プローブ法電場計測の課題：衛星電位の制御 & 衛星表面物性

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Abstract

プローブ法による「宇宙電場(および電位)計測」の精度は、衛星表面電位の「安定」、衛星表面電位の「影響排除」、およびプローブ電位の「安定」によって決定される。

この向上には、 1) 観測・実測をベースとした「良いモデル化・数値実験」、および2) 安定した光電子・二次電子放出を行う「良い表面材料」の探索と採用が鍵となる。

1. Introduction

Accurate measurement of electric field is an essential request for studies of macroscopic plasma convection, microscopic wave-particle interactions, violation of MHD approximation, etc. One of typical measurement techniques is 'Double Probe method', identical to that of a voltmeter: the potential difference between two top-hat probes [cf. *Pedersen et al.,* 1998]. The potential of a conductive material in plasma is mainly determined by the balance of outflow photoelectrons (I_{ph}) and inflow ambient electrons (I_e). In tenuous plasma, conductive materials are positively charged because number of outflow photoelectrons exceeds that of inflow ambient electrons. Such potential is highly variable associated with density and temperature of ambient electrons. For the stabilization of the probe potential, the bias current I_b is fed to the probe.

Double Probe method can measure electric field passively and continuously in all plasma conditions with high time resolution. However, accuracy, gain (effective length), and off-set are affected by a) the disturbance from ambient plasma and b) the disturbance from the spacecraft body. In this paper, we showed the results of the characteristics of DC electric field measurement by EFD-P aboard GEOTAIL [*Tsuruda et al.*, 1994], in order to evaluate the accuracy, gain, and offset controlled by ambient plasmas. The results contribute to the improvement of Geotail measurement, and will be used as a basis for the designs of future instruments.

2. EFD-P: PANT and EFD aboard the GEOTAIL spacecraft

Figure 1 shows an outline drawing of the PANT element. PANT is a pair of top-hat antennas composed of a conductive sphere with 105 mm attached at the tip of a stainless steel wire, 50m in length and 1.05mm. Wire surface except the outer portion 1 m is coated with Polyimide film for insulation, and its inner portion 44 cm is covered by a copper-mesh sleeve. The surface of Sphere and outer portion 1 m of wire is covered by Aerodag for photoelectron yield stabilization. By this design, PANT can act in different manners for DC and AC fields. For DC electric field (< ~100 Hz), PANT couples to the surrounding plasma at its top (Sphere and Conductive part of the wire), with effective resistance several 10 MΩ and the effective length about 50 m (antenna length). For AC electric field, PANT acts as a monopole wire antenna of 50m, and couples to the plasma with capacity (~100pF) and the effective length approximately 25 m (half of antenna length).

Output signal of the PANT is transferred to the receivers, EFD (Electric Field Detector) for DC fields and PWI (Plasma Wave Instrument) for AC fields. The EFD data was used for this analysis.

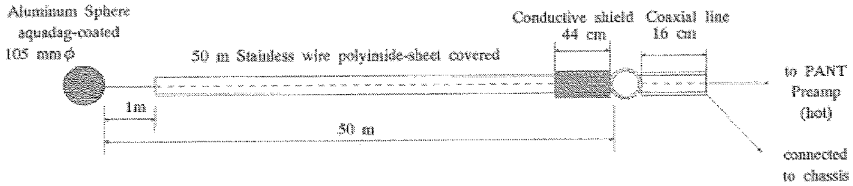

Figure 1. The PANT system aboard the GEOTAIL spacecraft [*Tsuruda et al.*, 1994]

3. Data Sets

In plasma with MHD approximation, generalized Ohms law can be written as

$$E + v \times B = \eta j + \frac{1}{ne} j \times B - \frac{1}{ne} \nabla \bullet P_e + \frac{m_e}{ne^2} \frac{\partial j}{\partial t} \qquad (1)$$

where $\boldsymbol{E}$, $\boldsymbol{v}$, and $\boldsymbol{B}$ are electric field, plasma velocity, and magnetic field vectors, respectively. In quiet cases, right side terms of Equation 1 can be negligible. Based on this, we compared DC electric field measured by EFD-P and $v_i \times B$ measured by LEP (Low Energy Plasma Analyzer) and MGF (Magnetic Field Experiment) aboard GEOTAIL. Used data set is summarized in Table 1. For this analysis, the accuracy of v_i and $\boldsymbol{B}$ are essential. Data selection criteria are shown in Table 2. Since LEP data after 1998 is not calibrated yet, analyses are done for the data in 1994-1997.

