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SLP: The Sweeping Langmuir Probe Instrument to Monitor the Upper Ionosphere on Board the PICASSO Nano-Satellite

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Abstract

The flourishing development of small/micro/nano platforms could offer the opportunity to decrease significantly the cost of science missions if suitable instruments can be operated from such platforms. Langmuir probe instruments have been used for decades on board large/medium-size satellites to measure ambient plasma properties (electron density and temperature together with ion density) but their operation on board smaller platforms raises several issues in addition to miniaturisation and drastic reduction of power consumption. The limited conducting area of the spacecraft will imply spacecraft charging and drift of the instrument's electrical ground during the measurements, which would lead to unusable data. Furthermore, given the limited dimensions of the spacecraft and thus the small dimensions of the probes and booms, some hypotheses required to apply traditional Langmuir probe theory to retrieve the plasma parameters are not fulfilled. Finally, the usually limited telemetry bandwidth available on nano- to small satellites requires the use of non-traditional measurement and data processing approaches. The Sweeping Langmuir Probe (SLP) instrument, that uses a novel measurement technique, has been developed at the Royal Belgian Institute for Space Aeronomy to overcome the above mentioned issues. SLP will fly on board the ESA scientific in-orbit demonstrator PICASSO together with the hyper-spectral imager VISION. PICASSO, a triple unit CubeSat, will be launched during the first quarter of 2020. The goal of the mission is to prove the feasibility of performing true science (with limited extent) with a nano-satellite and demonstrate the favourable cost / science ratio with respect to big missions. SLP will allow a global monitoring of the ionosphere with a maximum spatial resolution of the order of 150 m. The main goals are to study the ionosphere-plasmasphere coupling, the subauroral ionosphere and corresponding magnetospheric features together with auroral structures and polar caps, by combining SLP data with other complementary data sources (space- or ground-based instruments). SLP can measure plasma density from 1e8/m³ up to 1e13/m³ and electron temperature between 1000 K and 15 000 K. The results from the measurements performed in a plasma chamber prove the suitability of SLP to be used as a true scientific instrument on a CubeSat. Given its capabilities, miniaturisation, low power consumption and already high TRL, SLP can be easily accommodated in any (2U Cubesat or larger) satellite either as a plasma diagnostic instrument or as an accurate spacecraft potential monitor.

Keywords: Ionosphere, plasma, Langmuir probe, CubeSat.

1. Introduction

The Earth ionosphere, which lies between about 60 km and 1000 km altitude, is the part of the upper atmosphere which is ionised, mostly by solar radiations. Fig. 1 shows typical mid-latitude daytime and night-time electron density profiles during solar maximum and minimum conditions based on the International Reference Ionosphere (IRI) model. Fig. 2 shows the IRI model temperature for electrons, ions, and neutrals [1]. The ionosphere can be thought of as being composed of a series of overlapping layers in altitude, with each layer having an altitude of maximum density. These various regions differ in their primary ion constituents and absorbed UV wavelengths. The D-region is predominant in hydrated ions, the E-region in NO^+ and O_2^+, and the F-region in O^+. The D-region does not exist at night due to absence of solar ionization and the rapid recombination as the atmosphere is still relatively dense at that altitude. The E-region too essentially disappears at night. The F-region at low magnetic latitudes, however, is depleted at night, but is replenished by the plasmasphere. The ionospheric density and temperature profiles differ with latitude, longitude, and season due to variation in zenith angle of the incident UV and the Earth's geomagnetic field.

Ionospheric models like IRI only provide an average climatology of the ionosphere parameterized by solar activity, season, and geomagnetic activity indices. The actual day-to-day variability of the ionosphere in geomagnetically quiet conditions can approach up to 30% of the model averages [2], and becomes worse for geomagnetically disturbed conditions.

