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Controlling the Electric Potential of the Low-Earth Orbit Microsatellite in Ionosphere Observation via Langmuir Probe

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Abstract—Using a Langmuir probe mounted on a large satellite is a general method to directly measure ionosphere's plasma characteristics, such as electron temperature and electron density. Microsatellites are also being planned to be used for this task due to their apparent advantages, such as low cost and short development time. However, the deployment of Langmuir probe on a microsatellite faces with a problem that the satellite's electric potential fluctuates significantly as the plasma's currents are fed to a satellite's conducting surface which is not much larger than that of the probe. This in turn adversely affects the accuracy of the observation results. In this paper, a technique exploiting an electron gun is proposed to stabilize this fluctuation. The technique is tested in a space chamber and the obtained results are shown to demonstrate the effective controlling of the satellite electric potential.

Keywords—Microsatellite, satellite potential, ionosphere, Langmuir probe, electron density, and electron temperature.

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I. Introduction

THE ionosphere is a region ranging from 60 km to 1000 km above the atmosphere. It is plasmas that the air is ionized by solar radiation. The ionosphere is changed by a solar activity and the upper atmosphere. This change is influential in the High Frequency (HF) communication and the precise positioning by positioning satellites. Recently, it has been found that the ionosphere variation has relation to diastrophism of Earthquake with magnitude larger than 5 [1]. In order to clarify the details of this relationship, more ionosphere observation data on the Earth are required. The electron temperature T_e is one of the fundamental plasma parameters, which is needed for ionospheric research.

The most popular technique of ionosphere observation is the Langmuir Probe [2] installed on a large satellite, which can directly measure the electron temperature and an electron density. Langmuir Probe has been exploited in sounding rockets since 1947 when Reifman and Dow first measured the DC current-voltage curve by using this probe on board the V-2 rocket [3]. This instrument is simple, small, and low cost.

In recent years, microsatellites have been increasingly used in space science missions such as space technology research, remote sensing, ionosphere observing, etc. Among the advantages of a microsatellite are that it can be developed with low cost and short development time. The microsatellites are especially suitable for ionosphere observing because there is small air resistance in the ionosphere near the Earth. However, using the Langmuir Probe for ionosphere measurement has a significant problem in microsatellites [4]. Since the conducting area of microsatellites is not usually much larger than that of the probe the satellite electric potential changes easily when a sweeping voltage is applied to the probe. The satellite potential fluctuates because the balance of electrons and positive ions that are collected by the probe and the satellite body collapses. This variation is caused by not only the Langmuir Probe but also by the other devices. As the satellite potential is a reference voltage for the whole circuitry, the ionosphere observation results are adversely influenced by this fluctuation. Therefore, the control of satellite potential is needed for a successful application of ionosphere observation.

In this paper, we propose a new method using an electron gun to suppress the change of the satellite electric potential. The electron gun releases electrons that hit to the satellite body thereby controlling the variation of the satellite electric potential. We tested the performance of the technique in a space chamber and obtained results which demonstrated an effective way to control the satellite electric potential.

II. The Basic of Langmuir Probe Theory

In this section, the Langmuir Probe technique is described to measure electron density and electron temperature of plasmas. This technique consists of a bare metal wire, ball or disk, which is inserted into a plasma and electrically biased on a reference electrode (such as the satellite structure, ground of the earth

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and, etc) to collect electron, ion currents, or both. **Figure 1** shows an example of a system. When the voltage of the probe is changed to measure currents of the probe, we can get the current-voltage (*I-V*) characteristic that is obtained by measuring the drained current (I_p) by the probe for each bias potential (V_p). Figure 2 represents an idealized voltage current curve. This curve consists of three regions: an ion saturation region (A), an electron repulsion region (B) and an electron saturation region (C). The probe does not emit particles and in accordance to the V_p, the drained current $I_p = I_i + I_e$ from the plasma is composed of ion current (I_i) and electron current (I_e). In laboratory plasma, the electron energy distribution usually follows a Maxwellian distribution. **TABLE 1** shows the parameters of plasma for a Langmuir probe.