Figure 2 shows the relation between observed electric field by EFD-P, E_{obs} (Y-axis) and $v_i \times B$ (X-axis) in 1994-1997. Majority of miss-match is caused by non-reliable v_i, because of the limitation of energy range, limited field of view in Z-axis, and the lack of low energy part by spacecraft charging (in ion). Mismatch is more evident in the cases where 'LEP-electron' criteria are not adopted, because the reliability of ion density is not considered in this case.

We assume $v_i \times B$ as real electric field, E_{real}. Observed electric field E_{obs} can be written as:

$$E_{obs}\ [\mathrm{mV/m}] = A \times E_{real} + B \qquad (2)$$

where A and B is gain (= 'effective length'/'actual antenna length') and offset, respectively. Table 3 shows the parameter A and B derived from Figure 2. Since E_{real} has errors itself, we conclude that the accuracy of E_{obs} is better than 0.6 mV/m in E_x and 0.3 mV/m in E_y.

4. Gain and Offset

4.1. Variation

First, we evaluated the variation of the gain (A of Equation 2) and offset (B in Equation 2) from 1994 to 2000. Figure 3 summarizes the result. Gain slightly decreased in both E_x and E_y. For the offset, clear increase is found only in E_x. Both might be related to the enhancement of photoelectron non-uniform distribution around the spacecraft, caused by the increase of photoelectron production at the degraded spacecraft surface by ion implantation and/or UV flux. Since the solar activity is similar in 1994-1997, it does not play a major role. On the other hand, degradation is not found in the accuracy of the electric field measurement.

We note that Figure 3 does not include the effect of ambient plasma parameters (see the

Instrument	Data	dT	Available data
LEP	Ion: density(N_i), velocity(v_i), temperature(T_i)	12 sec.	1993.9~

	Electron: density(N_e), velocity(v_e), temperature(T_e)	12 sec.	1993.9~1998.1
MGF	Magnetic field vector (B)	12 sec.	1992.9~
EFD-P	Electric field vector (E), Spacecraft potential (V_{sc})	12 sec.	1992.9~

Table 1. Data sets used in this analysis. For LEP, the data after 1998 is not calibrated.

Instrument	Condition	
LEP- electron	Reliable density & temperature	$N_i/N_e = 0.8\sim1.2$, $T_e > 20\text{eV}$
LEP- Ion	Reliable density & temperature	$Ni > 0.1\ N(V_{sc})$, $T_i > 20\text{eV}$
	EA mode	FOV: center of $\theta = +65.5^\circ \sim -65.5^\circ$
MGF	Stable B	$B_{rms} < 0.05\ \lvert B \rvert$
EFD	Stable E	$E_{rms} < 1.0$ mV/m
General	Normal potential	No eclipse, No potential control

Table 2. Data selection criteria. Criteria of 'LEP-electron' can only be applied to the data in 1994-1997. $N(V_{sc})$ is derived from plasma potential by Equation 6.