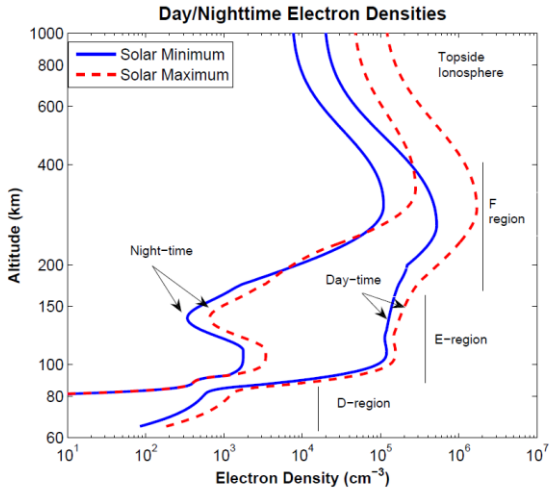

Fig. 1. Typical mid-latitude daytime and night-time electron density profiles showing the D-, E-, and F-regions of the ionosphere [1]

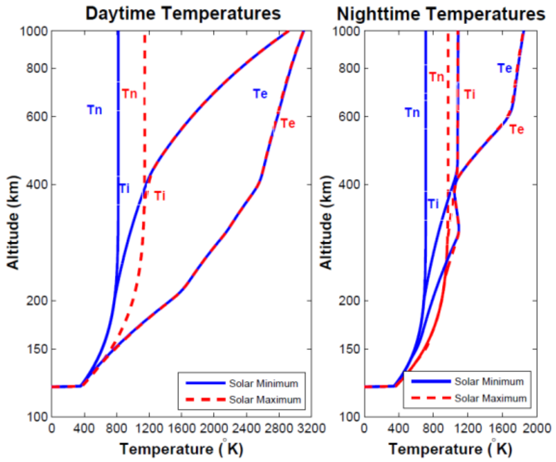

Fig. 2. Typical mid-latitude neutral, ion, and electron temperature profiles [1]

Furthermore, these models give only average values and do not give information about local phenomena such as the plasmaspheric trough, discrete aurora and polar cap arcs, which all play an important role in the dynamics of the ionosphere. One possible way to obtain the plasma parameters during local ionospheric events is to use incoherent scatter radar measurements such as with the EISCAT radars. Nevertheless, with this type of instrument the spatial resolution is in the km range and the accuracy of the retrieved data is quite limited for altitudes above 500 km. Another method, GNSS tomographic reconstruction, is not accurate above 200 km altitude. Therefore, in situ measurements are crucial for providing accurate observations with high spatial resolution of local plasma parameters such as density and temperature.

The scientific objectives of the Sweeping Langmuir Probe instrument (SLP) are presented in Section 2. The Pico-Satellite for Atmospheric and Space Science Observations (PICASSO) CubeSat and SLP are presented in Sections 3 and 4, respectively. The limitation of nano-satellite platforms for Langmuir probe instruments and the proposed solution are presented in Section 5. Section 6 concludes this paper.

2. Scientific objectives of SLP

The scientific objectives of SLP are the in-situ study of:

a) Ionosphere-plasmasphere coupling

The goal is to compare the density and temperature data from SLP with data obtained along magnetic field lines at different altitudes from other data sources (e.g. Cluster) in order to study the field-aligned density distribution and temperature effects.

b) Aurora structures

Because SLP measures density and temperature only at about 550 km altitude, supplementary data is needed. This data can be simultaneous measurements from other spacecraft on roughly the same field line (both in low or high Earth orbit, e.g. Cluster), EISCAT radar data, or ALIS data (ionospheric optical tomography). EISCAT can provide the overall ionospheric context in which SLP data should be interpreted. Having at the same time Cluster high altitude data would allow more detailed understanding of the phenomena that take place. The aim is to identify in what situations density enhancements can be expected at 550 km altitude, and when density depletions are created.

c) Survey of polar cap arcs

The objective is to monitor the density irregularities in the polar cap ionosphere and relate those to signatures of polar cap arcs, (e.g. those found in Cluster data). The main questions to be answered are:

- How often do such features occur?
- What is their size and motion?
- What is their relation to the ionospheric conductivity (as determined by electron density)?

The expected plasma parameters along the orbit of PICASSO are given in Table 1.

