SPACE CHARGE ENHANCED PLASMA GRADIENT EFFECTS ON SATELLITE ELECTRIC FIELD

MEASUREMENTS

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In magnetospheric plasmas, it is possible for plasma gradients to cause error in electric field measurements made by satellite double probes. In this paper, we discuss space charge enhanced plasma gradient error in general terms, presents the results of a laboratory experiment designed to demonstrate this error, and derive a simple expression that quantifies this error.

INTRODUCTION

It has been recognized for some time[1] that plasma gradients can cause error in magnetospheric electric field measurements made by rocket and satellite double probes[2]. Figure 1 is a schematic of a satellite double probe. The double probe technique is generally employed in the following manner: Two probes are placed 180° apart, each at the end of a long boom. The probes are conductors which are electrically isolated from the booms. They collect both ions and electrons from nearby plasma and photoemit electrons into nearby plasma. Both probes are biased to the same current, that is, equal values of current are made to pass through each probe. The difference between the probe voltages divided by the distance between the probes is taken to be a measure of the average electric field in the nearby plasma.

Error in this technique occurs when the contact, or sheath, potentials between the two probes and the ambient plasma are not equal. Differences in contact potentials can be caused either by differences in the probes themselves or by differences in the ambient plasma at each probe. The latter is often referred to as PGIE (Plasma Gradient Induced Error). This paper considers only PGIE, and it specifically examines space charge enhanced PGIE.

"Space charge" refers to electric charge that accumulates in a space or region. Space charge exists near electron emitting probes because of the finite time it takes emitted electrons to cross probe sheaths. This space charge modifies the structure of the probe sheaths in a way as to tend to repel emitted

1. Fiala, V., and Storey, L.R.O., "Plasma Wakes in Space and Laboratory, "Vol. 2 (1970).

2. Boyd, R.L.F., Space Sci. Rev. 7, 230(1967).

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electrons and force them back to the probe from which they were emitted. That is to say, electrons emitted from a probe tend to be repelled back to that probe by previously emitted electrons that are still in the sheath between the probe and nearby plasma. As a result, not every electron that is emitted from a probe necessarily escapes into the surrounding plasma. Those electrons which don't escape do not contribute to the electric current flow between the probe and plasma. Hence, for a given probe emissivity, the greater the space charge near a probe, the more negative the voltage of that probe must be for a given electrical current flow between the probe and nearby plasma.

Figures 2 and 3 graphically represent the physics discussed in the above paragraph. Figure 2 shows the qualitative potential structure near a double probe-satellite system when space charge effects are large enough to impede electron flow between the ambient plasma and double probe-satellite system. Figure 3 is a graphical representation of the emitted electron flow from one probe.

Relatively small amounts of plasma can have rather large effects on space charge[3]. As an electron emitter collects ions from the plasma, the conservation of angular momentum allows ions to spend long periods of time in the vicinity of the electron emitter, where they alleviate the negative space charge from the emitted electrons. Hence, it is possible for plasma gradients to indirectly cause error in double probe electric field measurements by causing differences in the space charge effects at each probe.

Figure 4 is the same as figure 2, except in figure 4 it has been assumed that the probe on the left has more space charge near it. Because of the greater space charge, the contact potential of the probe on the left must be lower than that of the probe on the right in order for equal electrical currents

to flow through each probe. For a situation such as that shown in figure 4, the measured electric field would be greater than the actual electric field.

3.Kindon, K.H., Phys. Rev., <u>21</u>, Series II, 408 (1923).

LABORATORY EXPERIMENT

A laboratory experiment was conducted to demonstrate space charge enhanced PGIE. The experimental conditions were, of course, not the same as those found in the magnetosphere. Efforts were made to ensure that the conditions were such that the relevant physics of the experiment applied as well to magnetospheric conditions.

