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Design on-board data processing for double Langmuir probe on lean satellite

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Abstract. The explosive growth of lean satellites (small/micro/nano/pico) has positioned this class of satellites as a unique tool for space science missions. Langmuir probe is one of the most frequently used payloads to achieve space plasma measurement missions because of their low requirement in terms of system development, size, and relatively low power requirements to drive the mission. Double Langmuir probe can overcome the limitations of a single Langmuir probe measurement as reference ground in the satellite is not required. The limitation of data communication speed is one of the problems that always occur in the development of a multi-mission lean satellite. Data communication speed can be improved by using another system such as S-band or X-band, but those will be required for high power consumption. One of the solutions is the reduced size of the data by using on-board data processing on satellites. On-board data processing aims to improve data communication speed when sending DLP data to ground stations and how to determine plasma parameters. On-board data processing for a double Langmuir probe will be calculated electron temperature and electron density by using Raspberry PI zero. On-board data processing aims to reduce the size of data so that the time of transmission between satellite and ground stations will be shorter. On-board data processing can be a pragmatic solution because processed data only contains useful information according to user requirements.

1. Introduction

HORYU-IV was a nanosatellite made by Kyushu Institute of Technology that was launched in July 2014. The main mission of HORYU-IV was to acquire an arc current waveform by on-board an oscilloscope and capture its image by a camera triggered by the oscilloscope. On the other hand, HORYU-IV had many scientific experiment payloads, one of such payloads was Double Langmuir Probe (DLP). DLP is a device to do plasma parameter diagnostics. It has two symmetric shape electrodes whose shape is either spherical, cylindrical, or planar. A DLP measurement system is more reliable when the reference ground is a critical issue, especially, in a space environment where a satellite potential is floating concerning that of plasma [1]. DLP is particularly advantageous over the Single Langmuir Probe (SLP) owing to no ground issue and symmetrical current-voltage characteristic and its circuitry cannot be damaged due to high electron current flowing in the saturation region [2].



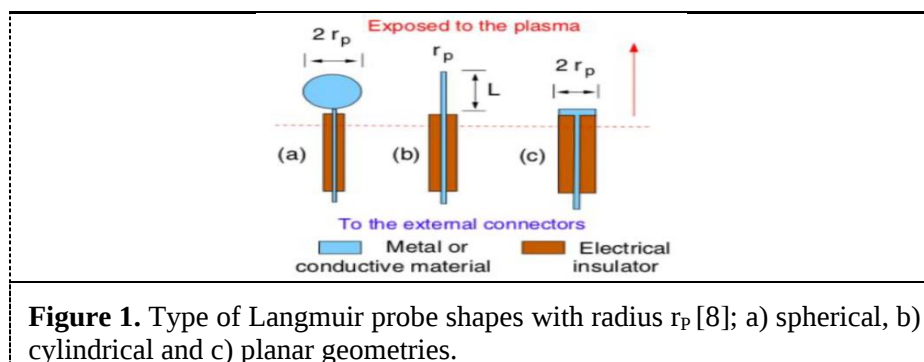
In a lean satellite, communication and data handling are usually used UHF/VHF for down-link and up-link. The communication system is a critical issue in the multi-mission satellite. In the HORYU-IV case, to transfer DLP data 800 kB which requires 2 until 3 days using a UHF link at a frequency of 437.375 MHz and a rate of 1.2 Kbps. For the solving problem with data transmission on a lean satellite, we can use high-speed communication systems with a rate of 9.6 Kbps, 1 Mbps, or more by using such as UHF, X-band, or S-band. To use high-speed communication on big satellites does not matter but for the lean satellite, that is a big problem. Adding one subsystem to a lean satellite is not easy because of the limitation of power consumption, satellite mass, and budget. The communication subsystem, one of the largest power consuming subsystems, is critical for establishing and maintaining both up-link and download speed and communication reliability [3]. Furthermore, the amount of data produced by instruments exceeds the downlink capability, leading to the need of implementing a selecting or a compressing mechanism on-board or on-board data processing on satellite [4]. On-board data processing is a technique to reduce the amount of data that can improve the performance and efficiency of the data transfer satellite system.

This paper will be explained how to calculate electron temperature and electron density on-board processing on a lean satellite. On-board data processing on the satellite is aimed to reduce the data size and to improve data transmission from satellite to ground station.