Table 1. Expected plasma parameters

	Minimum (> 95% probability)	Maximum (> 95% probability)
Plasma density (#/m³)	10^8 (10^9)	10^{13} ($5\text{x}10^{12}$)
Electron temperature (K)	600 (700)	10 000 (5 000)
Debye length (m)	5.4e-4 (8.2e-4)	0.69 (0.15)

3. PICASSO

PICASSO is a scientific CubeSat-based project initiated by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) in 2010. It was successfully proposed to the Belgian Scientific Policy Office and to ESA as an In-Orbit Demonstrator of scientific applications from LEO CubeSats. The objective of the PICASSO mission is to demonstrate the capacity of low-cost nano-satellites to perform remote and in-situ scientific measurements of physico-chemical properties of the Earth's atmosphere. In addition, PICASSO also aims at bringing the instruments and the on-board data processing components to high technology readiness levels to allow them to be incorporated in future scientific missions with a reduced risk. The satellite shall be launched during the first quarter of 2020 into a high inclination low-Earth orbit, at about 550 km altitude and will have a lifetime of at least one year.

PICASSO is built upon a 3U CubeSat platform (340.5 x 100 x 100 mm) weighing 3.9 kg and featuring four deployable solar panels (8.7 W average power generation), together with UHF/VHF and S-band communications. The expected downlink bandwidth is 100 MB/day. PICASSO includes two on-board computers and a high performance ADCS leading to a pointing accuracy of about 1° and pointing knowledge of 0.2°. The spacecraft carries two scientific instruments: VISION (Visible Spectral Imager for Occultation and Nightglow) and SLP.

The scientific objectives of VISION are the retrieval of polar and mid-latitude stratospheric ozone vertical profiles (via spectral observation of Sun occultations in the Chappuis band) and the upper atmosphere temperature profiling based on the Sun refractive flattening. VISION includes a Fabry-Pérot and spectral filters together with a commercial CMOS detector (2048 x 2048, RGB). The instrument has a field of view of 2.5 °, a spectral range of 400 to 800 nm and a full width at half maximum (FWHM) of less than 10 nm. VISION technology is based on the heritage of AaSI on board Aalto-1.

4. SLP instrument

SLP is a 4-channel Langmuir probe instrument. Its measurement principle is based on the conventional Langmuir probe theory [3]. By sweeping the potential of a probe with respect to the plasma potential while measuring the current from this probe, the instrument will acquire a current-voltage (I-V) characteristic from which the electron density and temperature, ion density and S/C (spacecraft) potential are retrieved. The measurements are performed in three regions: ion saturation, electron retardation and electron saturation regions. A typical current-voltage characteristic of such a probe is illustrated in Fig. 3. The ion density is derived from the ion saturation region, where the potential of the probes is sufficiently negative to repel electrons and attract only ions. The electron temperature and S/C potential are retrieved from the electron retardation region, where the potential of the probes is close to that of the plasma so that both ions and electrons are attracted. The electron density is derived from the electron saturation region, where the potential of the probes is sufficiently positive to repel ions and attract only electrons.

In nominal mode, SLP sweeps the potential of the probes from -5 V to +13 V with respect to the S/C potential in order to retrieve the electron density and temperature, together with the S/C potential and the ion density (where it is high enough). The sampling frequency is fixed at 10 kHz and the maximum sweeping frequency is about 50 sweeps/s. The limited downlink bandwidth does not allow performing linear voltage sweeps with very fine steps in nominal mode. Instead, the three regions (ion saturation, electron retardation and electron saturation) are measured with different step sizes. Ion and electron saturation regions are measured with large voltage step size (> 1 V). The electron retardation region is measured with smaller step size, which depends on the electron temperature: this region is measured with 30 steps, but the span is adapted as a function of the electron temperature. On board, the inflection point of the I-V curve which separates the electron retardation and electron saturation regions (the plasma potential) is determined after each sweep and is used to compute the span of the electron retardation region of the next sweep. The step size ranges from about 10 mV to 150 mV for electron temperatures of 600 K and 15.000 K, respectively.

