DEVELOPMENT OF GENERATOR CIRCUIT FOR ELECTRON TEMPERATURE AND DENSITY PROBE (TeNeP) FOR MYSAT

by

MUHAMMAD AADAM BIN ABDUL LATIF

Thesis submitted in fulfilment of the requirements for the Bachelor Degree of Engineering (Honours) (Aerospace Engineering)

June 2018

ENDORSEMENT

I, Muhammad Aadam bin Abdul Latif hereby declare that all corrections and comments made by the supervisor and examiner have been taken consideration and rectified accordingly.

(Signature of Student)

Date:

(Signature of Supervisor)

Name: DR. SITI HARWANI MD YUSOFF

Date:

(Signature of Examiner)

Name: DR. AHMAD FAIZUL HAWARY

Date:

DECLARATION

This thesis is the result of my own investigation, except where otherwise stated and has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any other degree.

____

(Signature of Student)

Date:

ACKNOWLEDGEMENT

All praise is due to God alone, for all the countless blessings given, and thanks to my family for their love and support.

I wish to express my sincere thanks to Prof. Ir. Dr. Mohd Zulkifly Abdullah, Dean of the School of Aerospace Engineering, and Prof. Ir. Dr. Mohd Rizal Arshad, Dean of the School of Electrical and Electronics Engineering, Universiti Sains Malaysia (USM) for providing me with all the necessary facilities.

I place on my record, my sincere gratitude to Mdm. Siti Harwani Md Yusoff and Dr. Norilmi Amilia Ismail, lecturers, School of Aerospace Engineering, for their constant encouragement and guidance.

I also thank Mr. Muhammad Azwan Nasirudin, research officer, and Mr. Ismail Mohamed Shorhami, assistant engineer, USM Space System Lab (USSL). I am extremely grateful and indebted to them for their expert, sincere and valuable guidance and encouragement extended to me.

I take this opportunity to record my sincere thanks to all the members of the USM Robotics Research Group (URRG), and Underwater, Controls, and Research Group (UCRG), School of Electrical and Electronics Engineering, and to all who, directly or indirectly, have lent their helping hand in this venture.

DEVELOPMENT OF GENERATOR CIRCUIT FOR ELECTRON TEMPERATURE AND DENSITY PROBE (TeNeP) FOR MYSAT

ABSTRACT

Malaysia Youth Satellite (MYSAT) is a scientific CubeSat-based project initiated by School of Aerospace Engineering Universiti Sains Malaysia in 2016. The objective of the MYSAT mission is to measure electron density in E-layer of ionosphere. This mission is driven from a study which reported that earthquake precursors can be analysed from the ionosphere, which opens the possibility in predicting future earthquakes. It was found that one of the common features shown from ionosphere data measurement from several earthquakes is the electron density. Electron temperature and density probe (TeNeP) is an instrument developed based on DC Langmuir Probe that could help researchers studies the ionosphere to potentially predict future earthquakes. The device develops a technique by measuring current-voltage (I-V) characteristics of an electrode immersed in charged plasma particles. The I-V characteristic of the plasma will then be retrieved from the device where the plasma's electron and ion density together with the temperature can be acquired. MYSAT, a Cube-Sat based on a 1U platform could contribute into this on-going research. Hence, an already developed TeNeP generator circuit based on a 2U platform needs to be redeveloped for MYSAT's 1U based platform. Several performance tests are performed to the TeNeP generator circuit in the preparation of the MYSAT mission.

PEMBANGUNAN LITAR PENJANA KUAR SUHU DAN KETUMPATAN ELEKTRON (TeNeP) UNTUK MYSAT

ABSTRAK

Malaysia Youth Satellite (MYSAT) adalah projek berasaskan CubeSat yang diasaskan oleh Pusat Pengajian Kejuruteraan Aeroangkasa Universiti Sains Malaysia pada tahun 2016. Objektif misi MYSAT adalah untuk mengukur ketumpatan elektron dalam lapisan E ionosfera. Misi ini didorong oleh kajian yang melaporkan bahawa prekursor gempa bumi dapat dianalisis dari ionosfera, yang membuka peluang untuk meramalkan gempa bumi masa depan. Telah didapati bahawa salah satu ciri umum yang ditunjukkan dari pengukuran data ionosfera dari beberapa gempa bumi ialah ketumpatan elektron. Kuar suhu dan ketumpatan elektron (TeNeP) adalah instrumen yang dibangunkan berdasarkan kuar Langmuir berarus terus yang boleh membantu para penyelidik mengkaji ionosfera untuk meramalkan potensi gempa bumi masa hadapan. Peranti ini mengembangkan teknik dengan mengukur ciri-ciri arus-voltan (I-V) elektrod yang direndam dalam zarah plasma tercas. Ciri I-V plasma kemudiannya akan diambil dari peranti di mana elektron plasma dan ketumpatan ion bersama-sama dengan suhu boleh diperolehi. MYSAT, sebuah Cube-Sat berdasarkan platform 1U boleh menyumbang kepada penyelidikan berterusan ini. Oleh itu, litar penjana TeNeP yang telah dibangunkan berdasarkan platform 2U perlu dikecilkan kepada platform berasaskan MYSAT 1U. Beberapa ujian prestasi dilakukan pada litar penjana TeNeP dalam persediaan misi MYSAT.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

MYSAT	Malaysia Youth Satellite
TeNeP	Electron temperature and density probe
DC	Direct current
I-V	Current-voltage
e	Elementary charge (unit)
esu	Electrostatic system of unit
OML	Orbital motion limited
SAL	Sheath area limited
ETP	Electron temperature probe
RF	Radio frequency
RC	Resistor-capacitor
AC	Alternating current
IC	Integrated circuit
UHR	Upper hybrid resonance
SHR	Sheath resonance

LIST OF SYMBOLS

e : Electron charge [e]