2. Research method

Irving Langmuir was one of the first to use electric probes to measure the Current-Voltage (I-V) characteristic by inserting a wire into the plasma to determine electron (T_e) and electron density (N_e) [4, 5]. DLP becomes a solution to overcome the problem introduced by the SLP method, which has a negligible influence on the discharges and yields accurate data to determine T_e , N_e , ion temperature (T_i), and ions density (N_i) in all types of discharge plasma [5, 6]. In its most basic form, the DLP consists of two probes with DC biased current collecting tips separated by a distance longer than the Debye length and the electrically isolated from the ground potential of the discharge [7]. The measured current is fixed at the ion saturation current.

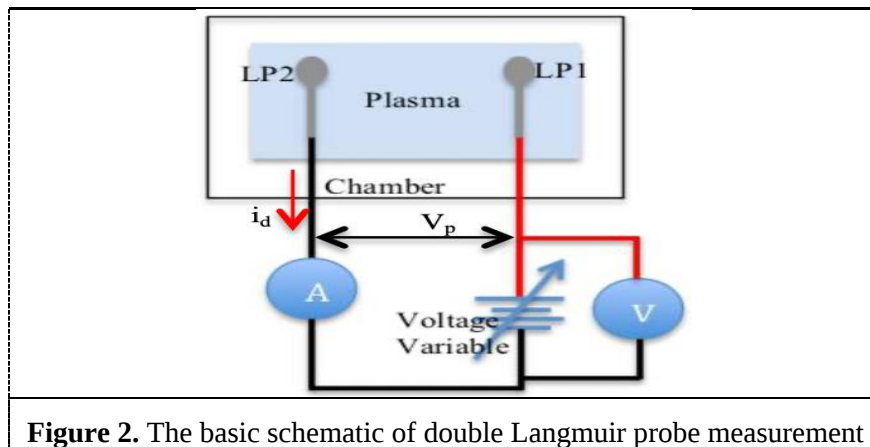
Langmuir probe (LP) diagnostics is a tool to measure plasma parameters such as temperature, density, and the electric potential of the plasma. In a broader sense, the electric probes measure the local plasma parameters by using stationary or slow time-varying electric fields to emit or to collect charged particles from the plasma [8]. The geometry of LP is chosen depending on the purpose of the measurements and the platform configuration [9]. These measuring techniques are suitable for low-density cold plasma, in the low-pressure electric discharges, ionospheric, in the lean satellite, and space plasma.



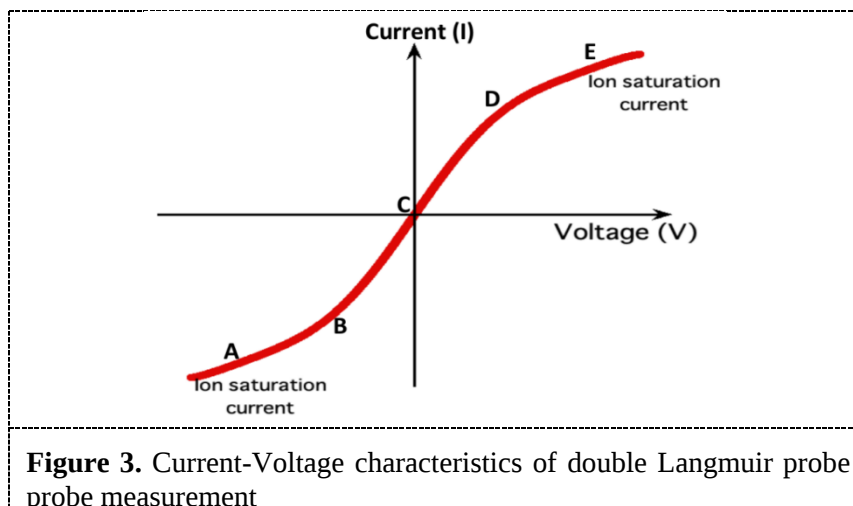
2.1. Concept of Langmuir probe

The most basic probe used in measuring the properties of plasma is an electrostatic probe. This concept is simply a small metallic electrode in the form of wire inserted into the plasma [10]. A

variable biasing voltage is applied on the probe which may be positive or negative voltage concerning the plasma. The DLP method can overcome the limitations of SLP by using two symmetric probes which are connected by a variable potential source. The basic schematic of an experiment of a double Langmuir probe is shown in figure 2. The probe is immersed into the charged particle plasma and polarized to the potential by an external circuit, the current-voltage (I-V) characteristics can be measured. The plasma parameters such as electron temperature and electron density are calculated from the I-V characteristics. The LP1 is connected to a variable voltage source and LP2 is connected to the voltage reference and then the current is measured on the LP1 where the current flowed from LP1 to LP2 passing through plasma.