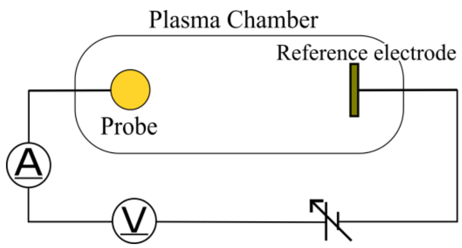

Figure 1 Schematic of basic Langmuir Probe for measuring plasma

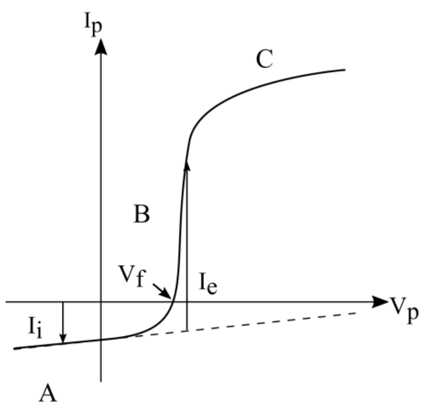

Figure 2 Example of an I-V curve in laboratory plasma

TABLE 1 PARAMETERS OF PLASMA FOR A LANGMUIR PROBE

Parameter	Symbol	Value	Units
Electron's charge	e	1.602×10^{-19}	C
Ion density	n_i	-	m^{-3}
Probe collecting area	S	-	m^2
Napier's constant	ε	2.718	
Boltzmann constant	k	1.380×10^{-23}	J/K
Electron temperature	T_e	-	K
Ion mass	m_i	1.672×10^{-27}	kg
Electron density	n_e	-	m^{-3}
Electron mass	m_e	9.109×10^{-30}	kg

A. The ion saturation region (A)

For very negative bias voltages V_p (at the region A in Figure 2) the electrons are repelled, while ions flow to the probe. The flow of ion current from the plasma is limited by the electric shielding of the probe. This current is denominated ion saturation current I_{is} and can be expressed in the following formula.

$$I_{is} = e \cdot n_i \cdot S \cdot \varepsilon^{-\frac{1}{2}} \cdot \sqrt{\frac{k \cdot T_e}{m_i}} \qquad (1)$$

where e, n_i, S, ε, k, T_e, and m_i are the electron's charge, ion density, probe collecting area, the Napier's constant, the Boltzmann constant, electron temperature, ion mass.

B. The electron repulsion region (B)

When V_p is lower than the plasma potential (V_s), or higher than the floating potential (V_f), the electrons and ions are the attracted. The ion currents (I_i) flowing into the probe decreases as the electron current (I_e) flowing increases. The bias voltages (V_p) where $I_p = 0$ is the floating potential (V_f), where the contributions of the ion and electron currents are equals. The current (I_e) can be expressed in the following formulas.

$$\left.\begin{aligned} I_e &= I_p - I_i \\ I_e &= e \cdot n_e \cdot S \cdot \sqrt{\frac{k \cdot T_e}{2\pi \cdot m_e}} \cdot exp\left(-\frac{e \cdot (V_s - V_p)}{k \cdot T_e}\right) \end{aligned}\right\} (2)$$

where n_e is the electron density, and m_e is the electron mass. Equation (2) shows that the slope of the (ln *I-V*) curve is exactly equals to $1/T_{eV}$ and is an appropriate measurement parameter of the electron temperature. It is convenient to write $k \cdot T_e/e$ as T_{eV} , the electron temperature T_{eV} in eV . The electron temperature T_e is can be calculate in the following formula.

$$\frac{d(\log I_e)}{dV_p} = \frac{e}{k \cdot T_e} \cdot \log(\varepsilon) \qquad (3)$$

Figure 3 shows a semilog plot of electron current from an *I-V* curve.

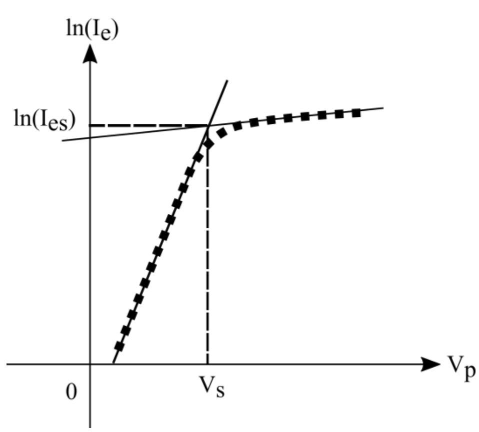

Figure 3 A semi-log plot of electron current from an I-V curve

C. The electron saturation region (C)

The exponential growth of I_e with V_p should continue until $V_p = V_s$, when none of the electrons is repelled by a negative potential. This current is denominated by the electron saturation current (I_{es}) and can be expressed in the following formula.

$$I_{es} = e \cdot n_e \cdot S \cdot \sqrt{\frac{k \cdot T_e}{2\pi \cdot m_e}} \qquad (4)$$

If T_e is already known, the electron density (n_e) calculates the next formula.

$$n_e = \frac{I_{es}}{e \cdot S \cdot \sqrt{\frac{k \cdot T_e}{2\pi \cdot m_e}}} \qquad (5)$$

However, I_{es} is not the saturated value. In this case, the I_{es} value uses the intersection (P) that is tangents of curves in the region B and C.