T_e : Electron temperature [K]

n : Concentration of electrons at any place of potential V [cm^{-3}]

n_e : Electron density [cm^{-3}]

n_i : Ion density [cm^{-3}]

n_0 : Concentration at a point where the potential is zero [cm^{-3}]

V : Potential at any point [V]

V_a : Anode potential [V]

V_s : Spacecraft potential [V]

V_p : Probe potential [V]

V_r : Retarding potential [V]

V_f : Floating potential [V]

V_{fa} : Floating potential with amplitude a [V]

V_{f2a} : Floating potential with amplitude $2a$ [V]

V_{in} : Input voltage [V]

a : Amplitude

G : Gain

I : Current density of electron or of single-charged positive ion [$A \cdot cm^{-2}$]

I_e : Electron current density [A]

I_d : Drift current density [$A \cdot cm^{-2}$]

I_i : Ion current density [$A \cdot cm^{-2}$]

I_0 : Electron current density in the plasma near the sheath edge [$A \cdot cm^{-2}$]

I_{es} : Random surface electron current $[A]$

m_e : Electron mass $[kg]$

m_i : Ion mass $[kg]$

v : Electron velocity $[ms^{-1}]$

M : Molecular weight $[kg/mol]$

x : Distance from emitter to collector $[cm]$

k : Boltzmann constant, $k = 1.38 \times 10^{-23}\ J/K$

S : Probe's surface area $[cm^2]$

θ : Phase angle $[degree]$

t : Time $[seconds]$

ω : Angular frequency $[rad\ s^{-1}]$

$J_n(z)$: n^{th} Bessel function of the first kind

$I_0(z)$: Modified Bessel function of the zeroth order

i : Imaginary unit, $i = \sqrt{-1}$

Z_s : Sheath impedance $[\Omega]$

Z_p : Probe impedance $[\Omega]$

f_{UHR} : UHR frequency $[MHz]$

f_{ce} : Electron gyro frequency $[MHz]$

f_{pe} : Electron plasma frequency $[MHz]$

CHAPTER 1

INTRODUCTION

1.1 Background study

Malaysia Youth Satellite (MYSAT) is a scientific CubeSat-based project initiated by School of Aerospace Engineering Universiti Sains Malaysia in 2016. The mission objective of the MYSAT is to measure the electron density in E-layer of ionosphere. Previous study shown the perturbation can be detected in the ionosphere before large earthquake occurred and might have the possibility in predicting future earthquakes. It was found that one of the parameters that shown significant change due to the seismic activity is electron density.

The DC Langmuir Probe, which measures the electron temperature (Te) and electron density (Ne) in plasma is suggested to be mounted on MYSAT. The device develops a technique by measuring current-voltage (I-V) characteristics of an electrode immersed in charged plasma particles. It is done by sweeping the immersed electrode potential's in reference to the plasma potential while measuring the current from the electrode. An I-V characteristic of the plasma will be retrieved from the device where the plasma's electron and ion density together with the temperature can be acquired.

1.2 Problem statement

Several concerns discussed on the possible factors that could affect TeNeP measurement accuracy, are found to be the probe installation, probe surface contamination, and analog circuit design. Analog circuit design is among the most concerned part in this project. The main issue related to this problem is the low measurement resolution to compensate the abrupt changes in plasma current which could heavily affect the accuracy of the TeNeP itself. This is due to the insufficient capability of the analog to digital converter which results in the low-resolution measurement. Another obvious factor related to this problem is the noise contained in the measurement which resulted from the interaction between the probe and the plasma. As solutions, this study focuses on improving the analog circuit design as well as the algorithm used in measurement.

1.3 Objective

This project objective particularly focuses on developing the TeNeP generator circuit. This generator circuit development requirement should comply with the already developed TeNeP analog circuit based on a 2 U platform, to be implemented in the 1 U platform.

CHAPTER 2

LITERATURE REVIEW

2.1 Electric discharge in plasma

Based on studies made by Langmuir, when a difference of potential is applied to two electrodes in a gas, and current flows through the gas between these electrodes, the potential distribution in the space forms randomly, but rather gives wide variety of predictions (Langmuir, 1932). This statement also has been discussed by Brown in his study on plasma physics (Brown, 1967). There are many types of discharge, which most potential drops are close to the cathode, the rest of the space has potential of anode. It is too vast that it is common to have potential maxima and minima, and also the potential maxima higher than anode, and potential minima lower than cathode.

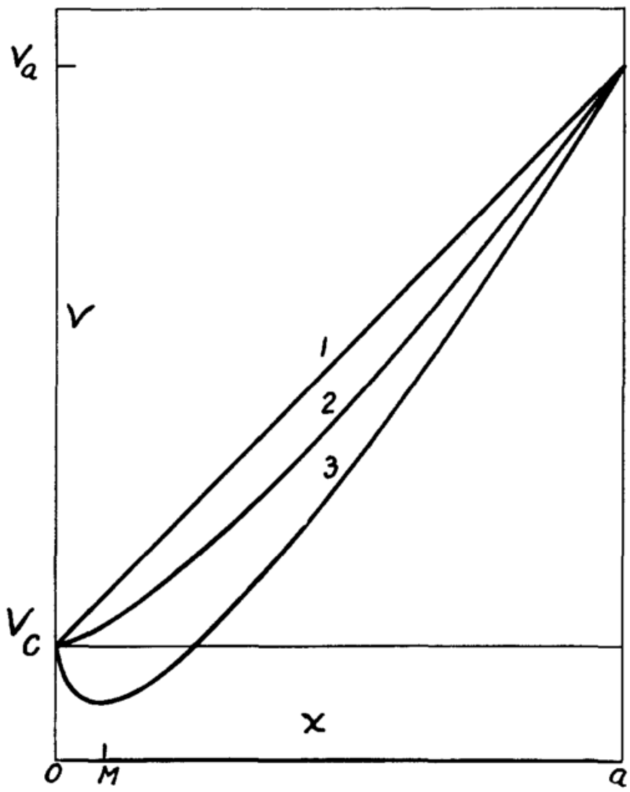

Figure 2.1: Potential distributions in unipolar discharges between parallel plane electrodes (Langmuir, 1932).