As a matter of convenience, a cylindrical, thermionically emitting probe 55 cm in length and 5×10^{-3} inch in diameter was employed in a cylindrical, stainless steel chamber that was 64 cm in length and 60 cm in diameter. The ratios of our probe's radius and length to the chamber's radius is the same order of magnitude as the corresponding ratios of the radii and lengths of satellite cylindrical double probes to magnetospheric DeBye lengths. Also, the current emitted by our probe is on the same order of magnitude as the currents emitted by satellite double probes. In this paper's theory section it will be shown that the space charge enhanced PGIE depends on probe current, rather than probe current per unit length or area.

Our probe was heated into thermionic emission by a variable, half-wave rectified, 60 Hz heating voltage. Voltage bias sweeps between -10V and 5V were applied to the probe though a CA3140E operational amplifier that was configured as a voltage follower. An ORTEC Brookdeal 9415 linear gate was employed to take data during the off cycle of the heating voltage. These voltage bias sweeps allowed probe current vs. voltage characteristics to be measured under a variety of conditions.

Plasma could be created by bleeding air into the machine until the pressure reached the 10^{-3} torr range. The voltage drop across the probe during

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the on part of the heating cycle was large enough that some of the electrons were emitted with enough energy to ionize. Once plasma had been created in the 10^{-3} torr range, plasma could be produced at lower pressure. The plasma density was roughly proportional to the neutral pressure.

Three problems made the measurements difficult. The origin of all three problems was the finite impedance between the primary and secondary of the heating voltage transformer. The currents that flowed through the transformer's finite impedance and also flowed through our measuring apparatus and thus were a source of error. The three problems and our solutions to them are discussed in detail in Appendix A.

Results and Discussion

The laboratory data shown in Fig. 5 demonstrate some of the possible errors in electric field measurements made by strongly emitting probes due to space charge effects in the presence of plasma gradients. Characteristics A and B suggest that under "certain conditions", one could measure a positive, zero, or negative electric field depending on the current bias that is chosen. We shall first discuss these errors that the data suggest and then discuss what we believe to be the causes of these errors, causes that are applicable to probes in space as well as in the laboratory.

In Fig. 5, electron current that is emitted from the probe and does not return to the probe is shown as positive current, while electron current that is collected by the probe is shown as negative current. The current vs. voltage characteristics A and B shown in Fig. 5 are characteristics of the same laboratory probe taken under different probe and plasma conditions. Specifically, probe emission was stronger and the plasma more dense when characteristic A was taken. In the next paragraph, we will assume that characteristics A and B are the characteristics of two probes on a satellite that are being used to make electric field measurements. This assumption will allow us to make several comments with regards to possible errors in satellite electric field measurements. It would of course be an improbable coincidence for the characteristics of any two probes on any satellite to be identical to characteristics A and B. It is not so improbable, however, that characteristics of space probes may, for "certain conditions", have the same features as those of characteristics A and B that give rise to the error. Later in this section the characteristics A and B will be examined in more detail. The focus of this

examination will the features that cause errors, the physical phenomena that give rise to these features, and the "certain conditions" for which we might expect these features.

So, let us suppose for the moment that characteristics A and B are the characteristics of two probes on a satellite that are being used to make electric field measurements. Let us further assume that both probes are biased to the same current (that is, that there is circuitry on board the satellite that changes the voltage of each probe until the net emitted current which flows through each probe is equal to the desired bias current) and that the voltage difference between the two probes is measured. The standard method for calculating the average electric field between two current biased probes on a satellite is to divide the measured voltage difference between the probes by the distance between the probes.

Using this standard method, the electric field calculated from characteristics A and B depends on the current bias that is chosen. If the probes are biased at a current of 12 µA, the probes will indicate an electric field that points from probe A towards probe B. If the probes are biased at approximately 9 µA, the voltage difference, and hence the calculated electric field also, between the two probes is approximately half the value it is for a current bias of 12 µA. If the current bias is chosen to be approximately 6 µA, then the probes will indicate that there is very little or approximately zero electric field. And, if a current bias of between 0 and 5 µA is chosen, the probes will indicate an electric field that points, not from probe A towards probe B, but from probe B towards probe A. Hence, the magnitude and even the direction of the calculated electric field will depend on the current bias that is chosen. It is disturbing that the electric field calculated by this standard method should depend on the current bias that is chosen.