In another mode, the instrument measures only in the electron saturation region at a higher rate, producing electron density with better spatial resolution in order to resolve fine plasma structures like those presented in [4]. This operating mode is based on the principle described in [5]. Although the telemetry is limited, the raw data will be downloaded to the ground because the measured current-voltage characteristics contain more information than only four parameters (electron density and temperature, ion density and S/C potential). For instance, in auroral regions multicomponent plasmas can be present, which requires more sophisticated analysis to derive the plasma parameters [6].

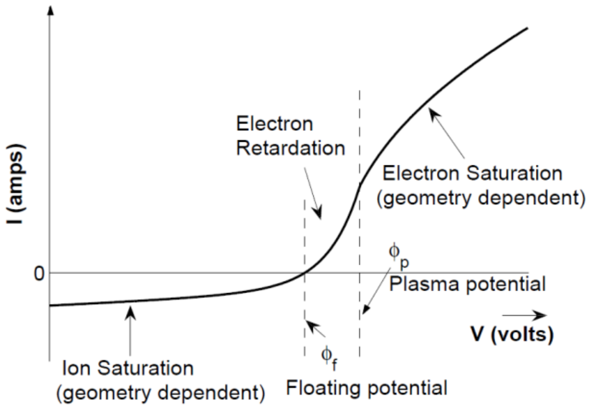

Fig.3. Typical Langmuir probe current-voltage characteristic

The four probes of SLP are mounted on the deployable solar panels, which act as deployable booms, as depicted in Fig. 4.

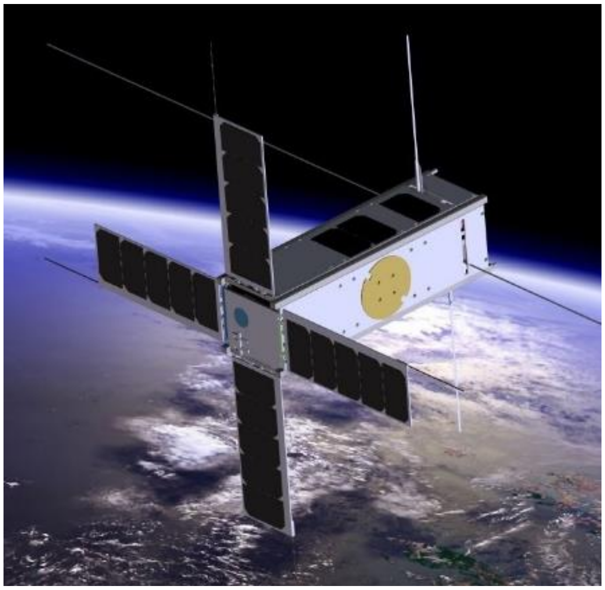

Fig. 4. SLP probes at the tips of the solar panels on PICASSO

This configuration ensures that at least one probe is out of the S/C wake at any time, in addition to providing redundancy. The probes are 40 mm long Ti tubes of 2 mm diameter. They are attached to the extremity of the solar panels via a 40 mm long boom, as depicted in Fig. 5.

Due to constraints related to the diameter of the probe and coax cable as well as the mechanical complexity inside the probe and boom, it was not possible to include a guard on the probe. Furthermore, a guard would increase the collecting area which would make the spacecraft charging effect more severe.

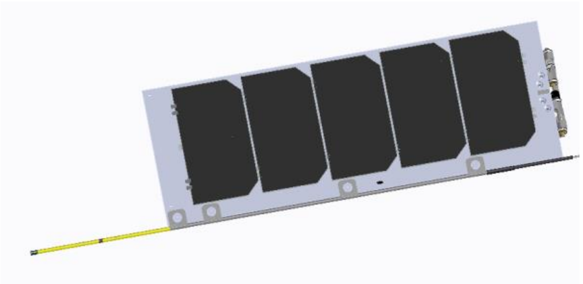

Fig. 5. Probe and boom (in yellow) at the extremity of the solar panel

There will be no active on-orbit cleaning of the probe surface. First, since PICASSO will fly on a high inclination orbit, it is expected that natural ion and electron sputtering will occur at high latitude where the spacecraft will encounter energetic ions and electrons. This natural sputtering seemed to be sufficient for several Langmuir probe instruments which did not show signs of contamination (Tiros-7, Explorers 17, 22, 23, 31, 32, Alouette-II, ISIS-1 and ISIS-2) [7]. Furthermore, for a significant part of the orbit, the temperature of the probe should reach about 200 °C which should help cleaning [8]. Finally, an active on-orbit cleaning would have significantly increased the complexity of the instrument and create additional constraints.