Referring to Figure 2.1, line 1 shows that the space charge is negligible, whereas curve 2 shows that en_e is large enough to be important, while curve 3 shows that electrons are emitted with initial velocities hence produces potential minimum M (Langmuir, 1923).

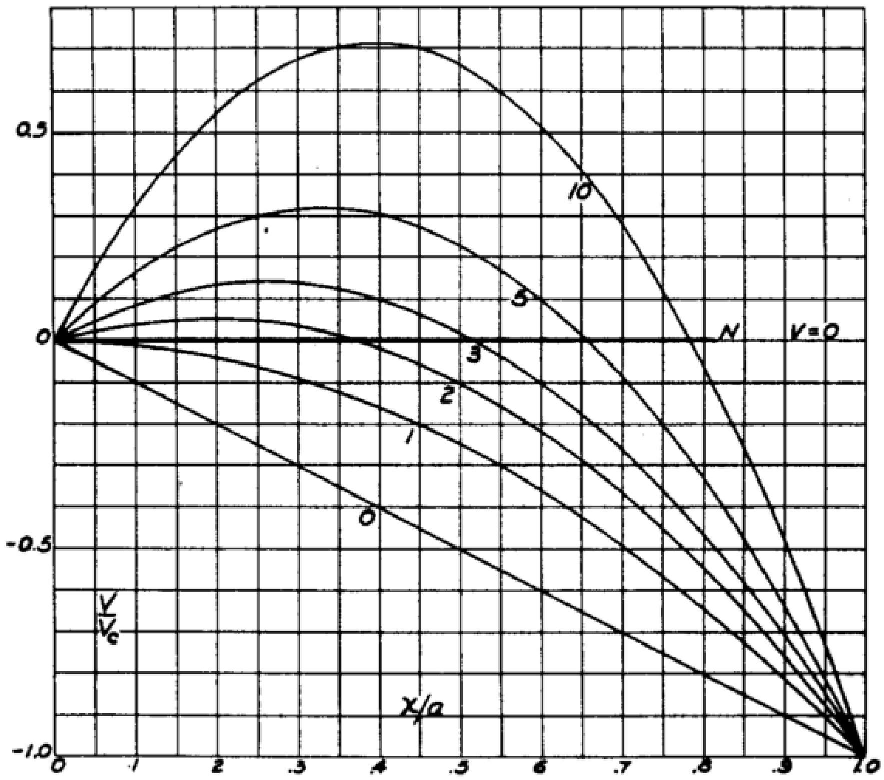

Figure 2.2: Potential distributions between parallel plane electrodes when ions are generated uniformly between them (Langmuir, 1932).

Let's assume K ions are produced per unit volume per second (Langmuir, 1929). An equal number of electrons are generated simultaneously as the positive ions are produced by the gas ionisation. If $K > K_1$, there will be a potential maximum between A and C whereas if $K < K_1$, there will be no potential maximum between A and C. In the event of $K < K_1$, the electrons will flow to the electrode A as fast as they are generated. There is therefore an electron current flowing in the opposite direction to C, but the electron current has no appreciable effect in the space charge. In the event of $K > K_1$, there is a tendency to develop a potential maximum. Since this maximum has a potential higher than both of the electrodes, the low velocity electrons produced by ionisation are trapped in the region above O-N (refer Figure 2.2) which tends to accumulate in large numbers. However, the presence of the accumulated electrons adds a negative space charge so that the potential of the region falls until it reaches a value at which the electrons can just escape to the anode as fast as they are produced. This potential is slightly higher than that of the anode since the electrons have initial velocities which enable them to travel against a small retarding field.

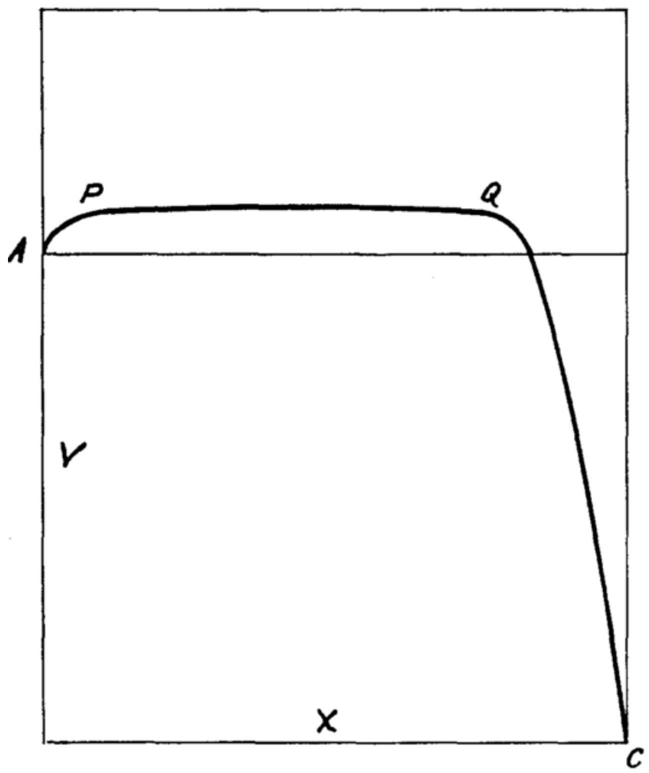

Figure 2.3: Potential distribution arising from the trapping of electrons in a region having a potential maximum (Langmuir, 1932).

