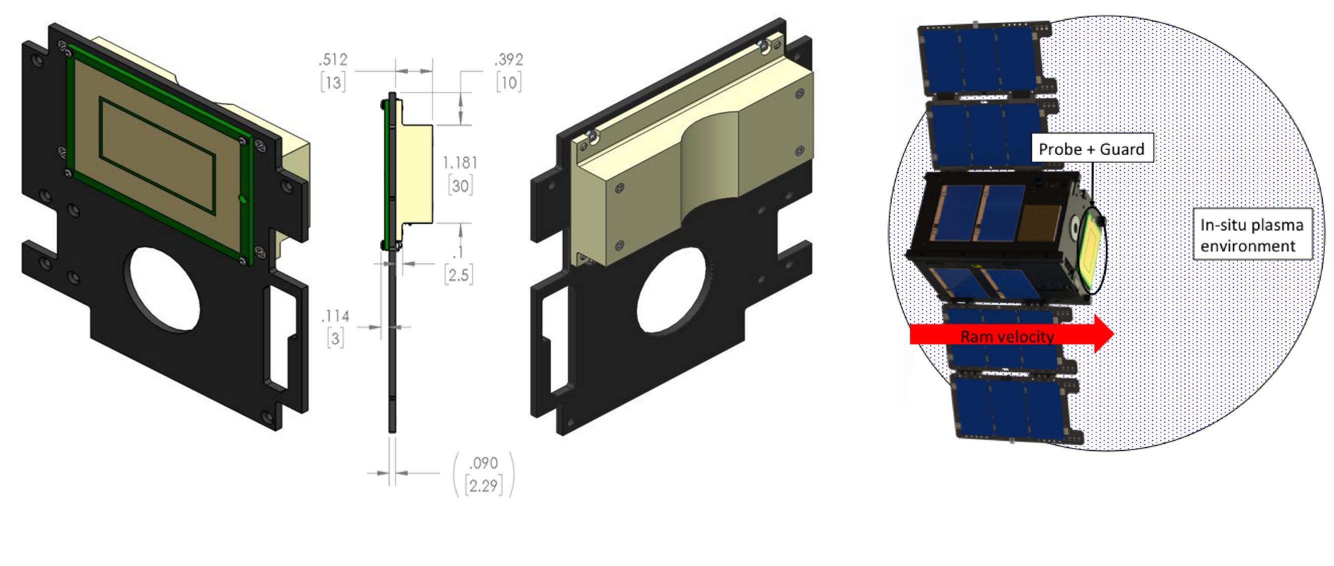
$$\eta = \frac{I_{ram}}{I_{thermal,i}} = u\cos\theta\sqrt{\frac{2\pi m_i}{k_B T_i}}$$

As can be seen above, η is a function of only four parameters, spacecraft velocity u, ion mass m, ion temperature T and the angle θ between the surface normal and the ram direction. For a θ of 0°, spacecraft velocity of 8 km/s, and singly charged atomic oxygen ion of 1000K, the unitless ratio η has a value of 27. An η > 10 implies that the thermal current collected by the probe is less than 10% of the ion ram current collection. Value of η drops from 27 to 10 when the ram angle offset is 68°. Thus, 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 Overall Design

PIP consists of two components: the Langmuir probe sensor and electronics processing board. Planar probe provides large-area ion collection, and guard strip around the probe provides infinite planar field geometry from the probe's perspective. The probe/guard are hard gold-plated to prevent corrosion and provide a uniform surface work function. Due to the nature of its working principle, PIP needs to be placed on a ram facing surface. Although as shown in the prior section, errors up to 40° in ram pointing are easily accommodated.