SLP electronics is made of two boards integrated between a bracket and a cover that shields the sensitive analog front-end, forming a partial enclosure, as depicted in Fig. 6. The dimensions of the electronics box are 104 x 98 x 25 mm (including the shielding cover and mounting bracket). The total mass of the electronics box is 128 g and the one of the four probes is 24 g (including the four booms, mounting clamps, cables and connectors). The average power consumption (100 % duty cycle) is 2.2 W.

The four channels are identical. They can all be used either as current meter with automatic gain control (AGC) capability or as floating potential meter. In current meter mode, each channel can measure the bias voltage applied to the probe. The instrument includes an internal current source for monitoring purpose. The time synchronisation of SLP is ensured either by reading the time from the payload computer (PLC) or by decoding directly the NMEA sentences and PPS signal from the GPS, when the GPS is turned on. Given the uncertainty on the PLC latency during operation, the latter option is used as the primary mechanism to synchronise SLP since it leads to better time accuracy. The other option (synchronisation from the PLC) is used as a backup.

Fig. 6. SLP electronics in its partial enclosure

5. Limitation of nano-satellite platform and proposed solution

One of the main issues implied by the use of a nano-satellite platform for a Langmuir probe instrument is the limited conducting area of the S/C. Because the conducting area of the S/C is not large enough as compared to the area of the probes, the S/C will charge negatively when the probes are swept with positive bias. This charging will lead to a drift of the S/C potential during the sweep, making the data unusable. There is also the risk that the potential of the S/C drops so much that the probes cannot be biased to measure properly in the electron saturation region.

In order to avoid this problem, a specific measurement technique which uses two different probes simultaneously has been developed: while one probe is biased and measures the current (traditional Langmuir probe technique), a second probe is used to measure the floating potential. By combining the measured floating potential with respect to the S/C potential and the probe potential with respect to the S/C potential (applied bias), the probe potential with respect to the floating potential can be known. Therefore, consistent current-voltage characteristics can be retrieved. The main advantage of this technique is that there is no need for an electron gun. This is particularly important since the filaments of electron guns have usually a limited lifetime while PICASSO should operate for at least one year.

To ensure that probes can sweep properly in the electron saturation region all along the PICASSO orbit, the conducting surface of the S/C has been increased to have at least 200 cm² on all sides of the S/C, including the solar panels, leading to 1200 cm² conducting surface area for the whole S/C. Given that the collecting area of the probe is about 2.5 cm², the ratio of total S/C collecting area to total probe collecting area is 472. The solar cells themselves are not coated and therefore do not participate to the S/C collecting area.

To investigate and quantify the charging of the S/C, particle-in-cell (PIC) simulations have been carried out.

5.1 PIC Simulations

The PIC simulations have been performed with SPIS (Spacecraft Plasma Interaction System). SPIS can be used to study charging in GEO, LEO or other environments, taking into account surface physics (e.g. secondary emissions, photo-emission, surface and volume conductivity) and volume physics (e.g. electrostatic, electromagnetism, kinetic or fluid description, collisions). The model is a conductive cube of 14.14 cm length side, leading to 200 cm² conducting area per side, as required for PICASSO. The probe is modelled as a 40 mm long cylinder of 2 mm diameter. To limit the computation time, the boom and solar panel are not modelled, as can be seen in Fig. 7. An example of the potential distribution at the surface of the S/C and the surrounding plasma is shown in Fig. 8. It can be seen that when 6.5 V is applied to the probe (with respect to the S/C potential) the probe is at about 2.5 V with respect to the plasma and the S/C chassis is at about -4 V with respect to the plasma.