D. Design of probe and circuits for our experiment

We use the Langmuir Probe system shown in **Figure 4**. Our system has a spherical probe that the voltage is applied from a signal generator (SG). The signal is a triangular wave, and the amplitude is controlled from outside.

This system measures the probe current that is converted to a voltage by the current/voltage conversion circuit in **Figure 4(a)**. This probe current is very small, measuring up to some tens microamperes including the applying signal. The input signal is separated by an instrumentation amplifier (INA), then we can get only the probe current.

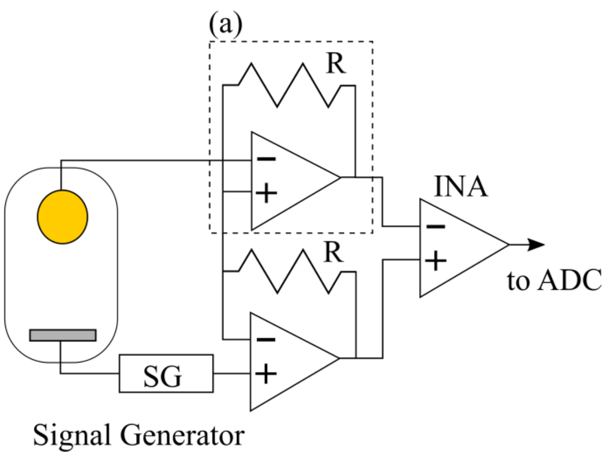

Figure 4 The schematic of the system circuit

III. Satellite Potential Variation

In this section, we describe the electric potential of a satellite flying in the ionosphere. In the outer space, the satellite potential is a reference voltage of the system, called a ground (GND). In a large satellite, a satellite potential variation is slow because a satellite body is big, whereas in a small satellite, this potential changes more easily because a solar power cell and sensors occupy a large area of satellite bodies. **Figure 5** shows the mechanism of variations CASE A and B.