The probe LP1 is connected to a variable biasing voltage and the LP2 is connected to the voltage source reference through an external circuit to measure the current. The bias voltage can be swept from negative to a positive or only positive voltage. The current is measured from LP1 to LP2 through the plasma. To understand I-V characteristics and how to collect current on DLP, we assume the bias voltage sweeping from negative to positive voltage. When the bias voltage is equal to zero, each probe will be collected zero net currents because there are no net potential acts in the current loop. This condition is shown in figure 3 at point C. If the bias voltage is a small negative, the LP2 will be collected more electrons and LP1 will be collected fewer electrons. This condition is shown in figure 3 at point B.



When the bias voltage is somewhat large negative, the LP2 will be collected the entire electron current and the LP1 is now more negative so no electron can be collected on the LP1. This condition is shown in figure 3 from point B to A. Furthermore, if the bias voltage increases negative voltage, it does not change in the current distribution because LP2 has already collected a sufficient electron current [11]. If the bias voltage is reversed to be positive, we will get the same curve on the top part because the DLP is the symmetry of the system, which is shown in point CDE in figure 3.

2.2. Determine electron temperature and electron density

The probe used in this work is an asymmetric double probe, that is, both probes have identical collection areas ($A=2\pi(0.015)^2$). One probe draws current I_1 while the other draws current I_2 , to find the electron temperature of the plasma, we have to consider the current to the probe for various potential differences between the probes [12]. Since the I-V characteristic for a double Langmuir probe is the superposition of two single probes, one must combine equations from both probes, to solve for the plasma temperature [13]. The double probes have no plasma reference (ground) connection since the probes are floating at V_f of the plasma and the total current in the probe must be zero. In this case the current through each probe as a following:

$$I = I_1 + I_2 = I_{oi} - I_{oe} \exp\left(\frac{e(V_f - V_p)}{k_B T_e}\right) = 0 \quad (1)$$

Where I_{oi} and I_{oe} are ion and electron current respectively

$$I_1 = I_{oi} \left[1 - \exp\left(\frac{eV_1}{k_B T_e}\right) \right] \quad (2)$$

$$I_2 = I_{oi} \left[1 - \exp\left(\frac{eV_2}{k_B T_e}\right) \right] \quad (3)$$

If the probe areas are equal, then $I_1 = I_2 = I_{is}$, saturation current densities given by [14].

$$I_{is} = \frac{1}{4} e n_e A \sqrt{\frac{8k_B T_e}{m_i}} \quad (4)$$

Where I_{is} , e , n_e , A , k_B , T_e , and m_i are the ion saturation current, electron's charge, electron density, the probe surface area, Boltzmann constant, electron temperature, and mass of the ion respectively. The electron temperature is related to the slope of I-V characteristic by :

$$\frac{dI}{dV} = I_{is} \left(\frac{e}{2k_B T_e} \right) \quad (5)$$

The electron temperature can be obtained from the double probe characteristic by means of the following equation for the case that both probes have exactly the same shape and surface area of collecting surfaces [15].

$$\frac{k_B T_e}{e} = \frac{I_{is}}{2 \left(\frac{dI}{dV_{p=0}} \right) - \left(\frac{dI_{is}}{dV_{p=sat}} \right)} \quad (6)$$

Where $dI/dV_{p=0}$ and $dI/dV_{p=sat}$ are the derivatives of the I-V characteristic of the double probe and the positive ion current to the potential difference between the probes, I_{is} is the ion saturation current [15]. The electron temperature is known, the electron density can be estimated by:

$$I_{is} = 0.61 n_e e A \sqrt{\frac{k_B T_e}{m_i}} \quad (7)$$

The factor of 0.6 is due to the reduction in the density of the ions in the pre-sheath, which is the region over which the ions are accelerated up to the Bohm speed [16].