From Figure 2.3, positive ions flow in an accelerating field from P to A and from Q to C. Electrons flow against a retarding field from P to A only. There are practically no electrons in the region between Q and C, as the strong retarding field bars them from entering this region. The space between P and Q is brought to nearly uniform potential by the electrons trapped in this space (assuming for the present that no electrons disappear from this region except those which travels to A). The reason for this levelling of potential is clear when we consider that the electrons, because of their high mobility, accumulate instantly in a potential maximum and thus lower its potential, whereas they travel out from a minimum and thus raise its potential. Since the region between P and Q is therefore a region of very small electric field, the number of electrons per unit volume in this space must be nearly the same as the number of positive ions, in other words, the electrons neutralise the positive ion space charge and we have $n_e = n_i$.

The needs for the development of a plasma in any discharge is that the rate of generation of ions shall be sufficient to produce a potential maximum within the tube. The calculation in this section serve to illustrate the fundamental factors which determine the occurrence of phenomena that are characteristic of gaseous discharges, as contrasted with the pure electron discharges that occur in high vacuum. Losses of ions to the walls of the tube and other secondary factors cause the currents needed to produce a well-defined plasma are somewhat greater than those calculated previously.

It is legitimate to consider a plasma to be a space or region where ions and electron accumulate together at the same capacity from each other, in other words, $n_e = n_i$. The recombination of ions and electrons at low pressure gases has been found to be almost negligible in typical plasmas. Electrons rarely collide with ions due to its path orbiting the ions which reduces its probability to recombine with ions. Ionisation process cannot give significant kinetic energy to the ion formed due to the electrons minute kinetic energy, thus the kinetic energy of the ions when first formed will be the same as those of the neutral gas molecule. However, it produces a new electron, hence there will be two electrons replacing the original one. Extra energy from the original electron after taken from ionisation, is divided between two electrons in variable ratios. Electrons generated by ionisation in the plasma therefore have considerable energy. Hence, few of the high kinetic electrons will escape through the anode sheath while the rest with lower kinetic energy trapped within the plasma between the sheaths that bounds them.

In the case of a typical plasma, a region where gas discharge accumulates in a long tube. Consider a current flow, there is normally a small potential gradient throughout the length of the cylindrical plasma. The electrons in the plasma are therefore being accelerated by the field which acts on them, but soon a stationary stage is reached in which the energy losses of the electrons by their collisions with gas molecules just balance the gain in energy produced by the field. With a long uniform positive column, the electron temperatures are then the same throughout the plasma, but the concentration is also uniform due to the potential gradient. Thus, the Boltzmann equation is not applicable to determine changes in concentration along the length of the tube, but it may well be used to determine variations of concentration over a cross-section. Therefore, two kinds of current must be able to be distinguished, one is the random current density I_e and another is the drift current density I_d. The energy input per unit volume into the plasma is thus the product of I_d by the potential gradient. Usually the random current density is several times greater than drift current density.

If the positive ions had kinetic energies approximately equal to those of the electrons and were also moving in random directions, it would follow that the positive ion current densities I_i would be less than I_e in the ratio of $m_e^{\frac{1}{2}}: m_i^{\frac{1}{2}}$. However, positive ions are generated without initial velocities. Thus, it is possible that the ions should also acquire Maxwellian velocity distribution.

As much as the potential of the plasma is not entirely uniform, the potential drop from the centre of the sheath edge is usually less than one volt. These ions gain their velocity much from the plasma field. Potential maximum can be found near the centre of the plasma, while the rest are approximately proportional to the square distance from the maximum potential point. Further from the radial distance is the much lesser electron concentration region, as applied to the plasma field from the Boltzmann equation. It is however not significantly affecting the ion concentration; hence large positive space charge is formed near the walls of the tube due to the rapidly decreasing electron concentration compared to ion. This means greater radial distance causes rapid potential declination which makes the electron's concentration fell close to zero. We can consider the region between sheath and plasma are separated from each other although the transition between them are not exactly discontinuous, but rather a very small distance.

A steady state plasma, which n_p remains unchanged over time, it is important for the ions to move out from the regions in which they are produced at the same moment they are generated. Presence of electric fields are required to draw the ions from these regions; which can be configured only by increasing the positive charge slightly within the plasma. High energy electrons will move out from the plasma, leaving behind a small excess of positive charge. This positive charge increases up to a point the ions flow out from the plasma into the surrounding sheaths at a rate equal as they are produced. At low pressure, the ions flow out without combining with gas molecules, as the ions movement obeys to Eqs. (3.2) and (3.3), except the fact that different ions originate in different positions must be considered.

As the plasma's potential value is the same as the walls' potential value, the walls should receive electron currents much greater compared to the positive ions reaching the walls. Steady state condition requires the positive and negative charges reaching the walls must be equal. Hence, the walls have to be highly-negatively charged to make the electrons goes back into the plasma, and at the same time render the walls to be covered with positive ion sheath. Boltzmann equation will be able to calculate the potential drop in the sheath.

The conditions with the typical unipolar discharge are the same through the positive ion sheath. Ions from the plasma moves towards the sheath edge radially within one volt of potential energy. As they enter the sheath region, the strong electric field accelerates them toward the walls in a rapid manner. Hence, it is applicable to employ Eq. (3.6) to the positive ion currents that enter the sheaths. Option to not neglect the effect of the initial velocities to the ions that enter the sheath, we may as well modify using the basis of Eq. (3.6). T can be equal to $\frac{1}{2}T_e$; V is the voltage drop within the sheath and I is equal to I_i, the positive ion current density in A·cm^{-2} which moves out from the plasma. Calculation can be proceeded for the sheath thickness by Eq. (3.6) or its modified counterpart. Higher positive ion current density should cause the sheath becomes thinner.