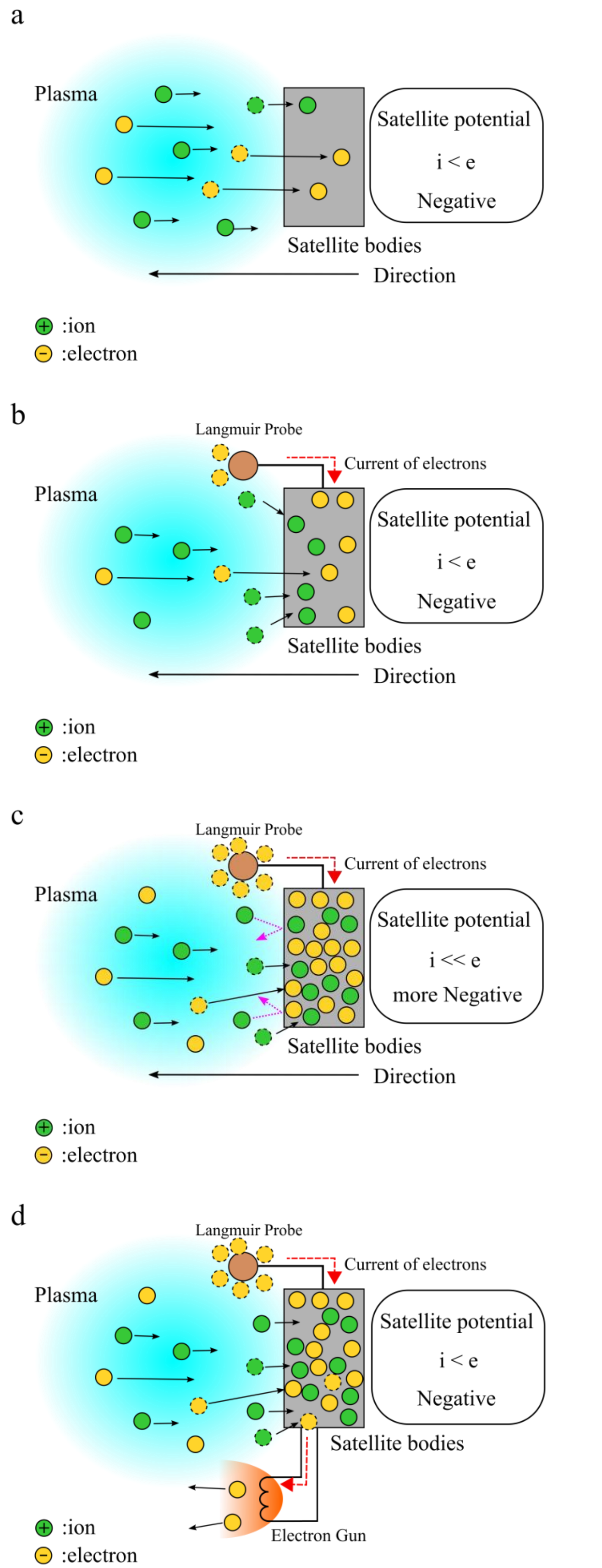

Figure 5 The mechanism of variation

A. General potential of satellites in the ionosphere

The ionosphere is the plasma of nitrogen occupying atmosphere. As nitrogen is ionized by the sunlight, some of its electrons get stripped off resulting some positively-charged ions and some electrons. The electrons and the ions always move in plasma. This moving speed is called thermal velocity. The electron thermal velocity is higher than the ion thermal velocity because the mass of an electron is much smaller than that of ion, and the electron temperature is higher than the ion temperature. The electron and ion mainly enter into the satellite body in the direction the satellite is flying in the ionosphere. The satellite body usually has a negative potential because an electron arrives earlier than an ion to satellite bodies by the relation of the thermal velocity (**Figure 5a**). The initial condition of satellite potential mentioned above varies according to the ionosphere status, and the altitude and position of the satellite. In this paper, we denote this potential as the default potential.

B. Satellite potential with Langmuir probes

We describe the satellite potential using Langmuir probe case under the default potential. The Langmuir probe applies a voltage to a probe and measures the current of the probe. This voltage is a triangular wave that has the positive and negative DC voltages. In the negative voltage phase, the probe attracts positive ions. The satellite potential does not change to positive direction because the number of electrons incoming to satellite body is more than that of ions. Then, the satellite potential does not change from the default potential. When the applied voltage to the probe increases during the positive voltage phase, the probe attracts electrons, and the satellite body gets positive ions. Also, the satellite potential does not change from the default potential because the number of ions and electrons are same. (Figure 5b)

When the voltage of the probe is increasing further, much more electrons will be attracted to the probe. Following this, the satellite body will have more ions for some time and electron will begin flowing from the probe to the satellite body. However, after some time, the satellite body will have so many electrons that the satellite potential will begin to decrease and become lower than the default potential (**Figure 5c**).

Thus, the Langmuir probe cannot measure the ionosphere status that calculates the relation between the applied voltages and the flowing currents of the probe.

C. Approach to a satellite potential control

The satellite potential changes with the value of collected electrons at satellite bodies. This variation is suppressed by using the emission of electrons to increase collection of positive ions at satellite bodies. We used the thermionic emission to emit electrons in satellite bodies. (**Figure 5d**) The thermionic emission is a method to release electrons in the metal using thermal energy to heat metal. The emission value of the thermoelectron differs according to metal type, thermal energy, and surface area. By this experiment, we used a tungsten string. The tungsten is winded up around a line like a coil and emits thermoelectrons by heating the tungsten string by electric current. If the tungsten filament is heated to about 2000 K, some of the electrons have sufficient kinetic energy to escape from the surface of the wire. We call this system the electron gun. Because the current of the probe is around several microampere, it is thought that we can control an electric potential change if the electron gun releases a thermoelectron at the same current from satellite bodies.

IV. Experiments and Results

This section describes two experiments in a laboratory plasma.