Work presented here is supported under LLITED (80NSSC17K0044) and SpEED Demon (80NSSC19K0773)



Planar Ion Probe Mechanical Design and placement in LLITED CubeSat structure

CubeSat PIP's Salient Features

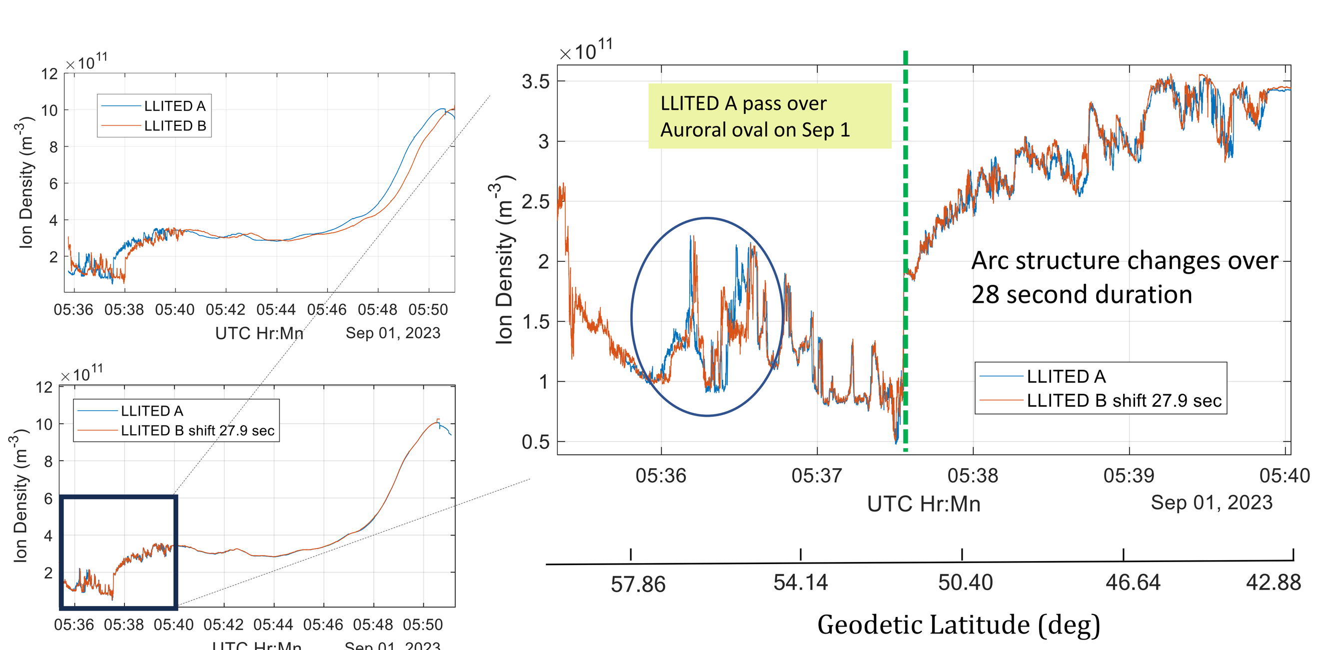
- Total 17cm^2 electronics board
- 4 x 6 cm sensor plate with 1 cm wide guard electrode
- Low mass components: instrument PCB 9 g, sensor 10 g, envelope 27 g
- Power draw of 125 mW at nominal ion density (2 x 10^{11} m^{-3})
- Power draw of 250 mW at maximum ion density (2 x 10^{13} m^{-3})
- Instrument boot-up time ≤ 350 ms
- Current measurement range from 2.05 nA to 20.5 µA corresponding to density measurement range of 2 x 10^{9} m^{-3} to 2 x 10^{13} m^{-3}
- Design resolution (noise floor resolution):
  - 306 pA (306 pA) = 3.13 x 10^{8} m^{-3} (3.13 x 10^{8} m^{-3}) low gain
  - 3.09 pA (~70 pA) = 3.16 x 10^{6} m^{-3} (~7.0 x 10^{7} m^{-3}) high gain
  - better than 10% precision throughout the four decades of measurement
- Max sample rate of 100 Hz