Sealing part of the glass wall which surrounds a plasma by a metal electrode or collector, the positive ions rate reaching the walls can be measured (Langmuir et al., 1924). As the collector is potentially negative referenced to the plasma, a positive ion current of density I_i goes to the collector and electrons moves out; and enough negative potential will result in no electrons left on the collector. This happens if the collector's potential surpasses -5 to -10 volts referenced to the surrounding plasma. Experiment proves that as electrons moves out completely, current that flow to a plane collector is almost independent of the voltage applied and considered actual value of I_i. Changing the voltage would change the sheath thickness around the collector, while over the glass walls remain unchanged. Sheath boundary would be formed near the collector's edges in curved surface shape. Equations derived to counter the effect are considered only for square and circular shaped collector. However, eliminating the effect can be done by covering the collector's edge with a guard-ring and at the same time to maintain its potential, while the current density is only measured from the inner collector.

As the collector's potential is being increased constantly to a point where no electrons are being repelled from the plasma, the current on the collector will be decreased from value I_i, since the collector is now having electrons and positive ions at the same time. Increasing the potential makes the current surpasses zero mark and increases with the opposite sign. Increments from the electron current accounts for measurement of electron current density I_e which indicates its ability to move against a negative potential from the collector. From Eq. (3.9) it is seen that the logarithms of these values of I_e should be linear to the voltage V and the slope obtained from the line from $\ln I_e$ against V plot which yields $\frac{e}{kT_e}$.

Experiments repeated through various conditions still gives semi-logarithmic plots, obtaining straight through 1000 I_e value increment range. These plots prove that regardless of any cases, Maxwellian velocity distribution always applies to electrons in a plasma. The distribution is furthermore maintained as the walls constantly remove the faster electrons, so the disturbed equilibrium must be regained quickly (Langmuir, 1925).

2.2 Langmuir probe

It is based on a study of Langmuir probe by Abe and Oyama (Abe and Oyama, 2013). It is a probe simply configured as an electrode immersed in a charged-particle plasma which yields its current-voltage (I-V) characteristics. The I-V characteristics itself able to convey more information about other parameters from the plasma such as its temperature and electron density number of the thermal electrons. Its ability to measure such parameters provided with its mobile configuration has been widely accepted to be used frequently on sounding rockets and satellites. Previous studies have shown that it also can give information the plasma's energy distribution characteristics and density number of ion.

The basic technique of the Langmuir probe in measuring I-V characteristics is to apply DC voltage sweep to electrodes immersed in the charged-particle plasma. This method has been applied in PIC.A.S.S.O. by the Royal Belgian Institute For Space Aeronomy (Ranvier et al., 2017). As simple as it sounds, there is no definite configuration of a Langmuir probe that is theoretically accepted to be used in any measurement condition. Achieving an accurate Langmuir probe measurement greatly dependent to a custom modification that consider these factors such as probe size and geometry, plasma temperature and density and platform velocity. Two important relationship to be considered in designing a Langmuir probe is between the probe dimension and Debye length of the plasma. There are two concepts used to express the current behaviour on the plasma immersed probe; orbital motion limited (OML) and sheath area limited (SAL). These two approximations are bounded to condition such as; OML is accepted when the probe is thinner than the sheath thickness surrounding the probe, while SAL is accepted when the probe is equal or thicker to the sheath thickness.

There have been measurements made to the ionospheric parameters using ground-based instruments, other than the Langmuir probe technique is the radar backscatter technique (Evans, 1962). Comparison shows that Langmuir probe data gives around 10% to 30% higher data compared to radar technique (Schunk and Nagy, 1978). Measurement accuracy of Langmuir probe can be greatly affected from probe surface contamination which tend to give higher electron temperature estimation value from the actual value. Hysteresis has also been one of the common effect of probe contamination.

Langmuir probe geometry are often designed based on cylindrical, spherical or even planar shape. As mentioned before, Langmuir probe design are not definite and has to be designed based on its platform configuration and measurement purposes. However, designers often choose the cylindrical geometric design, due to its nature to provide greater surface area by increasing its length without having to bulk up the geometric size, and at the same time satisfies the OML condition due to its thinner probe design. This design configuration allows a sufficient current attraction within OML condition even at low electron number of density. On the other hand, spherical probe is significantly more difficult to achieve OML condition under the same situation and at the same time to get a sufficient current attraction. But the approximation on the current emitted through photoelectrons contribution from the probe surface is easier to apply on spherical probe due to its constant contribution regardless of sunlight direction. Planar probe current emitted through photoelectrons contribution is rather simpler to be considered, as it can be represented by a simple function of the incident angle of the sunlight. In a case of sun-oriented spinning satellite, placing the probe surface parallel to the direction of sunlight can minimise the photoelectrons contribution.

Hirao and Oyama had highlighted the effect of probe surface contamination in compromising the electron temperature measurement accuracy (Hirao and Oyama, 1972). The problem forces them to propose a solution to this problem, which by developing a method to maintain the cleanliness of the probe surface (Oyama and Hirao, 1976). It is done by protecting the electrode surface within a glass tube until measurement starts. Planar probe concept design has been adopted on Japanese Akebono satellite (Abe et al., 1990). In fact, they installed two planar probes, both placed right-angled to the solar panel surface to ensure the probe surface is always parallel to the sunlight direction, hence minimising photoelectrons contribution.

OML and SAL factors should always be considered when deciding the probe dimensions. For OML condition to be met, the probe radius must be smaller than the sheath thickness around the electrode. On the other hand, for SAL condition to be met, the probe radius must be larger than the sheath thickness. Lower ionosphere typical conditions ($T_e \approx$ 1000-3000 K, $N_e \approx 10^4$-10^6 cm^{-3}) yields the sheath thickness in the order of 10^{-2} m, hence making it possible to make a probe that meets SAL condition. However, the sheath thickness becomes larger (~10^{-1} m) in the higher ionosphere and the plasmasphere. Thus, meeting SAL condition requires the probe to be designed small, which is unfavourable. The other, OML condition is easier to be met and hence, become a basis probe dimensional design which has been applied to numerous sounding rockets and satellites.