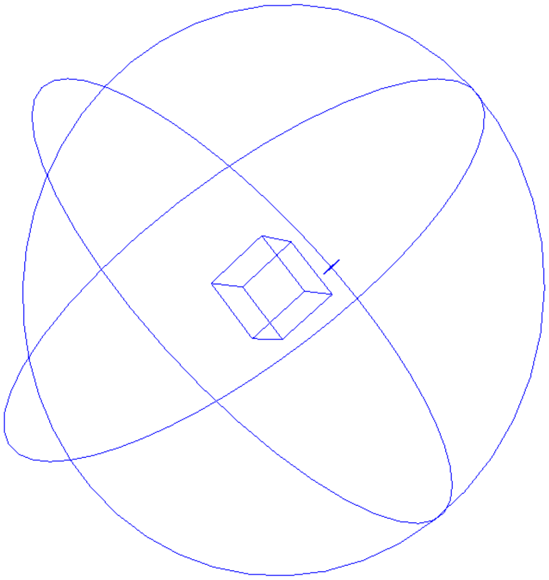

Fig. 7. SPIS model with one probe

The effect of S/C charging on the Langmuir probe measurement is illustrated in Figs. 9 and 10, where 6 V and 13 V bias steps are applied to the probe. It can be seen that the S/C potential is significantly affected by the Langmuir probe instrument operation and that the potential of the probe with respect to the plasma potential changes substantially during each step, making the measurement meaningless if the S/C potential is not known during the sweep.

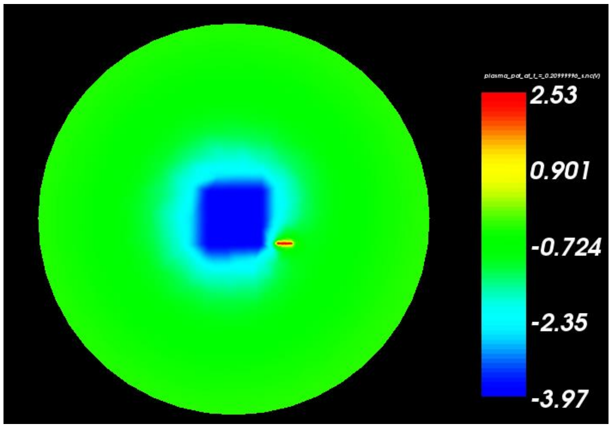

Fig. 8. Potential distribution at the surface of the S/C and the surrounding plasma. Applied bias voltage: 6.5 V

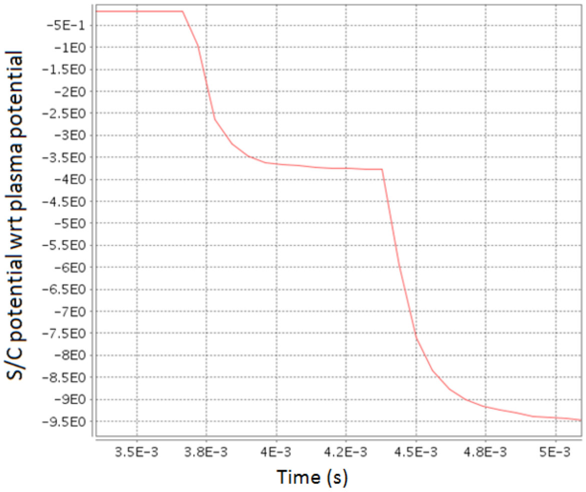

Fig. 9. S/C potential with respect to the plasma potential when 6 V and 13 V steps are applied to the probe. Electron density and temperature are set to 10^{11}/m³ and 600 K, respectively

To ensure that probes can sweep properly in the electron saturation region all along PICASSO orbit, SPIS simulations have been performed for density ranging from 10^8/m³ to 5x10^{12}/m³ for the two extreme values of electron temperature (600 K and 6000 K). The simulations have been performed for an eclipse scenario (no photoelectrons that can help to mitigate S/C charging), which is the worst case. It can be seen from Fig. 11 that, for an applied bias voltage of 13 V, the maximum probe potential (with respect to the plasma potential) is ranging from 10.8 V down to 1.8 V depending on the plasma parameters. It is shown that the S/C charging effect is more severe at low electron temperature and high plasma density. Since the floating potentials for electron temperatures of 600 K and 6000 K are -0.16 V and -1.9 V, respectively, it is always possible to sweep in the electron saturation region with SLP on board PICASSO.

