Electric field instrument onboard Japanese sounding rockets

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The electric field in the ionosphere is measured by the double probe instrument onboard a sounding rocket. For electric field measurement, a wire antenna has been used as a sensitive sensor onboard Japanese sounding rocket. And this antenna will be used for several spacecraft in the future mission. However, its extension mechanism is complicated and it is difficult for the sounding rocket to extend a wire antenna in the ionosphere. New type antennas were developed in order to measure the electric field by the sounding rocket. They fulfill the severe requirements to the antenna system, i.e., light mass, enough stiffness, compact storage, safe extension, and reasonable test efforts. One of them, the rigid monopole antenna, was successfully used in the ISAS/JAXA S-520-23 sounding rocket experiment in September 2007.

This paper describes about the basic techniques of the electric field instrument onboard the Japanese sounding rocket for measuring the electric field in the ionosphere. Then electric field data measured by the S-520-23 sounding rocket show that the new type sensor can measure the electric field in the ionosphere.

Key words: Electric field, double probe technique, ionosphere, sounding rocket.

1. Introduction

Measurements of electric fields are one of key elements for various space missions. The detection of electric field is useful to identify global plasma dynamics and energetic processes in magnetosphere and ionosphere. The concrete examples are as follows.

- Electric field structure associated with the charged particle precipitation.
- Electric field structure associated with the global motion of the ionosphere.
- The role of the electric field in the acceleration and heating mechanisms of ions.
- Propagation mechanism of the electric field in the auroral ionosphere to the low latitude ionosphere.
- Electric field structure in the equatorial ionosphere.

Electric field measurements have been carried out using the sounding rockets and satellites since 1960’s to achieve these purposes (Fahleson, 1967; Mozer and Fahleson, 1970; Pedersen et al., 1984). Many electric field measurements have been carried out in Japan, too. And the electric field detector onboard sounding rockets and satellites have been successfully used in the D, E and F regions of the ionosphere and in the magnetosphere (e.g. AKEBONO satellite (Hayakawa et al., 1990), Geotail spacecraft (Tsuruda et al., 1994), SS-520-2 sounding rocket (Ueda et al., 2003), and SEEK-1 and 2 sounding rocket (Pfaff et al., 1998; Pfaff et al., 2005)).

The double probe technique have been extensively used on sounding rockets and satellites in order to measure electric field in the ionosphere and magnetosphere. And the passive double probe technique has been proven to be a reliable technique in the high electron density plasmas of the ionosphere. The technique has been extended to the lower density plasmas of the D region of the ionosphere and of the inner magnetosphere.

In this paper we focus on the double probe instruments to measure electric field in the ionosphere by the Japanese sounding rocket and describe about new type antennas for electric field sensors.

2. Principle of Electric Field Measurement

The electric field can be calculated from any measurements of the potential between two same shaped metal electrodes in contact with the plasma, when the distance and geometry of the electrodes are known.

Figure 1 shows the schematic of the double probe technique for electric field measurements. The potential difference (V1 - V2) between a couple of electrodes (V1 and V2) that are the electrode on the tip of the antenna is measured and divided by the effective distance (L) between the electrodes in order to obtain the electric field component along the antenna. The effective distance between double probes is equal to the geometrical distance between the electrodes for the DC electric field measurement.

Ideally, the difference in the local plasma potential at these two electrodes is related to the sum of the ambient electric field (E) and the electric field, called v x B electric field, due to the motion of the sounding rocket across the Earth’s magnetic field. Thus the electric field E' measured by the double probe technique is given by

\[ E' = (V1 - V2)/L = E + v \times B \]  

where v is the velocity of the double probe system relative to the Earth and B is the Earth’s magnetic field (Maynard, 1998). The magnitude of v x B (about 50 mV/m) electric field is always larger than ambient electric field E (about 1 mV/m) in the ionosphere (Pfaff et al., 2005).
3. Instrument

The electric field instruments for sounding rocket comprise two main parts: sensors and the electronics. The two pairs of double probe antenna is usually used as sensors in order to obtain the two orthogonal components of electric field. The potentials gathered by the probes are detected with high impedance preamplifier. Amplified signals are input to a main electronics including low-pass filters and calibration circuits.

In this section, we describe the sensors and main electronics which are actually used by Japanese sounding rocket for the electric field measurements. And new sensors for sounding rocket is explained in detail.