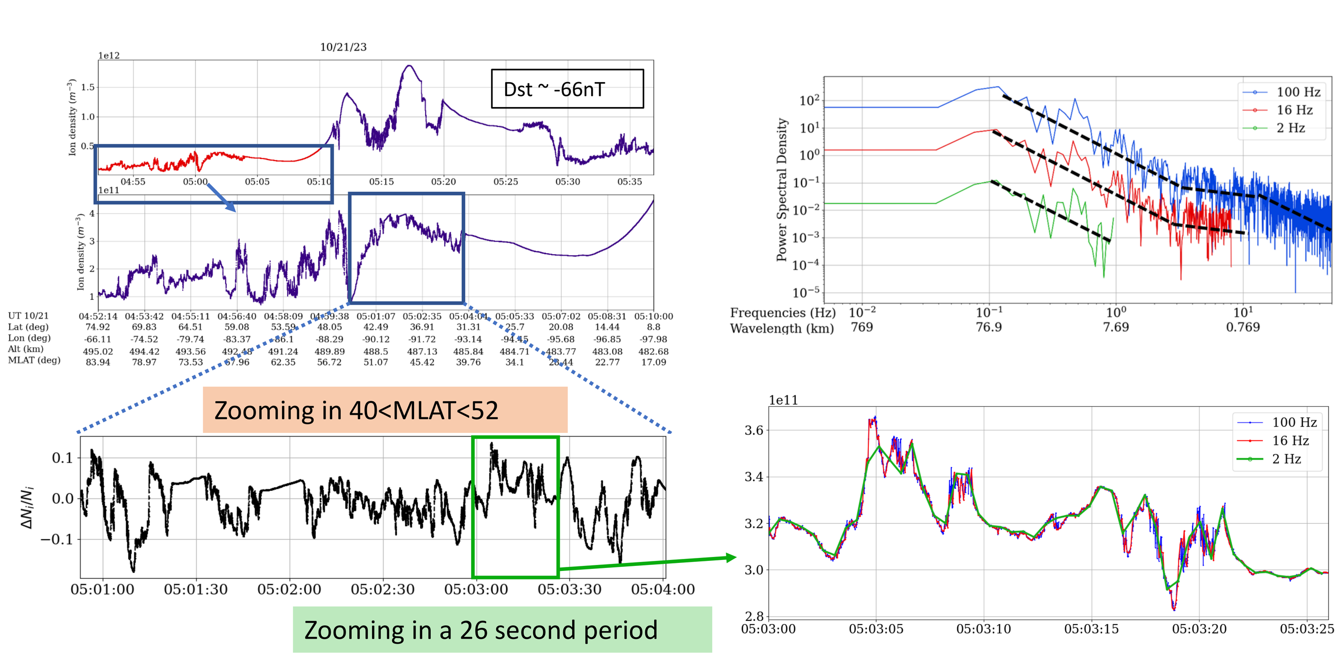
Low Size, Weight and Power (SWaP) is an important concern for severely constrained CubeSat designs. PIP's electronics board is very space-efficient and is approximately a fifth of a typical CubeSat stack PCB in area. PIP is provided +/-15V and +5V regulated supplies by the spacecraft power system. Other salient features are shown in the column to the right.

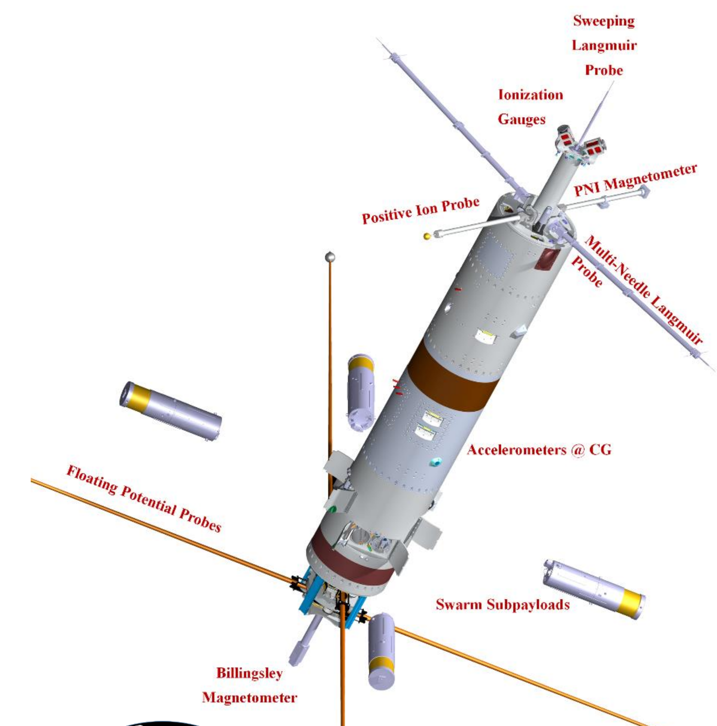
The PIP being presented in this poster is designed for a 2x10^{9} to 2x10^{13} m^{-3} dynamic range measurement. Although, it could be designed for any four decades of density measurement along with an appropriate gain and sensor design. To accomplish this, dual 16-bit channels with gains of 1 and 100 cover the dynamic range. For our current range, 10% minimum resolution yields a physical 2 x 10^{8} m^{-3} resolution. At its designed 100Hz sample rate, 80m spatial resolution is possible. Although similar instrument has been used on sounding rocket missions with 5kHz sample rate. The probe is biased -7V in order to place the probe assuredly in the ion saturation region. The electronics PCB is housed directly behind the sensor PCB in effectively its own faraday cage. This isolates the instruments; i.e. the instrument neither affects nor is affected by electromagnetic interference from other satellite electronics.