3. Result and discussion

To achieve the goals, it is important to identify the major component of the double Langmuir probe electronic circuit. DLP board circuit has four main components such as digital to analog converter (DAC) analog to digital converter (ADC), current to voltage converter, and Raspberry PI[®]. The electronic circuit design is based on the previous research that has success installed in the HORYU-IV satellite. The DLP board circuit is divided into two parts: the digital part and the analog part. Between the digital and analog parts are isolated from the satellite bus using an operational amplifier (OP-Amp) isolator and serial peripheral interface (SPI) isolator. Figure 4 is shown the on-board data processing system that is used in this work. Isolating is needed to avoid the floating potential issue of single Langmuir probes and isolating the digital part entirely from the satellite bus system became a salient requirement [17].

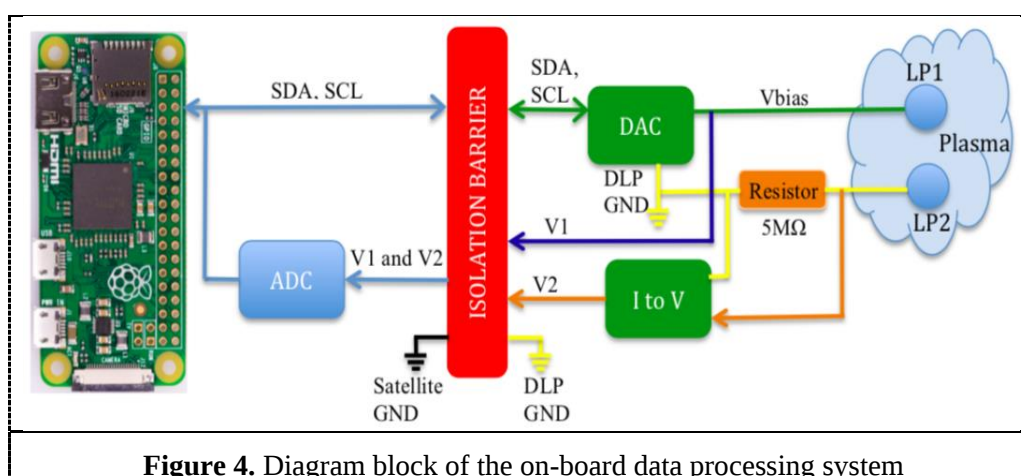


Figure 4. Diagram block of the on-board data processing system

The analog part will be generated bias voltage and measure the current passing LP_1 to LP_2 through plasma. The analog part consists of the DAC and current to voltage converter. The digital part will be converted to the analog signal to be a digital number, recording current and voltage, sending a command to DAC and ADC, and data analysis. The digital part consists of Raspberry Pi[®] and ADC. Raspberry Pi[®] will be sent commands to the DAC through SPI communication to generate the voltage range from 0V to +5V as a variable voltage source. DAC output is connected to the LP_1 and LP_2 . V_2 is measured to calculate the ion current passing through the shunt resistor in the circuit of the current to voltage converter. V_1 is the actual sweep voltage of the DAC output voltage to supply bias voltage. ADC will be converted analog signals from V_1 and V_2 to the digital number. The differential V_1 and V_2 will be given a representation of the I-V characteristic of DLP.

Bias voltage will be swept from 0V to +5V with every step 10mV. The source of the bias voltage is provided from DAC output. From the result of HORYU-IV satellite observations, the temperature in space is approximately about 0.1eV. It would have been more appropriate to bias from 0V to +5V and it needed a higher frequency for more detailed data sampling to reveal the plasma temperature in orbit [17]. Figure 5 is shown the DLP circuit for the measurement of current and voltage. In this circuit, a buffer amplifier was used as an electrical impedance transformation from one circuit to another, to prevent the signal source from being affected by whatever currents that the load may produce.