3.1 Sensors

The ambient potential distribution of sensors in the ionospheric plasma can be modified by the presence of the support structure and rocket. All surface will charge to some degree in the plasma to maintain their own current balance. These potentials cause a plasma sheath to form which shields the potentials from the plasma. The characteristic dimension of the sheath is the Debye length which is expressed as the function of electron temperature and the elec-
tron density. The potential cannot be measured by the sensors in the sheath. It is important to put the sensors on the position separated enough from the Debye length. The Debye length is less than about 0.01 meters in the ionosphere (Fahleson, 1967). Therefore it is necessary for sensors to separate more than 1 meter from the rocket body in order to measure accurately the potential of sensors.

In previous sounding rocket experiments sensor for electric field measurements has been used wire boom antenna (cf. SS-520-2 sounding rocket (Ueda et al., 2003)). However the wire of antenna boom is very flexible, therefore there is a possibility that the wire antenna twines around the rocket payload. The extension of wire antenna has been used by the rocket spinning. The rocket spinning frequency is very fast (about 1 Hz) so that it is difficult for the sounding rocket experiment to extend the wire antenna during the flight. And the extension mechanism of wire boom antenna is complicated. The antenna to extend certainly and the simple extension mechanism are necessary in order to measure the electric field by the sounding rocket.

So Beryllium-copper (Be-Cu) rod antennas have been used in many sounding rocket experiments. Be-Cu can be fabricated with a built-in memory. They form into a cylindrical shape as they are deployed. They can be made more rigid by interlocking the edges or building in a helical twist which creates a tight overlap with length. In Western countries, a spherical sensor can be supported by these structures. Theses antennas can be deployed up to 20 meters from three-axis stabilized vehicles, subject to design and spacecraft constraints (Maynard, 1998).

In Japanese sounding rocket experiment, the end of Be-Cu rod is used as the cylindrical sensor in order to measure the electric field. This rod antenna length is about 1 meter in maximum as shown Fig. 2(a). The outer surface of Be-Cu rod is coated with an insulator such as Kapton film while the part of 10 centimeters from the end of Be-Cu rod is left bare to provide the sensor (see Fig. 2(b)). This Be-Cu rod is an improvement on the sensor which is used as an impedance probe onboard the sounding rocket. The extension mechanism of Japanese Be-Cu rod antenna is used by the self-extraction of the rolled Be-Cu element by its elastic force. This method is the simplest, using only wire cutter. And the storage case of this antenna is small (60 mm × 30 mm × 25 mm). Therefore the Be-Cu rod antenna was used at S-310-37 sounding rocket experiment in Japan. Six Be-Cu rod antennas (S-1 ∼ S-6) was deployed in the ionosphere as shown Fig. 3. The S-310-37 sounding rocket was installed two Langmuir probes to measure the electron density and temperature. It was able to be prevented from twining with Langmuir probes by using the Be-Cu rod antenna.

The antenna element better than the Be-Cu rod antenna was investigated, which were based on light weight, high rigidity, softness for compact storage, straightness after extension, and small degradation after repeated extension and
A tri-axially woven fabrics (TWF) carbon fiber reinforced plastic (CFRP) (Kasaba et al., 2010) was selected. Figure 4 shows the structure (left panel) and the open section tubular member (right panel) made of TWF-CFRP. Its density is 0.7 g/cm³, much smaller than that of other candidates such as Be-Cu, which we have used as antenna elements for sounding rocket experiments (8.3 g/cm³). In similar mechanical strength, the mass can be about 1/4. It partially contributes to the reduction of weight and momentum of the extendible part. Since CFRP is a conductive material, it can be used directly as antenna elements. We considered its weaved structure shown in Fig. 4, because the conductivity of TWF-CFRP was assured only along its coiled fibers.

As the extension mechanism the inflatable mechanism was used with an inflatable thin film tube as an extension actuator. The design concept of “space inflatable structure” (cf. Higuchi et al., 2006) is adopted for a monopole antenna system. In this design, pressured N₂ gas is supplied into an inflatable tube made by thin soft film (ex. polyolefin). The tube pushes the rolled CFRP tubular member and extends it. After the extension, the CFRP member has enough rigidity to keep its straight structure even if the inflated inner tube contracts due to the loss of gas, and can act as a monopole antenna. In this extension system, motor and its drive unit (including heater unit, gear mechanism, power supply, etc.) can be replaced by a small inflatable actuation system with a simple gas supply unit.

A new dipole antenna called SPINAR (SPace INflataion Actuated Rod) (cf. Higuchi et al., 2009) was used in the S-520-23 sounding rocket experiment. For ionospheric electric field measurements to meet the scientific objectives of
this sounding rocket experiment, the antenna element had non-conductive boom and the electrode only at each edge of boom, in order to have longer effective length of the dipole antenna and reduce the capacity coupling with the rocket body. The charging of non-conductive surface was not high in the mid-latitude ionosphere, several few V. Therefore, as another non-conductive material, TWF quartz fiber reinforced plastic (QFRP) was used in this sounding rocket experiment. The length and diameter of the antenna elements were 2.4 m and 2 cm, respectively. Total mass of the system, which includes two monopole antennas and their extension control units (see Fig. 5), was 4.3 kg. The mass of each extendible part was 80 g.