PIP Flight Data

LLITED was placed into a 513 km x 495 km orbit with a near sun-synchronous 97.4 deg inclination. It operated and collected data from Sept 2023 to Aug 2024. Due to power limitations, LLITED A PIP was operated on the night side transit (45 min) for three orbits per day, whereas LLITED B PIP and MIGSI (Miniature Ionization Gauge from Aerospace Corp and UNH) were operated on night side for a single orbital pass of 45 minutes. During the passes when the two CubeSats were in proximity, indicate the dynamic nature of several ionospheric phenomena observed. Data indicates that the minimum sampling needed in the ionosphere is >16 Hz.



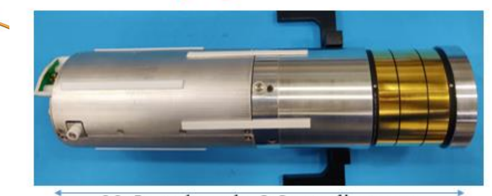




Subpayload Electronics

14.5 cm length , 6.5 cm width

Subpayload Shell



33.5 cm length, 8.8 cm diameter

Suborbital Dropsonde PIP's Salient Features

- Wrap-around gold plated flexible PCB
- 2 cm wide sensor and 1.5 cm each side guard
- Low mass components: instrument PCB 50 g, sensor 10 g
- Power draw of 1200 mW at nominal ion density (1 x 10^{11} m^{-3})
- Power draw of 1400 mW at maximum ion density (3 x 10^{12} m^{-3})
- Current measurement range from 0.25 nA to 25.0 µA corresponding to density measurement range of 3 x 10^{7} m^{-3} to 3 x 10^{12} m^{-3}
- Noise floor resolution:
  - 50 pA = 5.0 x 10^{6} m^{-3} low gain
  - 25 pA = 2.5 x 10^{6} m^{-3} high gain
  - better than 10% precision throughout the four decades of measurement

The dropsonde PIP's electronics board is designed to fit inside NASA's ejectable swarm payloads. This version of the PIP is provided unregulated +7 to +40V and internally generates all the necessary regulated voltages.

The PIP being presented in this poster is designed for five decades of dynamic range measurement: from 3x10^{7} to 3x10^{12} m^{-3}. Although, it could be designed for any other five decades of density measurement along with an appropriate gain and sensor design. The instrument currently has a 24-bit ADC with simultaneous multi-channel sampling. Instrument sampling rate, as flown, is 5 kHz, although higher is possible. A version of the instrument is slated to launch as part of the NASA ESCAPADE satellites to Mars in Fall 2025.

Dropsonde Flight Data

First flight of the dropsonde PIP was on the NASA SpEED Demon mission in Aug 2022. The rocket flew through a Sporadic E (Es) layer on both Upleg and Downleg and performed the *first 5 point simultaneous in-situ measurement of an Es layer*. The dropsondes measured separations ranging from few tens of meters to well over a km. The overall layer profile was similar but small-scale perturbations were seen at the top side gradient, bottom side gradient, as well as the peak density.

(left) Horizontal displacement of the ROB subpayloads from main payload. Black marks indicate the Es layer intersections. (right) All five density profiles for the Downleg Es layer intersection.