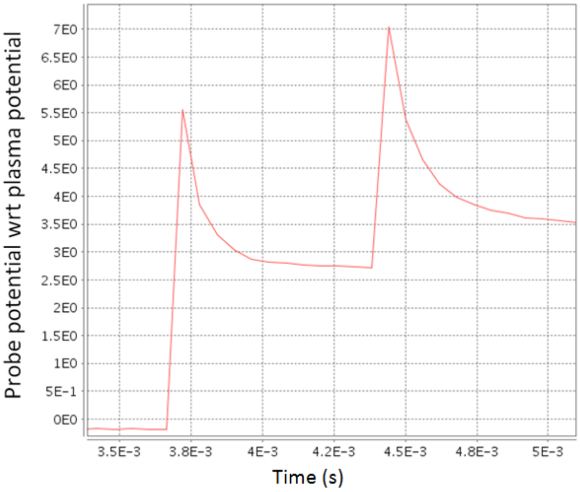

Fig. 10. Probe potential with respect to the plasma potential when 6 V and 13 V steps are applied to the probe. Electron density and temperature are set to 10^{11}/m³ and 600 K, respectively

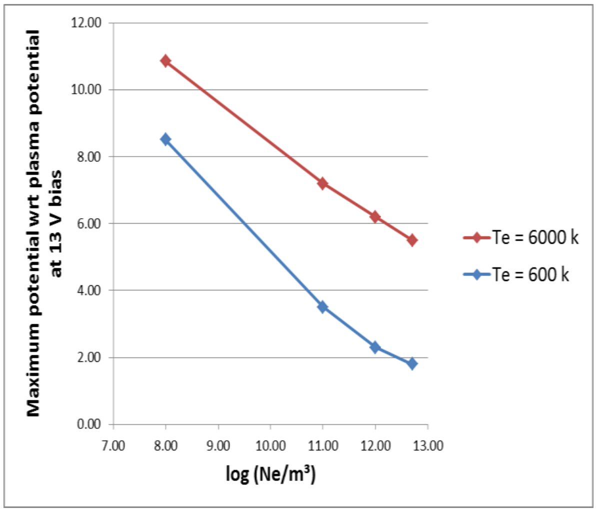

Fig. 11. Maximum probe potential with respect to the plasma potential at 13 V bias

5.2 Validation of the measurement principle

The measurement principle has been validated with measurements in a plasma chamber. Although the size of PICASSO with deployed Langmuir probes is small enough to fit into some plasma chambers, it was not possible to test the full spacecraft due to time and budgetary constraints. Instead, functional test in a representative plasma environment have been carried out in a plasma chamber at ESTEC (Space Environments and Effects section, ESA, Noordwijk, the Netherlands) with an electrically representative model, a cube of 141.4 mm-long sides, as depicted in Fig. 12.

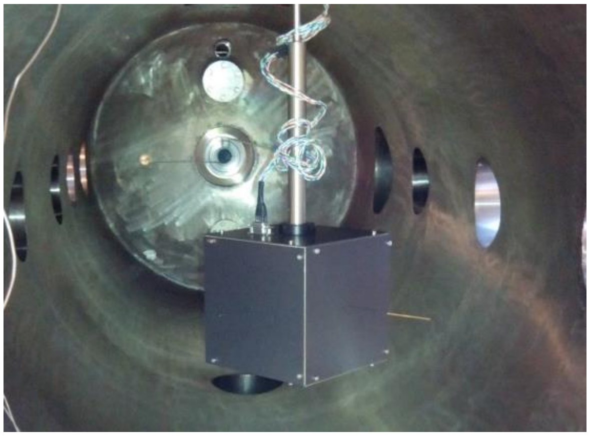

Fig. 12. Electrically representative model of PICASSO in the plasma chamber at ESTEC

An I-V curve measured during the functional tests in the plasma chamber is shown in Fig. 13. The blue curve is the current as a function of the applied bias (with respect to the S/C potential), whereas the red curve represents the same current but with respect to the floating potential.