As a spacecraft being charged either positively or negatively, sheath will be formed surrounding the probe surface, affecting its measurement. The probe characteristics has to be modified, should the probe be on the inside of the negatively charged spacecraft sheath, despite being outside. Olsen *et al*. suggested that the probe characteristics are mostly deviated from the usual OML favoured design, which directly affecting the process of collecting plasma parameters from the measured I-V characteristic curves (Olson et al., 2010). In the event of such situation, sheath effect must be taken into consideration on the Langmuir probe usage since the Debye length increases as the electron temperature or density increases.

Wake produced due to the space drag acting on the satellite varies in shape, depending on the satellite's shape and velocity, and the plasma's surrounding temperature and number of density. To reduce the wake effect, boom installation should be considered so the probe can be attached further to avoid region of disturbed plasma.

This is also helps in reducing the shock effect from the spacecraft which also able to compromise the measurement reliability.

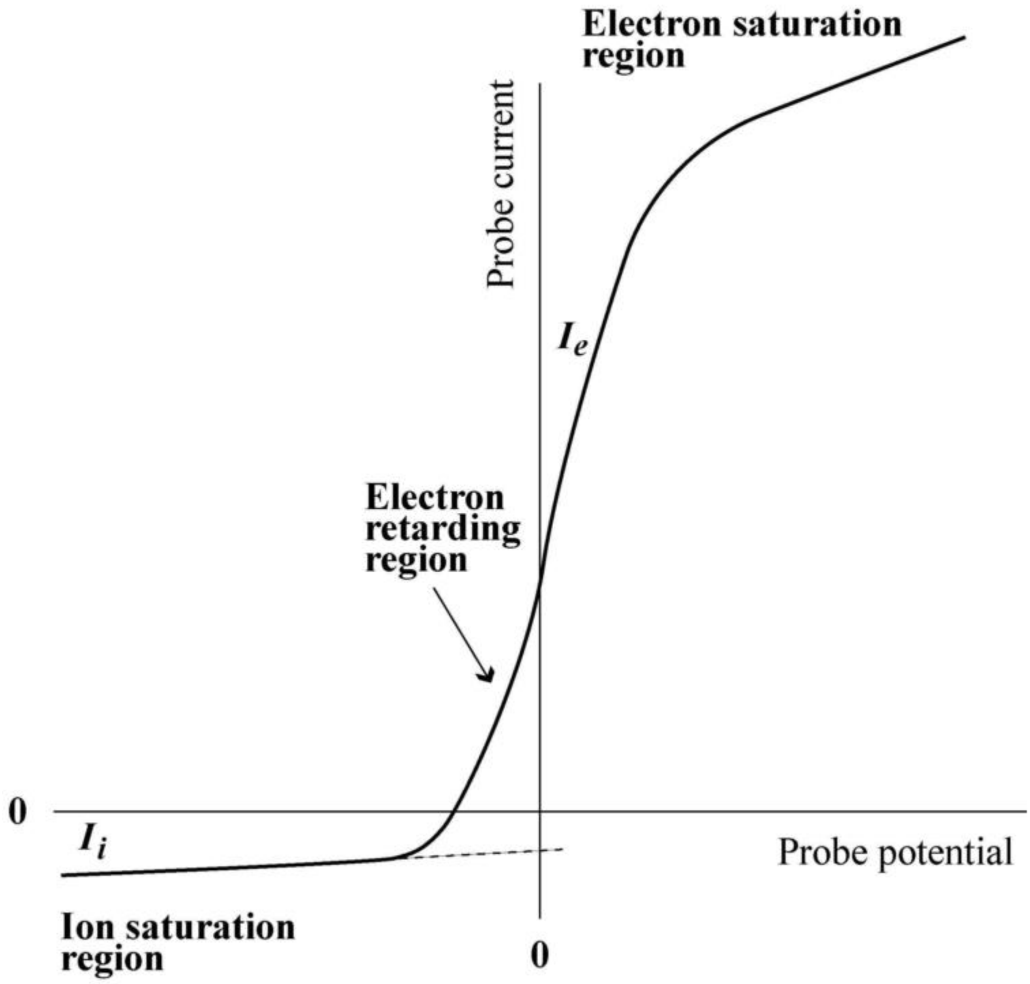

Figure 2.4: I-V characteristic from a Langmuir probe (Abe and Oyama, 2013).

I-V characteristics from a Langmuir probe is shown in Figure 2.4. As the probe voltage, V_p, is swept referenced from the spacecraft potential, V_s, the net current, I, is measured which contains both ion current density I_i, and the electron current density I_e. There are three important regions to take note; 1) region where electrons are repelled but ions are collected which is called ion saturation region, 2) region where electrons contribute most of the current produced, by determining number electrons that can overcome retarding potential V_r (= V_s - V_p) which is called electron retarding potential region, and 3) situation opposite to the first region which instead called electron saturation region.

The electron current calculation is done by subtracting the ion current from the probe current, estimation of ion current is by extrapolating ion saturation current. The temperature of electron can be found from the gradient, which is inversely proportional to T_e, from log (I_e) plot. The random surface electron current is a function of the electron temperature and density, knowing the random surface electron current and temperature of electron enables electron density number calculation. The inflection point between the electron retarding and electron saturation regions can be considered as plasma potential, they vary linearly from log (I_e) plot.

2.3 Electron temperature probe (ETP)

Typically, as discussed before, the plasma potential is uniform apart from the sheath region. In the above equation, I_i is the ion current density. Decreasing the probe voltage to a point it is lower from plasma potential, electrons will be repelled, and ions will be attracted. In the opposite situation, where probe voltage become higher than the plasma potential, sheath potential effect will no longer exist to reflect electrons, thus electron current saturates, and I_{es} is called the random electron current.