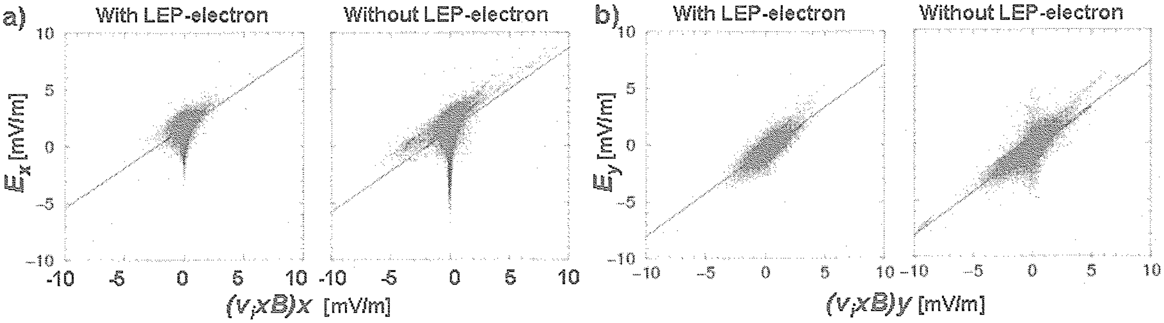

Figure 2. Relationship between E (Y-axis) and $v_i \times B$ (X-axis) in 1993-1997: a) E_x and b) E_y.

E_x	Criteria with LEP-electron	$(E_{obs})_x = +0.704 \times (E_{real})_x + 1.64$	$\sigma \sim 0.63$ mV/m
	Criteria without LEP-electron	$(E_{obs})_x = +0.724 \times (E_{real})_x + 1.40$	$\sigma \sim 0.94$ mV/m
E_y	Criteria with LEP-electron	$(E_{obs})_x = +0.756 \times (E_{real})_x - 0.44$	$\sigma \sim 0.33$ mV/m
	Criteria without LEP-electron	$(E_{obs})_x = +0.768 \times (E_{real})_x - 0.38$	$\sigma \sim 0.46$ mV/m

Table 3. Parameters fitted to '$E_{obs} = A \times E_{real} + B$' from Figure 2. A and B is gain and offset.

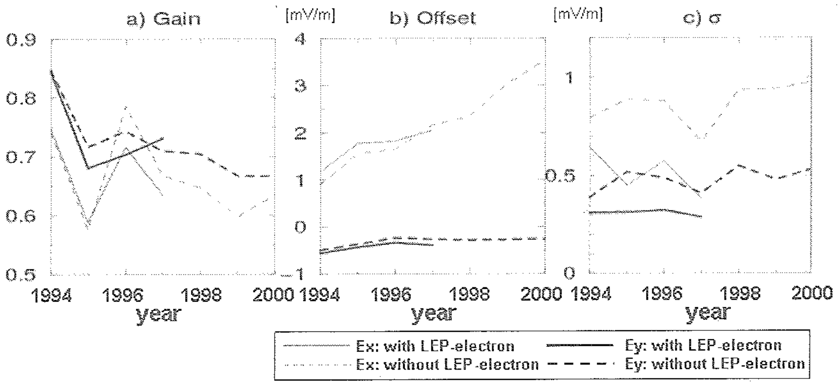

Figure 3. Time variation of a) Gain, b) Offset, and c) Error in 1994-2000.

next section). Difference between 1994 and 1995~2000 is partially caused by the difference of orbit, 'Distant-tail phase' before Nov. 1994 and 'Near-tail phase' after that.

4.2. *Correction by* V_{sc} and T_e (or T_i)

We tried to refine the relationship shown in Table 3 according to the ambient plasma parameters. We can assume that photoelectron outflow is constant. Potential itself is mainly affected by the ambient electron flux proportional to $N_e v_e = N_e \sqrt{T_e}$. And photoelectron from and the potential structure around the spacecraft are as disturbance factors, which are related to the spacecraft potential V_{sc} and Debye length λ_D. Since λ_D and V_{sc} are controlled by N_e and T_e, independent parameters are two. In this analysis, we used V_{sc} and T_e as correction variables. Since the electron moment data is not always reliable, we also used ion temperature T_i. The accuracy in this case is worse because T_i is not always correlated to T_e. [EUV flux and magnetic field vector may also affect the production and motion of photoelectron. We do not take care of them in this paper.]