A. Thermionic emission Experiment

As mentioned, the quantity of electrons that are emitted from the electron gun depends on metal type, thermal energy, and surface area. This experiment was conducted to study the relation between thermionic emission and three conditions such as the thickness of wire, winding numbers, and applied thermal energy. We show the measuring system in **Figure 6** and other conditions in **Table II**. The system consists of a cathode, which emits thermoelectrons, and an anode, which receives the emitted electrons from the cathode in a vacuum chamber. The cathode is applied with constant electrical current and heated. Then, the voltage is applied to the anode to collect thermoelectrons from the cathode. The electric current flows to the ammeter connected to the anode when a thermoelectron begins to be emitted. We use the ammeter to measure a micro-ampere because the anode current is a weak electrical current.

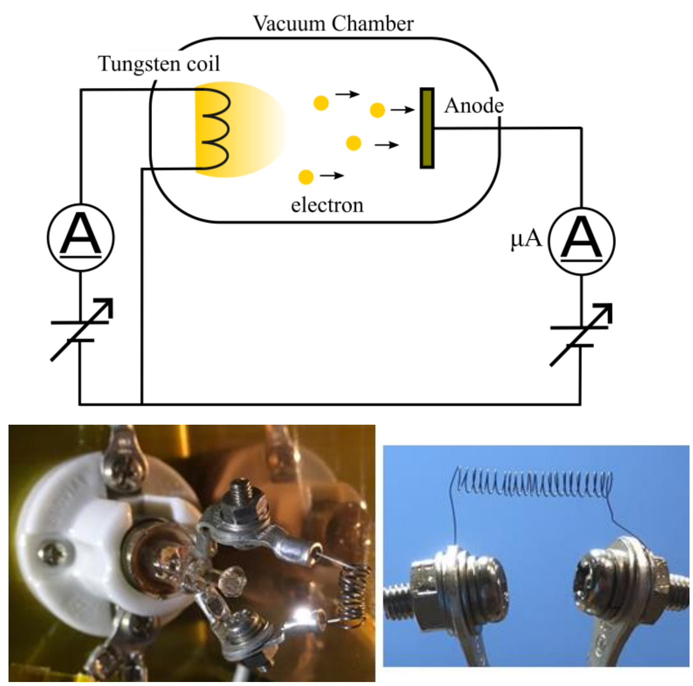

Figure 6 Schematic of thermionic emission experiment (top), and electron gun (bottom)

TABLE II CONDITIONS

Parameter	Symbol	Value	Units
Space Chamber			
Gas	-	nitrogen	-
Pressure of the chamber	-	1.88×10^{-2}	Pa
Electron Gun			
Materials	-	tungsten	-
Diameter of wire	-	0.15	mm
Length	l	150	mm
The number of the winding	-	20	-
Diameter of winding	-	0.8	mm
Surface area	S	7.07×10^{-5}	m^2
Cross section	S_c	1.77×10^{-8}	m^2

Figure 7 shows the result of thermionic emission experiment using laboratory plasma. The vertical axis indicates the anode voltage and the horizontal axis indicates the anode current by thermal electrons. The current of tungsten coil at 1.7 A and the anode voltage at 5 V are necessary to emit thermal electrons at 7 μA.

Richardson-Dushman's formula obtains the value of thermoelecrons.

$$J = A \cdot T^2 \cdot exp^{\frac{-e \cdot W}{k \cdot T}} \ [\mathrm{A/m^2}] \tag{6}$$

where J is thermionic emission amount [A/m^2], A is Rechardson constant (1.2×10^6 [A/m^2·K^2] at tungsten), T is absolute temperature [K], k is Boltzmann's constant (1.38×10^{-23} [J/K]), W is work function (4.53 [eV] at tungsten), e is elementary electrical charge (1.6×10^{-19} C).

The absolute temperature (T) can be calculated by a tungsten resistivity (ρ). The ρ has nonlinear characteristics by temperature T. When the high temperature regions over 1000 K, we can use the next approximation expression.

$$\rho = 1.77\left(\frac{T}{1000}\right)^2 + 26.52\left(\frac{T}{1000}\right) - 3.44 \ [10^{-8} \ \Omega \cdot \mathrm{m}] \tag{7}$$

The tungsten resistance R is calculated by next formula.

$$R = \frac{\rho \cdot l}{S_c} \tag{8}$$

The measured resistance value of tungsten coil is about 4.53 Ω by Ohm's law.