The probe potential is floating due to the probe voltage applied referenced to the plasma potential, which is negative enough to repel some slower electrons and attract ions to maintain zero net probe current as shown in Figure 2.5.

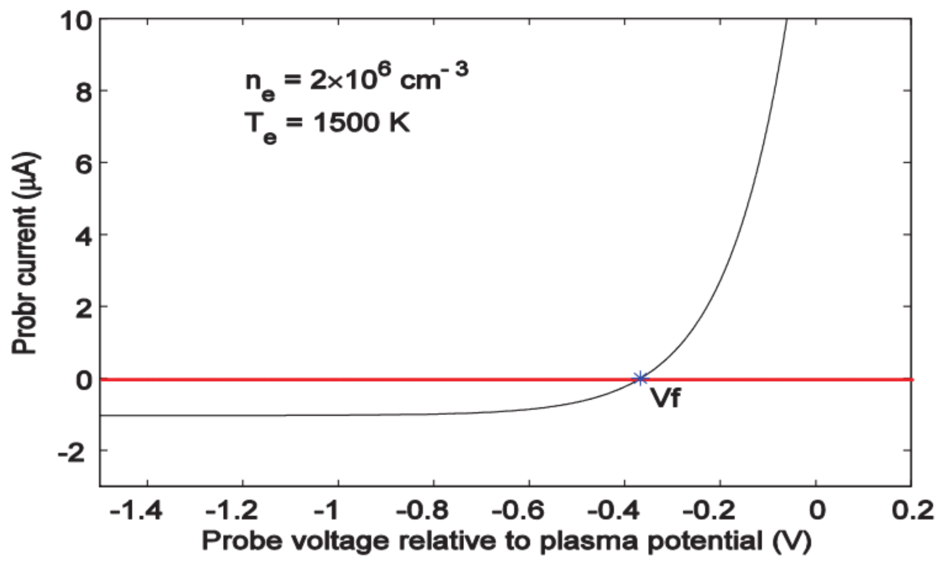

Figure 2.5: Example of I-V curve (Oyama and Cheng, 2013).

The I-V characteristic curve are prone to shift into the side of the negative potential as the Langmuir probe's voltage sweep is being added with a high frequency sinusoidal wave. The result can be seen as in Figure *3.1* (Takayama et al., 1960; Buckley, 1966; Dote and Ichimiya, 1967).

ETP has been considered to be used on sounding rockets and satellites several times instead of using the Langmuir probe. This is due to its ability to not be influenced by the probe contamination which has been discussed in previous subchapter to be a serious problem. It is difficult to avoid contamination of the probe on board, which often when it comes to obtaining the data, hysteresis is inescapable. It is found that hysteresis is a result from the capacitance exist on the probe due to contamination. The ETP electrode design helps improves contamination management which resulted the capacitance estimation to be several µF due to its minute thickness. Another important aspect is the usage of high frequency sinusoidal wave on ETP, which able to decrease the effect of impedance of contamination capacitance compared to the sheath impedance to a point where it can be neglected. It is considerable to conclude that ETP output signal is not influenced by probe contamination.

2.4 TeNeP probe

TeNeP probe introduced by Oyama has been improved based on the working principle of Langmuir probe and ETP (Hsu and Cheng, 2014). It is done by considering the impedance effect on the probe during measurement, based on the impedance probe principle. This impedance probe technique has been discussed diligently by Spencer et al. and Raunch et al. (Spencer et al., 2017; Rauch et al., 2016).

Antenna produces electrostatic waves. As the antenna being immersed in a charged plasma particle, the electrostatic wave radiated from the antenna will excite the plasma region which affects the impedance of the antenna. An absolute electron density can be obtained by applying sweeping frequency sinusoidal wave to the probe, through impedance measurement from each frequency probe current measured.

CHAPTER 3

METHODOLOGY

3.1 Theory

Potential gradient at any point in space are governed by Poisson's equation,

$$V = \frac{\delta^2 V}{\delta x^2} + \frac{\delta^2 V}{\delta y^2} + \frac{\delta^2 V}{\delta z^2} = 4\pi e(n_e - n_i) \tag{3.1}$$

From Eq. (3.1), e is the elementary charge, n_e is the electron density, and n_i is the univalent positive ion density.

Consider the passage of electron from a heated plane cathode at zero potential to a parallel plane anode at potential V_a (Langmuir, 1913; Langmuir and Compton, 1931). If the initial velocities of the electrons leaving the cathode are neglected, it follows that at any point at potential V

$$\frac{1}{2} m_e v^2 = V_e \tag{3.2}$$

$$n_e e = \frac{I_e}{V} \tag{3.3}$$

From Eqs. (3.2) and (3.3), I_e is the electron current density, e is electron charge, m_e is electron mass and v is the electron velocity. The solution of Eq. (3.1) for parallel plane electrode is

$$I = \frac{\sqrt{\frac{2e}{m}}\sqrt{V^3}}{9\pi x^2} \tag{3.4}$$

$$\frac{e}{m} = 5.279 \times 10^{17} esu \tag{3.5}$$

$$I = 5.462 \times 10^{-8} \sqrt{M} \sqrt{V^3} \frac{1}{x^2} A \cdot cm^{-2} \tag{3.6}$$

From Eqs. (3.4), (3.5) and (3.6), I is the current density of electrons or of single-charged positive ions, M is the molecular weight of the current carriers (Oxygen = 16), and x is the distance from emitter to collector in cm.

The electron space charge is hundreds of times smaller than the positive ion space charge based on Eqs. (3.7) and (3.8)

$$en = I \sqrt{\frac{m}{2Ve}} \tag{3.7}$$

$$\frac{n_e}{n_i} = \sqrt{\frac{m_e}{m_i}} \tag{3.8}$$

Electron temperature becomes uniform along the plasma region, the current density I which moves against the retarding field in the sheath is proportional to the electron concentration n and thus lays out Eq. (3.9)

$$I = I_0 \, exp\left(\frac{Ve}{kT_e}\right) \tag{3.9}$$

From Eq. (3.9), I_0 is the electron current density in the plasma near the sheath edge.