Figure 4 summarizes the preliminary corrections based on the data in 1994-1997, selected by all criteria in Table 2. Qualitatively, V_{sc} is important factor for the gain (positively) and the offset (negatively). T_e is less correlated to the antenna gain (negatively) and the offset (negatively). Corrected electric field by 'V_{sc}', and 'V_{sc} and T_e (or T_i)' is written as Equation 3-5:

$$(E_{real})_y = [A_0 + A_1 * \log(V_{sc})] \quad (E_{obs})_y + [B_0 + B_1 * \log(V_{sc})] \tag{3}$$

$$(E_{real})_y = [A_0 + A_1 * \log(V_{sc}) + A_2 * \log(T_e)] \, (E_{obs})_y + [B_0 + B_1 * \log(V_{sc}) + B_2 * \log(T_e)] \tag{4}$$

$$(E_{real})_y = [A_0 + A_1 * \log(V_{sc}) + A_2 * \log(T_i)] \, (E_{obs})_y + [B_0 + B_1 * \log(V_{sc}) + B_2 * \log(T_i)] \tag{5}$$

Each parameter is summarized in Table 4. We also note that T_e (and T_i) is not always reliable. Correction by Equation 3 (only by 'V_{sc}') will be easier and reliable.

4.3. *Effect of Spacecraft Debye Length*

We also evaluated the gain and offset associated with Debye length λ_D, correlated to $\sqrt{(T_e/N_e)}$. Figure 5 summarizes the result. When the Debye length is less than antenna length (102m in tip--to-tip), the gain, offset, and error of the measurement is relatively stable. On the other hand, when the antenna length beyond Debye length of ambient plasma, error becomes larger, but the electric field can still be measured. Offset in E_x is reduced, and the gain increases.

Figure 5 summarizes the result. When the Debye length is less than antenna length (102m in tip-to-tip), the gain, offset, and error of the measurement is relatively stable. On the other hand, when the antenna length beyond Debye length of ambient plasma, error becomes larger, but the electric field can still be measured. Offset in E_x is reduced, and the gain increases.

4.4. *Summary*

We concluded that the GEOTAIL electric field measurement by the PANT system potentially has the accuracy better than 0.5 mV/m in E_x and 0.3 mV/m in E_y. The error would be less, because those values are limited by the accuracy of plasma velocity measurement. Further refinement will be done not only by the rejection of the ambiguity in particle observations but also by the comparison with EFD-B (electron beam technique) data [*Tsuruda et al.*, 1994].

We will also establish the quantitative model of double probe system, including the 'shorting out' effect in the gain and the offset caused by the potential structure and non-uniform photoelectron distribution around the spacecraft [cf. *Pedersen et al.*, 1998]. Numerical model will be made and compared with the observations. We also expect the comparison to Cluster probe with guard electrode.

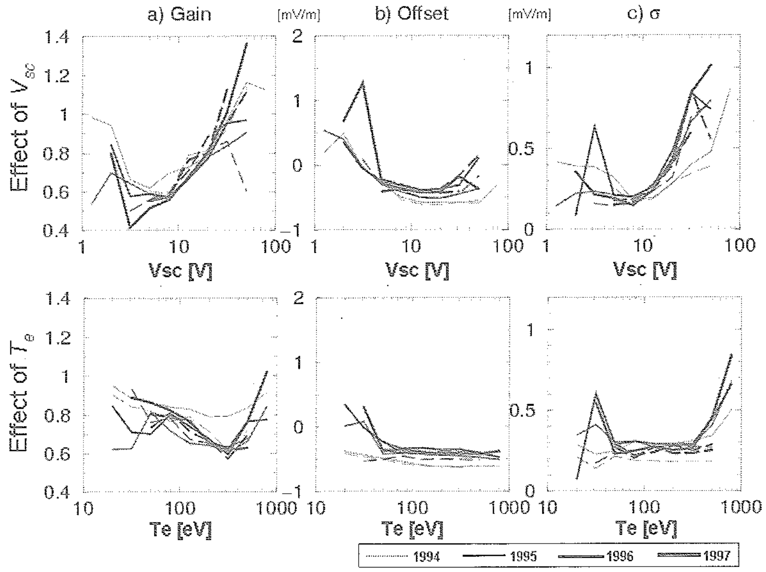

Figure 4. Dependence of a) Gain, b) Offset, and c) Error on 'V_{sc}' (Upper Dashed line is T_e = 100~158eV) and 'T_e' (Lower: Dashed line is V_{sc} = 10~15.8V.), for E_y in 1994~1997.