The S-520-23 sounding rocket deployed its nosecone at 55 sec after launch. At 59.4 sec after launch (85 km altitude), the SPINAR started the extension by opening its pneumatic valve for N2 gas, which pushed the inflatable tube at the pressure of 200 kPa. The full length was reached about 2 sec. later, i.e., with the extension rate of ~1.2 m/sec. The SPINAR was the first successful use of an inflatable structure as a flight antenna. It extended without any problems as shown Fig. 6.

3.2 Electronics
The electronics to measure the electric field consist of preamplifier and main electronics. The sensor is connected to the preamplifier. The electric potential difference induced between the probe and the common ground of the rocket is picked up by the preamplifier which has unity gain amplifier and high input impedance. The resistance between the sensor and the plasma is of the order $10^6$ Ω or smaller in the dense ionospheric plasma (Pedersen et al., 1998). Therefore it is necessary that the input impedance of preamplifier is more than $10^9$ Ω. Figure 7 shows the preamplifier circuit onboard the Japanese sounding rocket. When the receiver measures the MF band radio wave at the same time, the high frequency signal is passed through the high pass filter which consists of a capacitance and resistance.

The signal picked up by preamplifier input to the main electronics. The main electronics consists of a low pass filters, calibration circuits, power supply circuits, an analog to digital conversion circuit (A/D converter) and so on. Figure 8 shows the block diagram of one component in the electric field instrument onboard S-520-23 sounding rocket. This main electronics consists of a low pass filters, two A/D con-
verter, a calibration circuit and a power supply circuit. The low pass filter and the A/D converter are explained in this section.

The single probe signal and the double probe signal are low pass filtered in order to reject the high frequency components. The cut-off frequency of low pass filter for the single probe signal is 20 Hz (the 3rd order filter). The single probe signal is sampled through the 8 bits A/D converter with sampling frequency of 400 Hz. On the other hand, the low pass filter of double probe signal is the 7th order filter with the cut-off frequency of 40 Hz. The double probe signal is sampled through the 16 bits A/D converter with sampling frequency of 400 Hz by using an oversampling converter.

On the S-520-23 sounding rocket experiment, the sensors used two types of antenna. One is the Be-Cu rod antenna (tip-to-tip 2 m), and another is SPINAR (tip-to-tip 5 m). And Ex component of electric field was measured by using the Be-Cu rod antenna, and Ey component was measured by the SPINAR. This electric field instrument has the performance that can measure the natural electric field in the ionosphere as shown in Table 1.

4. Example of Measurements Results (S-520-23 Sounding Rocket Experiments)

The S-520-23 sounding rocket was launched on 2 September 2007 at 19:20 LT from the Uchinoura Space Center (USC) in Japan. The rocket achieved an apogee of 279 km at 268 sec after launch. The purpose of S-520-23 rocket experiment is the investigation of the process of momentum transportation between the atmospheres and the plasma in the thermosphere during the summer evening.
Table 1. Specification of the electric field instrument onboard S-520-23 sounding rocket. Two electric field components (E-field Ex and E-field Ey) values are derived on the assumption by using the distance between the probes of 2 m (Ex) and 5 m (Ey).

<table>
<thead>
<tr>
<th>Output data</th>
<th>Frequency Range</th>
<th>Dynamic Range</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single probe data</td>
<td>DC - 20 Hz</td>
<td>± 10 V</td>
<td>0.078 V (8 bits)</td>
</tr>
<tr>
<td>E-field (Ex: tip-to-tip 2 m)</td>
<td>DC - 40 Hz</td>
<td>± 0.5 V/m</td>
<td>0.015×10^{-3} V/m (16 bits)</td>
</tr>
<tr>
<td>E-field (Ey: tip-to-tip 5 m)</td>
<td>DC - 40 Hz</td>
<td>± 0.2 V/m</td>
<td>0.006×10^{-3} V/m (16 bits)</td>
</tr>
</tbody>
</table>

Fig. 9. Raw data of electric field measured by the double probe system onboard S-520-23 sounding rocket during the ascent. The upper panel shows the Ex component obtained by the Be-Cu rod antenna and the lower panel shows the Ey component obtained by the SPINAR.

time at mid latitudes.