The T is obtained by Equation (9).

$$\left.\begin{aligned} 1.77\left(\frac{T}{1000}\right)^2 + 26.52\left(\frac{T}{1000}\right) - 3.44 &= \frac{R \cdot S_c}{l} \\ T &= 1900 \ [\mathrm{K}] \end{aligned}\right\} \tag{9}$$

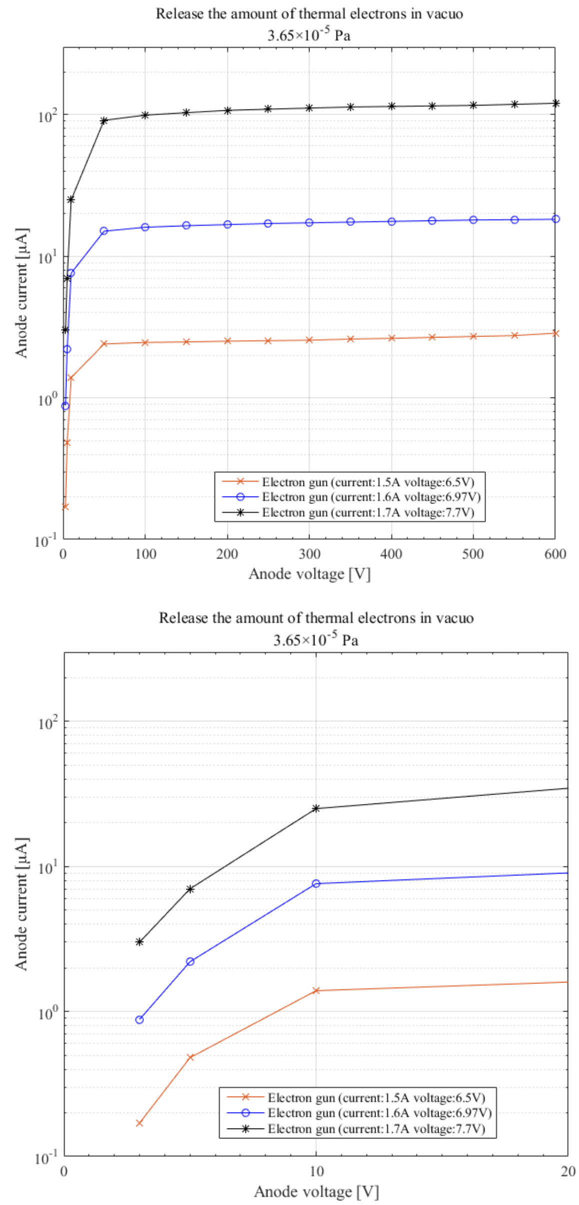

Figure 7 Result of release the number of thermal electrons

By putting the value of T into (6), the value of thermoelecrons is calculated as,

$$J = A \cdot T^2 \cdot exp^{\frac{-e \cdot W}{k \cdot T}} = 4.44 \tag{10}$$

$$\left.\begin{aligned} I_{anode} &= J \cdot S \\ &= 3.14 \cdot 10^{-4} \ [\mathrm{mA}] \\ &= 314 \ [\mu\mathrm{A}] \end{aligned}\right\} \tag{11}$$

As a result, the measured value of the anode electron current is different from the calculated value. Because of variations in the temperature, the tungsten coil has the thermal electron emission that is uneven.

From a saturation current (I_{sc}) of thermal electrons, the temperature (T) is also calculated from the formula.

$$\left.\begin{aligned} \log_{10}\left(\frac{I_{sc}}{T^2}\right) &= -\frac{1}{2.303}\cdot\frac{W\cdot e}{k}\cdot\frac{1}{T} \\ &\quad + \log_{10}\left(\frac{4\pi\cdot e\cdot m_e\cdot k^2\cdot S}{h^3}\right) \\ T &= 1840\ [\mathrm{K}] \end{aligned}\right\} \quad (12)$$

where h is Planck's constant (6.626×10^{-34} J·s).

We can conclude that the temperature of tungsten is between 1840 K and 1900 K from these results.

B. Satellite Potential Control Experiment

We carried out an experiment to control the satellite potential using the electron gun, which we developed based on the result of experiment A. Figure 8 shows the satellite system.