We now examine characteristics A and B in more detail. The focus of this examination will be the features of the characteristics that give rise to the errors described above, the physical phenomena that give rise to these features, the "certain conditions" for which we might expect these features, and whether these conditions are possible in space.

Although characteristics A and B are similar in many ways, they are not identical. In particular, satellite probes are biased at "intermediate" currents, that is currents that are not close to the saturation currents, and at intermediate currents the slope of characteristic A is steeper than the slope of characteristic B. It is this difference in slopes that allows the voltage difference between characteristics A and B to vary with current. Hence, the features of the characteristics which lead to the errors described are the slopes of the characteristics at intermediate currents, slopes which are not equal to one another.

Characteristics A and B were taken under different probe emission and plasma conditions. It is the difference in plasma conditions that is primarily responsible for the difference in slopes of the characteristics at intermediate currents. The saturated emitted electron current and the saturated collected current of characteristic A are greater than the corresponding currents of characteristic B. This indicates that the probe was more strongly emitting and that the plasma was denser and/or hotter when characteristic A was measured.

THEORY

It has been known for some time[4] that small amounts of plasma can greatly affect the space charge near an electron emitter. Quantifying the effects that an arbitrary number of ions have on the space charge surrounding a particular electron emitting probe can be rather difficult, and we do not attempt to do so here. Rather, we take a more general approach to the problem. For a given probe emissivity and a given probe bias current, the voltage of a probe is minimum when the probe is in a vacuum because that is when the space charge near that probe is maximum. Likewise, for a given probe emissivity and bias current, the voltage of a probe is maximum when the probe is in a plasma which is dense enough that the plasma ions alleviate the space charge near the probe to a level of insignificance. In this paper, we derive an expression for the maximum steady state space charge enhanced plasma gradient error in the electric field measurements taken by two identical, current biased probes by considering on of those probes to be in a vacuum and the other probe to be in a plasma which is dense enough that the plasma ions alleviate the space charge near the probe.

The reader should beware that although we derive an expression for maximum error, we do not take into account many things which might change that maximum error. Among the effects that we do not take into account are: most particularly, transient effects, i.e., gradients which pass by the probes quickly enough that their effects are capacitively coupled to the probes; the nonzero temperatures of emitted electrons; magnetic fields; and leakage currents, i.e., currents which flow directly between the probes and the

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satellite without passing through the ambient plasma.

To begin our derivation of a simple expression of the maximum expected space charge enhanced PGIE, the reader is referred to figure 6. The potential structures around two probes, the "left" probe and the "right" probe, are shown in figure 6. For simplicity, the electric field in the ambient plasma has been ignored and the potential structure of the satellite has been omitted. Further, we will assume that the left probe is in a vacuum (or near vacuum). Also, we assume that $d_1 \sim d_2 \sim \lambda_D$, where λ_D is the DeBye length of the ambient plasma.

Note the minimum in the potential structure of the left probe. This minimum is created by space charge. If the minimum, and the potential structure of the left probe, is to stay constant with time, then the space charge at and near the minimum must remain constant with time. For this to happen, and it is the steady state condition which we assume, the current that flows from the probe to the minimum must be equal to the current that flows from the minimum to the ambient plasma. Further, when the two currents are equal to one another, as we assume, then they are also equal to the current which flows from the probe to the plasma. We denote these currents by I_L.

Now, when considering I_L to be the current from the left probe to its associated potential minimum, I_L can be rewritten as

eq. 1 $I_L = I_s \exp(-e\Delta\phi_3/T_e)$

where I_s is a constant that is often referred to as the emitted electron saturation current and Te is the temperature of the emitted electrons.