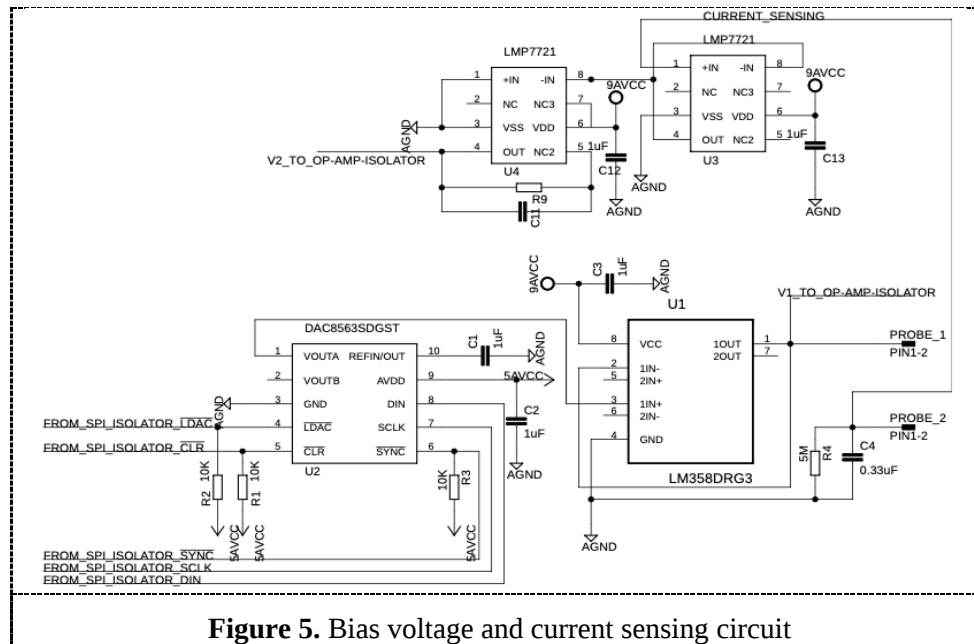


Figure 5. Bias voltage and current sensing circuit

During LP₁ charging, the bias voltage represents the voltage at the LP₁ or V₁. Voltage V₂ is measured to calculate the current passing through the plasma and the 5MΩ resistor. The difference voltage V₁ and V₂ are shown the differential voltage on the two probes during the biasing. The trans-impedance OP-Amp configuration converts an input current source into an output voltage and the current to voltage gain is based on the feedback resistance and the circuit is able to maintain a constant voltage bias across the input source as the input current changes [18]. Select the gain resistor as followed:

$$R_2 = \frac{V_{outmax} - V_{outmin}}{I_{max}} \quad (8)$$

The current can be calculated as followed:

$$I = \frac{V_2}{R_2} \quad (9)$$

The V_{out} maximum is limited to 3.3V because the OP-Amp isolator (ADuM4190) has a maximum input of 3.3V. The current to voltage converter circuit only can be measured maximum current of 5μA due to during experiment in the laboratory using source meter (Keithley 2400) and looking at DLP data on HORYU-IV satellite, the current was not more than 5 μA. If the input current is bigger than 5 μA, the current to voltage converter will not work and the output voltage is always maximum value. 16 bits ADC is used to measure the current and voltage of DLP. It can measure the minimum input voltage of 152.58 μV.

3.1. Experiment

The experiment used the square chamber at the Laboratory for Spacecraft Environment Interaction Engineering (LaSIENE) of Kyushu Institute of Technology. The plasma was made by a radio frequency (RF) generator and Argon gas was controlled by a flow-meter. The RF generator has used a frequency of 13.56 MHz. During the experiment, the power level of the RF generator was set 25 watts and the argon gas was set at a flow rate of 30 ccm. Figure 6 shows the DLP board, experiment setup, and position double Langmuir probe in the square chamber. The pressure inside the square chamber was maintained at 1.2×10^{-2} Pa and the probes use spherical shape with a radius of 1.5 cm.

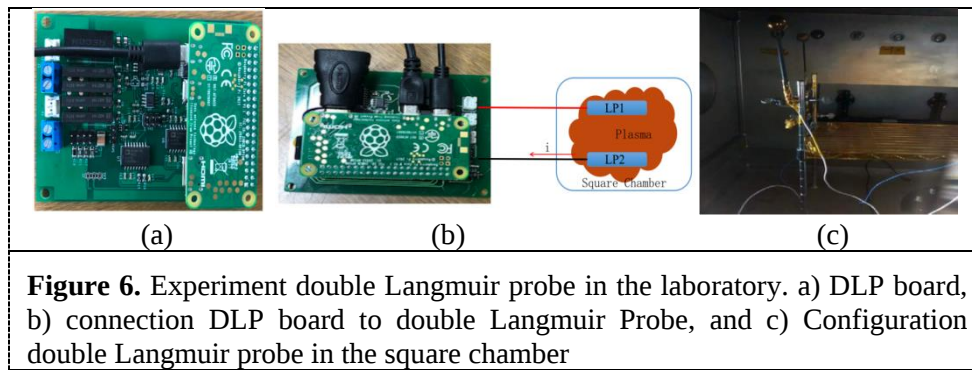


Figure 6. Experiment double Langmuir probe in the laboratory. a) DLP board, b) connection DLP board to double Langmuir Probe, and c) Configuration double Langmuir probe in the square chamber