The interactions between electrons and elastic collision with gas atoms produces a random motion among the electrons which its velocities follow a typical Maxwellian velocity distribution as described in Eq. (3.10) (Langmuir, 1928; Tonks and Langmuir, 1929).

$$v = e\sqrt{\frac{n}{\pi m_e}} \tag{3.10}$$

A randomly moving electrons presents a definite random current density I_e of electrons passing per second per unit area across any imaginary plane within the plasma. From equations of kinetic theory, the current density is given by Eq. (3.11)

$$I_e = en_e\sqrt{\frac{kT_e}{2\pi m_e}} \tag{3.11}$$

Gas molecule at thermal equilibrium tends to concentrate differently at places of different potential energy in a steady field force, hence, a Boltzmann equation is used to determine the electron distribution, as in Eq. (3.12)

$$n = n_0\, exp\left(\frac{Ve}{kT_e}\right) \tag{3.12}$$

From Eq. (3.12), n is the concentration of electrons at any place of potential V, and n_0 is the concentration at a point where the potential is zero. The equation relates that as long as there is a difference in potential, there would also be difference in concentration provided the thermal equilibrium assumption is valid.

In the electron retarding potential region, the electron current is expressed as Eqs. (3.9) and (3.13)

$$I_{es} = en_e\sqrt{\frac{kT_e}{2\pi m_e}}S \tag{3.13}$$

From Eq. (3.13), I_{es} is the random surface electron current, S is the probe's surface area. In reality, the current obtained in the electron retarding region includes both electron and ion currents. As for cylindrical probe, the random surface electron current equation as in Eq. (3.13) is given a slight modification, given by the following equation:

$$I_{es} = en_e\sqrt{\frac{kT_e}{2\pi m_e}\frac{2}{\sqrt{\pi}}}S \tag{3.14}$$

Consider an immersed electrode in a plasma region, applied voltage to the electrode triggers a current flow through the electrode is given as Eq. (3.15) (Mott-Smith and Langmuir, 1926)

$$I_p(V) = I_{es}\,exp\left(-\frac{eV}{kT_e}\right) - I_i \tag{3.15}$$

As probe voltage equals to the plasma potential, Eq. (3.15) becomes

$$I_p(V) = I_{es} - I_i \tag{3.16}$$

The probe voltage can be considered as floating potential when the probe current $I_p(V)$ value becomes zero. The floating potential referenced to the plasma potential is calculated from Eq. (3.15) as

$$V_f = -\left(\frac{kT_e}{e}\right)\left[ln\left(\frac{I_i}{I_{es}}\right)\right] \tag{3.17}$$

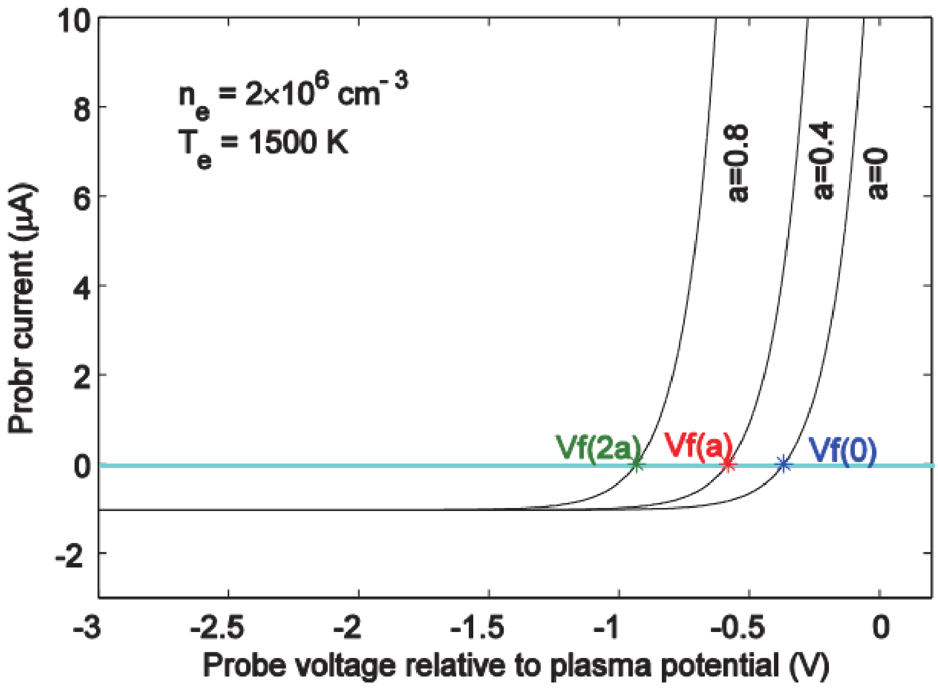

Figure 3.1: The shifts of I-V characteristics curve (Oyama and C.Z.Cheng, 2013).

The Langmuir probe voltage sweep is being modified to shift the I-V characteristic curve, which can be controlled by adjusting the high frequency sinusoidal wave amplitude, $a\cos\omega t$. The probe current then becomes

$$\begin{aligned} I_p(V + a\,sin\,\omega t) &= -I_i + I_e\,exp\left(-\frac{e(V + a\,sin\,\omega t)}{kT_e}\right) \\ &= -I_i + I_e\,exp\left(-\frac{eV}{kT_e}\right)exp\left(-\frac{ea\,sin\,\omega t}{kT_e}\right) \end{aligned} \tag{3.18}$$

It is to be found that the ion current does not respond to the wave voltage but continues to remain at the same value, this is due to the heavy nature of the ions which causes it to