E_x	A_0	A_1	A_2	B_0	B_1	B_2	σ
Correction by V_{sc}	+0.72	+0.60	--	+3.67	-1.88	--	0.49
Correction by V_{sc} & T_e	+1.19	+0.82	-0.34	+2.47	-1.99	+0.60	0.41
Correction by V_{sc} & T_i	+1.30	+0.73	-0.27	+1.92	-1.81	+0.57	0.45
E_y	A_0	A_1	A_2	B_0	B_1	B_2	σ
Correction by V_{sc}	+0.72	+0.20	--	-0.09	-0.34	--	0.33
Correction by V_{sc} & T_e	+0.99	+0.34	-0.19	+0.10	-0.37	-0.07	0.31
Correction by V_{sc} & T_i	+1.12	+0.29	-0.18	+0.04	-0.38	-0.03	0.33

Table 4. Correction by 'V_{sc}', 'V$_{sc}$ and T_e', and 'V$_{sc}$ and T_i' in 1995-1996 data

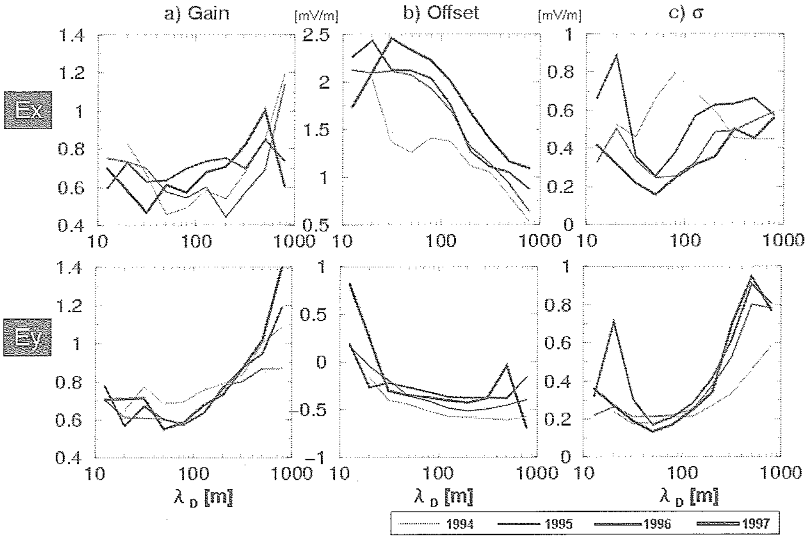

Figure 5. Dependence of a) Gain, b) Offset), and c) Error on Debye length in 1994~1997.

5. How to achieve the better accuracy?

Key of the achievement of the better accuracy of electric field measurement is 1) Reduction of the interference from the spacecraft and 2) Stability of the probe potential to the ambient plasma.

For the former requirement, the stabilization of the spacecraft potential is most important. For those purpose, the spacecraft surface materials should be conductive and grounded to the structure by low impedance, in order to keep the potential difference less than the order of 1 V (Most impact is at the selection of conductive MLI / Cover glass and their grounding processes.). However, the spacecraft potential itself is difficult to be reduced. It is possible by the ion beam emission from the spacecraft, but it causes disturbances to ambient plasmas. Therefore, the potential structure of the electrode is considered in order to reject the effect of 'spacecraft potential' to the probe itself. Past US and European spacecraft have been several those challenges. Most recent example is Cluster spacecraft. Such thin space plasma condition can not be achieved in the laboratory, so the establishment of the probe design is actually difficult. Good numerical simulation is essential for such trials, and we are trying to develop and test the probe design by such methods. Numerical simulations with increasing calculation power will be one of strong 'propulsion powers' for future space programs.

For the latter requirement, the selection of the probe surface material is essential. Probe potential is determined by the photoelectron and secondary electron yields. The uniformity and the less degradation of those parameters are most important. The past spacecraft have used Aquadag, a carbon powder in the heritage of the early rocket and laboratory measurement. Recently, TiN etc. is tested as a substitute of it, and it is used in Cassini spacecraft etc. The search of such material requires the cooperation between space and material scientists. Such kind of interdisciplinary cooperation will produce many contributions in all fields in future space programs.

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