3.2. Algorithm Software

A DLP board was installed on the Raspberry operating system which is built based on Linux Debian and this system was programmed using Python programming. There are some reasons to use Python programming, the first, Python is a programming language that has recently become very popular that it is now the fourth most popular programming language. The second is just one of the many programming languages that can be used on the Raspberry Pi[®]. The third has been selected as a good practice to start when learning about programming by providing a rich set of coding tools while still allowing simple programs to be written without a fuss [19]. There are four main programs in this system: generated bias voltage, current and voltage measurements, data recording, and data analysis. Figure 7 shows the algorithm software of on-board data processing for a double Langmuir probe.

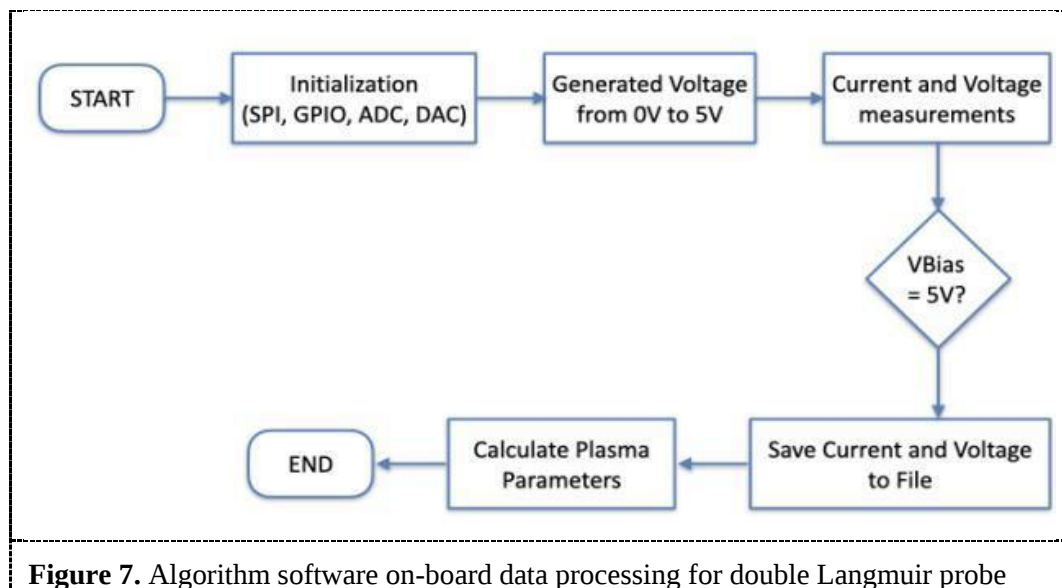


Figure 7. Algorithm software on-board data processing for double Langmuir probe

The initialization is defined as variable, SPI, general port input-output (GPIO), ADC, and DAC configuration. Initializing SPI is defined as a bus, chip select, speed, and mode (slave or master). DAC is configured to use an internal reference of 2.5V, gain = 2, disable LDAC pin, and power-up mode. ADC is configured to use 32 CLK, single SDO mode, maximum input as same as $V_{REF} \times 2$, single-ended input, internal reference of 2.5V, and straight binary format. After initialization, the bias voltage will be swept from 0V to 5V with pre-set voltage steps of 10mV. For the best resolution of electron temperature, the step voltage increment should be a few times smaller than the minimal value of electron temperature [20]. During the process of measuring the current and voltage, data is temporarily stored in the array that has been defined at the initialization step. This process will continue until the

bias voltage equals 5V. If the DAC output channel is equal to 5V, data in the array will be stored permanently into the text file after the subroutine data analysis was executed.

3.3. Computing electron temperature and electron density

Determining the plasma parameters from the I-V characteristic involves several steps such as data smoothing, interpolation, and linear curve fitting. The electron temperature was evaluated from the I-V characteristic. Figure 8 shows how to collect all variables to compute electron temperature and electron density. The polyfit method was applied in this data processing to reduce the noise by using the least-squares polynomial calculation for a given data set. For calculation electron temperature and electron density were used a double slope method in the retarding and saturation region.