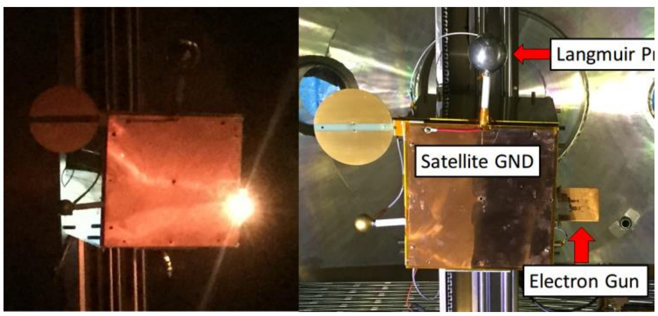

Figure 8 State of the experiment using the electron gun (left), and experiment system (right)

We measure the satellite potential on three conditions;

1. The satellite body is connected to the chamber wall and has infinity areas.
2. The satellite body is not connected and in a floating condition.
3. The electron gun is used to control the satellite potential.

When an electron temperature is 1600 K, an electron density is 2.34×10^{-5} cc/mm^3.

In this paper, case 1 is named GND, case 2 is named Floating, and case 3 is named Electron gun. Each result is shown in the **Figure 9**. In the Case 1, the satellite potential has a constant value at 0 V. The probe is applied with a voltage equal to the signal voltage.

In the case 2, when the applied voltage increases up to 2.25 V, the probe voltage does not increase. The satellite potential decreases to the negative potential. This decrement is the difference between the applied voltage and the probe voltage.

In the case 3, when the applied voltage increases up to 2.5 V, the probe voltage do not increase. The decrease of satellite potential can be suppressed with the electron gun, and the measurable applied voltage range is improved around 0.25V. The **Figure 10** shows each satellite potential. When using the electron gun case, the satellite potential variation can be suppressed up to 0.22V compared to the floating case. The satellite potential becomes a stable condition assuming that the electron which enters the inner part of a probe from the plasma cancels by the thermoelectrons of the electron gun.

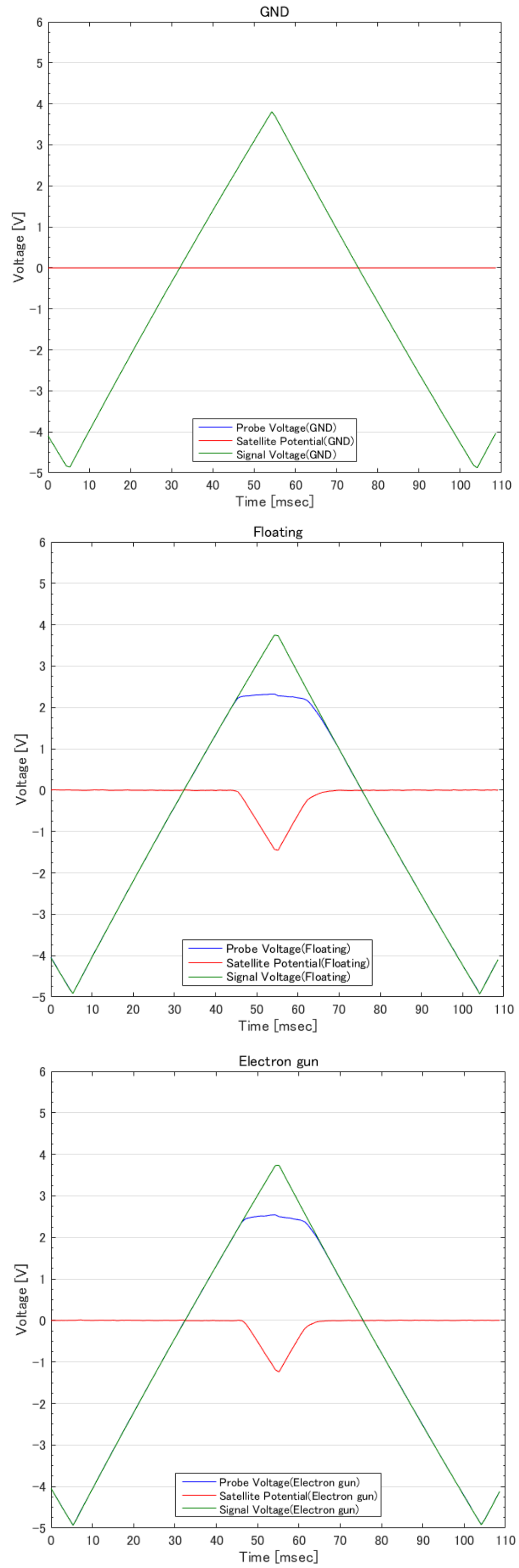

Figure 9 Result of the satellite potential control experiment

However, the electron gun proposed in this paper could not suppress the satellite potential variation perfectly. The assumed value of thermoelectrons to control the satellite potential is about 3 μA when the anode voltage is 3V (**Figure 7**). We consider that a plasma potential of ionospheres, which collects electrons from the electron gun is around 2V, and the probe current is around 1 μA from several papers.