The current I_L from the minimum to the ambient plasma can be rewritten as

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eqs. 2 $I_L(\mu A) \simeq 14.7\Delta\phi^{3/2}$ when the probe and its sheath are cylindrical

and, $I_L(\mu A) \simeq 29.4\Delta\phi^{3/2}/\alpha^2$ when the probe and its sheath are spherical

where α^2 is very weakly dependent on the ratio of the probe radius to λ_D. α^2 is

on the order of 5. Equations 2 are just the well known Child-Langmuir Law[5 6 7]

rewritten in our notation for the situation depicted in figure 6. The

Child-Langmuir Law describes the current flow from a region of zero electric

field to a boundary. It is appropriate to use the Chile-Langmuir Law to

describe the current flow form the minimum in the potential structure of the

left probe to the ambient plasma because the electric field at the minimum is

zero. The reader may wish to note that for simplicity, we have assumed that T_e

is zero when writing the Child-Langmuir Law.

The current I_R that flows from the right probe to the plasma is

eq.3 $I_R = I_s \exp(-e\Delta\phi_4/T_e)$

where the I_s and T_e have been assumed to be equal to those of eq. 1 because the

physical characteristics of the left and right probes have been assumed to be

the same. Also, if the probes are biased to the same current I_B, as we assume,

then $I_R = I_B = I_L$. It follows that $\Delta\phi_3 = \Delta\phi_4$.

The reader should take the time to make sure that he or she understands

4.Kingdon, K.H., Phys. Rev., 21, Series II, 408 (1923).

5.Langmuir, I., and Blodgett, K., Phys. Rev. 22, 347 (1923).

6.Child (1911).

this last point, that $\Delta\phi_3 = \Delta\phi_4$. It is important. By inspection of figure 6, the reader should see that when $\Delta\phi_3 = \Delta\phi_4$, $\Delta\phi_1 = \Delta\phi_2$. By further inspection of figure 6, the reader should also see that $\Delta\phi_1$ is the space charge induced PGIE.

Once these things are understood, it is trivial to write an expression for the maximum expected space charge enhanced PGIE from equations 2 as

eq. 4 E_M(Volts/meter) $\simeq [I_B(\mu Amps)/15]^{2/3}/d$(meters) when the probe and

sheath are cylindrical,

and, E_M(Volts/meter) $\simeq [I_B(\mu Amps)\alpha^2/30]^{2/3}/d$(meters) when the probe and

sheath are spherical

where E_M is the maximum expected error in double probe electric field measurements due to space charge enhanced PGIE, I_B is the current to which each probe of the double probe is biased to, and d is the distance between those two probes. Typical values of α^2 are 0.509, 1.022, 2.073, 4.002, 5.324, 6.933, and 8.523 which correspond to ratios of sheath radius to probe radius of 1.8, 4.4, 14, 160, 1000, 10000, and 100000, respectively[5] [Langmuir Blodgett (1923)].

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7. Langmuir (1913).

Appendix A

The measuring of probe current vs. voltage characteristics was complicated by the finite impedance between the primary and secondary of the heating voltage transformer. Fig. *7/25,1 is a schematic of the electrical components that are pertinent to this discussion. Components A through C provide the voltage that heats the probe D into thermionic emission. Component A represents the line voltage (120 V, 60 Hz), B is a variac or variable voltage transformer, and C is an isolation transformer. Component E is a voltage ramp (that is, a voltage with respect to ground that increases linearly with time) which is applied to the probe through the voltage follower F. G is the point at which the "probe voltage" or "bias voltage of the probe" is measured. Component H represents the vacuum vessel wall and its ground. I depicts the vacuum or plasma that lies between the probe and vacuum vessel wall.

Note that there are four grounds, M, H, K, and N. The current that we are interested in, the current which is suppose to correspond to the current in a probe's current vs. voltage characteristic, is the current that flows between the probe D and the ground H. The impedance between the probe D and the ground N should be quite large; it should be on the order of the input resistance of the voltage follower F, which is a CA3140 op amp and has a nominal input resistance of $10^{12}\Omega$. Ideally the impedance between the probe D and ground M is also quite large because of the large impedance between the primary and secondary of the isolation transformer C. In this case, the current that flows from ground H to probe D completes its circuit by flowing from probe D through the voltage follower F and the resistor J to ground K. The current through the probe is then calculated by dividing the voltage measured at point L by the resistance of J.