The raw data of electric field measured by S-520-23 sounding rocket is shown as example. Figure 9 shows the raw data of electric field measured by the two orthogonal double probes during the ascent. The upper panel of Fig. 9 shows the Ex component obtained by the Be-Cu rod antenna and the lower panel shows the Ey component obtained by the SPINAR. The sine waves result from the probes rotation at the spin frequency of 0.93 Hz. The largest contribution to the electric field measurements by such probes moving through the ionosphere at mid-latitudes is that due to the \( \mathbf{v} \times \mathbf{B} \) fields created by their motion across the ambient magnetic field, where \( \mathbf{v} \) is the rocket velocity in the Earth-fixed coordinates and \( \mathbf{B} \) is the ambient magnetic field. The offset voltages of both Ex and Ey data are clearly seen during the entire flight as shown in Fig. 9. They are considered to be caused by coating the different material on the probe surface. One surface of probe is coated by “Aerodag” (a carbon micro powder) and the other is not coated.

Figure 10 shows a magnification of the raw electric field data measured between 100 and 110 seconds after launch. The waveforms are modulated at the spin frequency and are 90° out of phase, since the double probes are orthogonal. In order to determine the DC electric field, model sine waves at the spin frequency of 0.93 Hz are fitted to the Ex and Ey data for the entire flight. The sine wave fits are computed by using the method of least squares for every data points of both the Ex and Ey waveforms. An amplitude, a phase and an offset voltage of both the Ex and Ey component are read from the sine wave fits thus obtained. Consequently, the DC electric field data are essentially low pass filtered below the spin frequency of 0.93 Hz. Figure 11 shows the amplitudes of Ex (upper panel) and Ey (lower panel) components, which obtained from the sine wave fit, during the ascent. These data is included the components of \( \mathbf{v} \times \mathbf{B} \) field.

Since the electric field component along the spin axis, Ez, was not measured, vector of electric fields are obtained assuming \( \mathbf{E} \cdot \mathbf{B} = 0 \), where \( \mathbf{E} \) is the electric field and \( \mathbf{B} \) is the magnetic field. Namely this assumption means that there are no electric fields parallel to \( \mathbf{B} \). The next step is to subtract the \( \mathbf{v} \times \mathbf{B} \) components from the Ex, Ey and
Fig. 10. A magnification of the raw data measured between 100 and 110 seconds after the launch.

Fig. 11. Amplitudes of Ex (upper panel) and Ey components (lower panel) obtained from the sine wave fitting.
Ex components. And the attitude data are used to rotate the electric field from the rocket reference coordinates into geophysical coordinates.

5. Conclusion

In this paper, it was described that the electric field instruments used passive double probe systems onboard the Japanese sounding rocket have provided a DC electric field in the ionosphere. And it was described to have developed a Japanese original new sensor. The electric field instruments with these sensors have been successfully used in the D, E and F region of the ionosphere.

One of the new type antenna was the Be-Cu rod antenna. The length of the Be-Cu rod antenna was about 1 meter, but the electric field in the ionosphere was able to be observed enough with this antenna. The extension mechanism of Be-Cu rod antenna was very simple and reliable. For the length of Be-Cu rod antenna, if the problem in manufacturing, which is an oven to shape the rod antenna from Be-Cu plate, is solved, the length of the antenna can be lengthened.

Another is the antenna based on CFRP technologies, which fulfill stringent design requirements, i.e., enough stiffness, light mass, compact storage, safe extension, and reasonable test efforts. This antenna, rigid monopole sensor with the inflatable extension system, was used in the ISAS/JAXA S-520-23 sounding rocket experiment in September 2007, and became the world’s first successful flight of the inflatable-type antenna.

An Inflatable Tube Antenna (ITA) is developed for next sounding rocket experiment, non-stiff antenna based on the inflatable system. The ITA is a medium-length antenna at lower cost, and the extension mechanism of the ITA is very simple. Because its extension system is inflatable without QFPR structure like a SPINAR. The inflatable tube is made of polyethylene terephthalate (PET), which itself is conductive due to the copper coating. It can be extended to a length of 2.5 meters (tip-to-tip 5 meters) in the spin plane, which can only be achieved by more expensive and complicated antennas like wire antenna system currently. Thanks to the refined design, the total mass will be less than 2 kg including the extension system. The ITA will be used in S-520-26 sounding rocket experiment in 2011.

These antenna and electric field instruments will be expected as one of the core elements for future projects, such as space electric field and plasma wave sensors for the SCOPE mission, compact radio sensors for landing missions, radar antennas for Lunar, Martian, Jovian, and asteroid missions.

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References


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