In this experiment, it is found that the maximum probe current is 8.7 μA when the plasma potential is around 1.5 V.

From the results of experiment A, the thermoelectrons emission is around 1.4 μA when the anode voltage is 1.5 V, and the anode current is 1.7 A. This plasma potential value for this experiment was even smaller than our estimation. The maximum satellite potential in the floating case is 1.45 V in **Figure 11**.

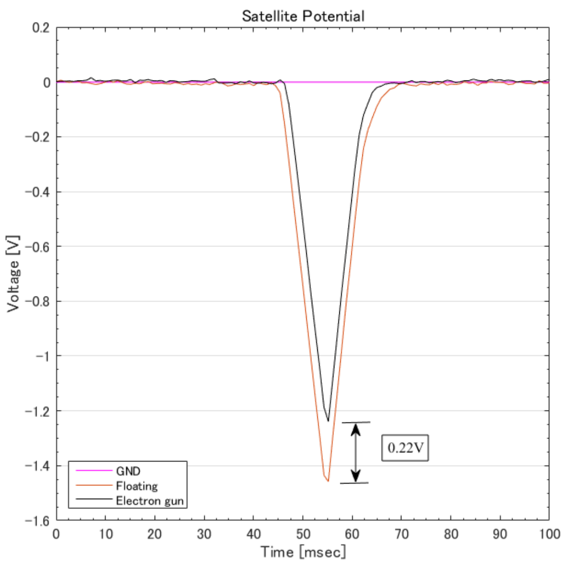

Figure 10 Comparison of each satellite potential

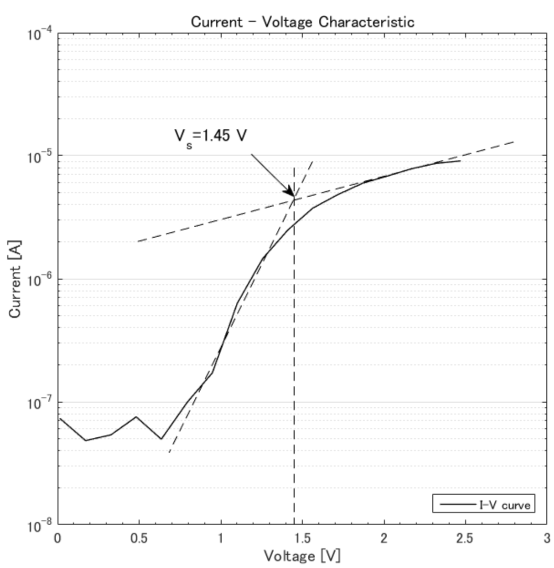

Figure 11 I-V characteristic

If the thermoselectron emission is needed to be equal to the maximum probe current, which is 8.7 μA to control this satellite potential, we can calculate the improved satellite potential value by the following formula:

$$I_{te} = J \cdot S = 1.55 \cdot 10^{-3} \cong 1.20 \cdot 10^{-3} \qquad (13)$$

This calculation result coincides with the experiment results.

We can deduce the following from these things:

1. The electron gun can control satellite potential variations.
2. The emitting electron of the electron gun is calculated by a plasma potential and a probe current at the plasma potential.

In this experiment case, the electron emission capability of the electron gun is required the current which equal the anode current of 8.7 μA at the applied the voltage 1.5 V to prevent satellite potential variations completely.

V. CONCLUSION

As the Earth observation trend using the satellite changed from the large satellites to the microsatellites, real-time and global ionosphere observations developed. Therefore, the studies of the ionosphere increased and the measurement of ionosphere characteristic became more important from a geophysical point of view. The microsatellite using Langmuir probe had a problem that this method could not measure the plasma because the satellite potential changed to a negative potential. We proposed a satellite potential controlling method using thermal electron emission to solve this problem. As a result of the experiments, the satellite potential variation was controlled by the electron gun which we developed. Also, the present result suggested that the value of thermal electron emission to control the satellite potential equaled to the probe current at the plasma potential. Further studies are needed to develop the satellite potential control system which changes an electron gun power by plasma conditions.

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