Unfortunately, the impedance between the primary and secondary of our isolation transformer C is small enough to allow significant current to flow between ground M and grounds H and K. In fact, during most times in the heating cycle, the current flowing to our ground K is dominated by current flowing from M through C, F, and J to K and not by the current that we wish to measure which is the current that flows from H through I, D, F, and J to K.

There are two types of impedance across C that are of concern, capacitance and resistance. There is finite capacitance between the primary and secondary windings of C because of their proximity to one another. Fig. *7/25,2 is a simplified approximation of Fig. *7/25,1 and depicts the circuit elements essential in understanding how we avoid the problem caused by the capacitance across the isolation transformer. V_p in Fig. *7/25,2 corresponds to the voltage across the primary of the isolation transformer and Z_c is the value of the impedance due to the finite capacitance across the transformer. E is a voltage sweep of the same value as the voltage sweep depicted in Fig. *7/25,1 and represents the output of the voltage follower F, R_J is the resistance of the resistor J, and R_s is the "sheath" resistance or the approximate resistance between the probe D and the ground H.

It is common practice to make R_J much less than R_s, and Z_c is usually much greater than either R_J or R_s. In other words,

$$Z_c \gg R_J \gg R_s \qquad\qquad \text{*Eq. 7,25,1}$$

Hence, most of the current that flows from ground M flows to ground K and not to ground H. Also, the phase of this cyclical current proceeds V_p by $\pi/4$; the current passes through zero when V_p passes through its maximum and minimum. We can essentially eliminate the effect of this unwanted current on our

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measurements of probe current vs. voltage characteristics by monitoring V_p and triggering a temporally short voltage pulse at the minimum of each cycle of V_p. This voltage pulse is in turn used to trigger a linear gate, which samples the voltage at point L in fig. *7/25,1 during (and only during) the voltage pulse. In this way, data are sampled periodically at a time in the cycle of the unwanted current when the amplitude of the current is near zero.

There is also a finite resistive impedance across the isolation transformer C. The resistance across our particular transformer only becomes troublesome when the heating voltage is applied to the probe for over 20 seconds. It is our conjecture that with time the transformer becomes warm, the resistance across C decreases, and as a result the current across the resistance increases and starts to be noticeable on the measured current vs. voltage characteristic.

Our solution to this problem is to simply measure the characteristics quickly, before there is a noticeable resistive current. There are of course limits as to how quickly the characteristics can be measured. We've noticed that the emitted current continues to increase for the first few seconds after the heating voltage is applied before leveling off to a constant value. Presumably, the probe is warming up during these first few seconds. Note that the warming takes place immediately after the heating voltage is applied to the probe while the resistance does not become too small for making measurements until some time after. Further, these two currents are of opposite sign, that is, warming increases the emitted current while the finite resistance decreases the measured emitted current (because some of the emitted current flows through ground M rather than ground K). Hence, we have a check on these two effects. We measure each characteristic twice, with enough time between the measurements to allow the transformer to cool down. The first characteristic is measured by

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sweeping the probe from low voltage to high voltage; the second characteristic is measured by sweeping from high to low. The measurement is good when there is good agreement between the two characteristics. When the warming of the probe and/or the warming of the transformer is a problem, the two characteristics do not agree at either low and/or high voltages, that is, at either early and/or late times in the sweeps.

Lastly, if our conjecture is correct that the resistance across the transformer decreases with time as the transformer heats up, an increase in the size the transformer might help by increasing the time it takes the transformer to warm up. However, increasing the size would probably also increase the capacitance between the primary and secondary. An increase in this capacitance would make the problem of finite capacitive impedance more acute.