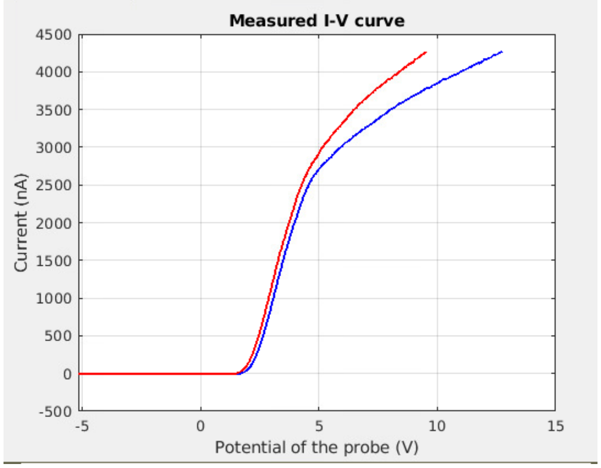

Fig. 13. Measured current as a function of probe potential 1) with respect to the S/C potential (blue), 2) with respect to the floating potential (red).

The measured potential of the floating probe, with respect to the S/C GND, is shown in Fig. 14. It can clearly be seen from these two figures that when the probe is scanning the ion saturation and electron retardation regions (i.e. bias from –5 V to about +4 V), the S/C potential is close to the potential of the floating probe, whereas when the probe is in the electron saturation region (bias from about 4 V onward) the S/C potential drops and the voltage between the floating probe and the S/C GND increases, which is in line with the simulation results shown above.

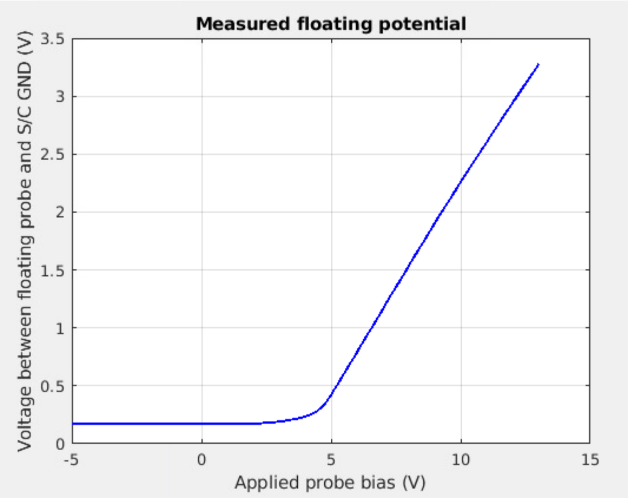

Fig. 14. Measured potential of the floating probe (with respect to the spacecraft GND) as a function of the applied bias.

6. Conclusions

SLP, which is part of the payload of the PICASSO CubeSat, is a Langmuir probe instrument that has been developed at the Royal Belgian Institute for Space Aeronomy to monitor the upper ionosphere. The scientific objectives are to study the ionosphere-plasmasphere coupling, the subauroral ionosphere and corresponding magnetospheric features together with auroral structures and polar caps, by combining SLP data with other complementary data sources (space- or ground-based instruments). By processing the I-V curves acquired by SLP, the electron density and temperature together with the ion density and S/C potential can be inferred.

The main issue implied by the use of a nano-satellite platform for a Langmuir probe instrument is the limited conducting area of the spacecraft, which leads to spacecraft charging and drift of the instrument's electrical ground during the measurement. A specific measurement technique that includes the simultaneous measurement of the potential and current of different probes has been developed to retrieve consistent current-voltage characteristics that can be used to estimate the plasma parameters mentioned above. Particle-in-cell (PIC) simulations have been performed to analyse and quantify the charging of the spacecraft. It is shown that, given the dimensions of the probe and the conducting area of the S/C, it is possible to sweep the probe in the three regions of interest (ion saturation, electron retardation and electron saturation regions) even in the most unfavourable condition of the PICASSO mission (eclipse with high plasma density and low electron temperature). The instrument has been tested and the measurement principle has been validated in a plasma chamber.

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