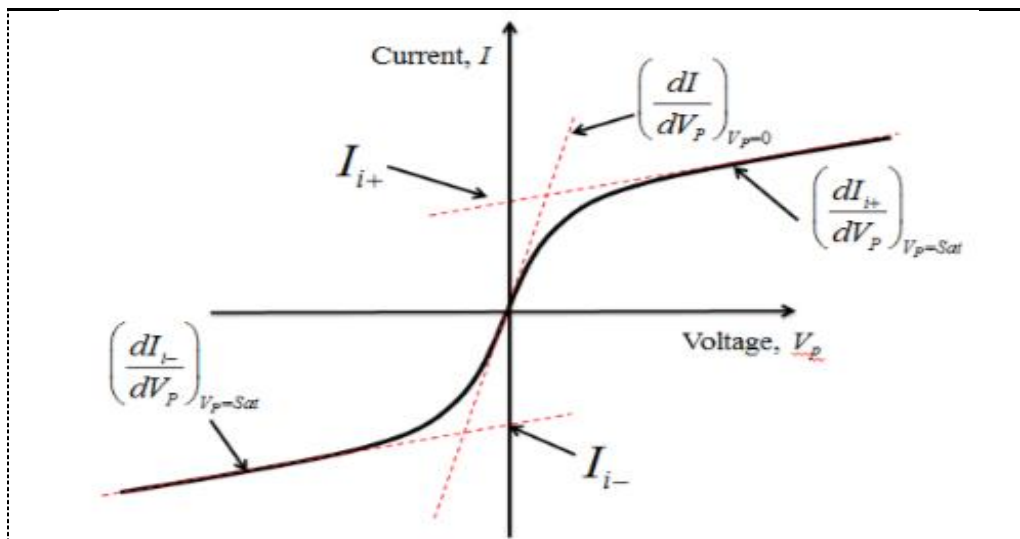
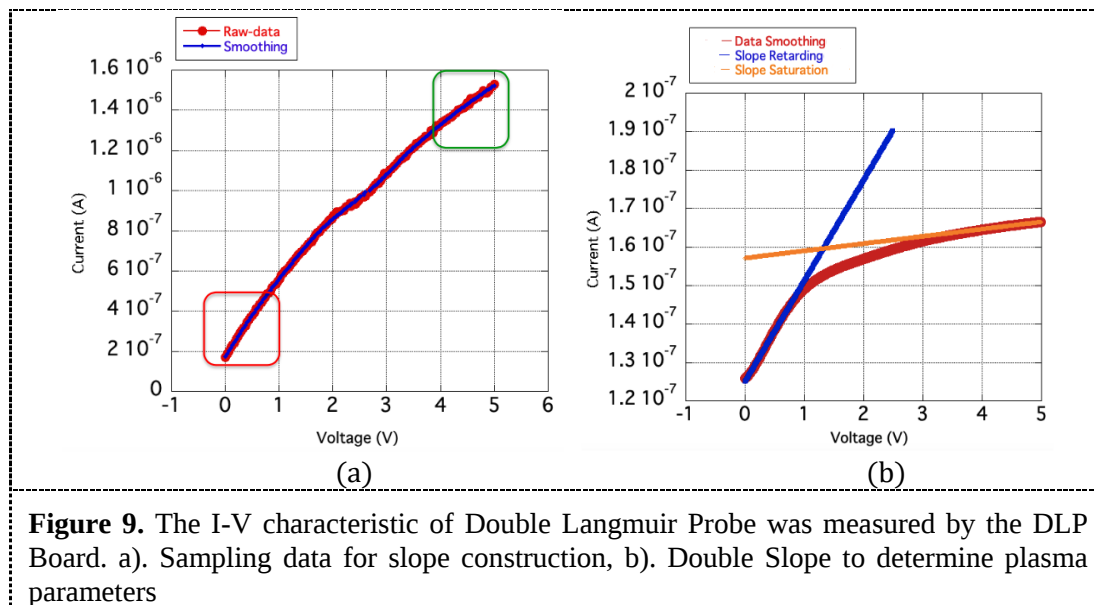


Figure 8. Determining variable value to computer T_e and n_e from I-V characteristic

The Langmuir probe technique involves applying a voltage to a probe immersed in plasma and observing the current and the benefits of the simplicity of this technique, however, are offset by the complexity of the theory required to analyze the I-V characteristic [9]. The I-V characteristic depends on the geometry of the Langmuir probe. Nevertheless, the I-V characteristic of the double Langmuir probe can be qualitatively described as shown in figure 8. By evaluating the slope of the I-V characteristic at the retarding region and the ion saturation current, electron temperature and the electron density values can be estimated. Consider constructing the I-V characteristic in the plasma consisting of positive and negative ions of equal mass and temperatures, in this case, due to the thermal speeds of the positive and negative plasma constituents are identical, expectation $V_p = V_f = 0$ and $I_{+is} = I_{is}$ [5].

The first slope ($dI/dV_{p=0}$) is drawn at a retarding region and the second slope ($dI/dV_{p=sat}$) is drawn in the ion saturation current. The I_{is} was estimated from the ordinate of the intercept between the first slope and the second slope. The probe theory suggests that electron temperature and electron drift velocity can be estimated from the slope of the characteristic at V_p because the slope of the characteristic curve is affected by electron temperature [21, 13]. The first slope is drawn by sampling 10-15% of total data in the retarding region and the second slope is drawn by sampling 10-15% of total data in the saturation current region. Figure 9a shows sampling data for slope construction and figure 9b shows the results of making the two slopes. The simple regression method is used to make a slope in data analysis, the use of this method due to the data has only one independent variable and one dependent variable. The current and voltage are defined as the independent and dependent variables.



The simple linear regression can be used to model a linear relationship between one response variable and one explanatory variable and to predict the value of a continuous response variable [22]. the model of simple linear regression can be written as :

$$y = ax + \beta \quad (10)$$

Where y , x , α , β are the predicted values of the response variable, response variable, intercept, and coefficient respectively. The software will predict the dependent variable as a function of the independent variable by formula $y=ax+b$. The value of $dI/dV_{p=0}$ provides information about the electron temperature of the plasma. The value of $dI/dV_{p=0}$ can be taken at any point in the slope retarding region (blue line) in figure 12 after the point of intersection. The value of $dI/dV_{p=sat}$ can simply be taken as the saturation current over the point of intersection on the orange line in figure 10b. The electron density can be calculated from the ion saturation and electron temperature using Equation (7). Table 1 shows the results of calculations of electron temperature and electron density from experimental data.

Table 1. The result computed electron temperature and electron density

Experiment	By Program		By Hand	
	T_e (eV)	N_e (m^{-3})	T_e (eV)	N_e (m^{-3})
1	1.10	2.6×10^{11}	1.60	2.1×10^{11}
2	1.11	2.5×10^{11}	1.61	2.1×10^{11}
3	1.15	2.5×10^{11}	1.61	2.1×10^{11}
4	1.21	2.3×10^{11}	1.59	2.2×10^{11}
5	1.20	2.6×10^{11}	1.60	2.1×10^{11}
6	1.11	2.6×10^{11}	1.61	2.1×10^{11}

As a validation, the calculation results using the software are compared with the calculation results manually. The value obtained from calculations using software is smaller than the results of manual calculations with the difference between 0.4 to 0.5 eV. This is due to drawing the slope of $dI/dV_{p=0}$ and the slope of $dI/dV_{p=sat}$ draw manually by following the existing curve shape. Determining the value of I_{is} , $dI/dV_{p=0}$, and $dI/dV_{p=sat}$ are done by moving the cursor at a certain point. Making the slope of $dI/dV_{p=0}$, $dI/dV_{p=sat}$, and determining the value of I_{is} can give different results.

4. Conclusion

With send of the electron temperature and electron density values of the results on-board data processing, data transmission can be increased due to the data size becoming much smaller than the data before it is processed. Electron temperature and electron density are calculated using the double slopes method. A double slopes method for computing plasma parameters consists of the steps followed: data smoothing, drawing the linear line at the regarding and the saturation regions, and extract information from the I-V characteristic. To make a linear line at the retarding and the saturation regions, it is done by making two slopes. Both slopes are made using simple linear regression. The first slope is used to get the value of $dI/dV_{p=0}$ and the second slope is used to get the value of $dI/dV_{p=sat}$. The value of $dI/dV_{p=0}$ can be taken at any point in the slope retarding region after the point of intersection. The value of $dI/dV_{p=sat}$ can simply be taken as the saturation current over the point of intersection. The accuracy of the electron temperature and electron density is determined by how to make slope at the retarding and saturation regions.

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