Retarding Potential Analyzer (RPA) for Sounding Rocket

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Problems associated with Retarding Potential Analyzer (RPA), which can be used to measure ion temperature and density in the lower E region where ion temperature is 200–300 K, are discussed. Two major factors which need to be taken care of to get accurate ion temperature of extremely low values are the effect of mesh size of the grids to be used and the effect of electrode contamination. An electrode baking and vacuum sealing mechanisms are designed to keep the electrode surface clean. The effect of mesh sizes on the calculation of ion temperature is discussed by using simulation studies as well as laboratory experiments. The study suggests that the uniformity of the electric field in the RPA sensor is critical. The manuscript describes the principle of the RPA, the effect of the mesh size using computer simulation studies, and the mechanical design of the sensor sealing to remove electrode contamination.

Key words: Lower ionosphere, ion temperature, electrode contamination, mesh size effect.

1. Introduction

Retarding Potential Analyzer (RPA) or Ion Trap, which can measure the ion temperature ($T_i$), the ion composition and density ($N_i$) of individual ion species in the ionosphere, is one of the powerful tools to measure ionospheric parameters. Accordingly, RPA has been flown in many low earth orbiting (LEO) satellites such as OGO 6 (Hanson et al., 1970), Atmosphere explorer (Hanson et al., 1973), Dynamic Explorer (Hanson et al., 1993), FORMOSAT 1 (Chao and Su, 1999, 2000; Chao et al., 2003), and DMSP (Defence Meteorological Satellite Program) satellites which routinely installed Retarding Potential Analyzer (Bankov et al., 2009). RPA was also installed in Pioneer Venus Orbiter (Knudsen et al., 1979), Viking 1 and 2 Mars landers (Hanson and Mantas, 1988).

Although RPA is useful for satellite measurements, RPA has not been flown in sounding rockets frequently (Minami and Takeya, 1982). The reason is that RPA makes use of the satellite velocity (7–8 km/sec), which is usually much higher than the ion thermal velocity except for hydrogen ions. However, the velocity of the rocket (1–2 km/sec) is much slower than the satellite velocity. The ram direction speed, which is needed to perform reliable $T_i$ measurement, changes during the rocket flight, and therefore the data analysis needs information on the rocket attitude with respect to the rocket motion. Another reason why RPA was not used for sounding rocket experiments very often is that the ion temperature in the height range where the rocket can survey (100–300 km) is less than 1/10 of the $T_i$ value in the satellite altitude.

In order to measure $T_i$ of 200 K at the height of 100 km with enough accuracy, three factors need to be taken into account. One factor is the electrode contamination. Because $T_i$ is very low (∼0.02 eV), the effect of electrode contamination becomes much more serious at the rocket altitude than at the satellite altitude, and without doubt, the electrodes need to be free from the contamination. Another factor is the frequency response of the amplifier. The rocket moves in the ionosphere with a velocity of 1–2 km. If we need to get 1 km height resolution, we need to sweep the operation voltage in 1 second. Because the sounding rocket usually has a spin rate of 1–3 Hz, the signal from RPA might be modulated by the rocket spin. Accordingly the voltage sweeping rate needs to be higher than 1 Hz to avoid the spin modulation of the RPA signal. (Even though RPA is formed symmetric and located at the front of rockets, the spin rate is still an important issue, considering the instabilities and precession motion while rocket flight.) Thus, RPA needs to pick up very small current ($10^{-9} - 10^{-11}$ A) with high frequency response of 5–10 Hz. This constraint requires special attention to the electronic circuit design. The third factor is the size of the meshes which are used for the voltage grids, which determines the uniformity of the electric field inside the sensor. In this manuscript we mainly discuss the problems associated with the electrode contamination and mesh of the electrodes. Then, we describe future tasks that need to be pursued.

2. Principle of RPA Measurement

The DC Langmuir probe collects both ion and electron currents, and therefore $T_i$ cannot be measured by the DC Langmuir probe. To measure $T_i$, we need to pick up only the ion current from the ambient plasma. In order to separate the ion current from the ambient plasma, basically we have two options: (1) we first repel electrons by a grid mesh with a sufficient negative voltage with respect to the plasma potential, and measure the ion current by changing the collector voltage, (2) we sweep the grid voltage, and the collector is biased negatively to repel electrons. However, only two electrodes (one grid and one collector) cannot provide accurate measurement due to three reasons. One reason is

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that the secondary electron current from the collector is usually added to the ion current and it is sometimes larger than or comparable with the true ion current. Another reason is that the sweeping voltage which penetrates into the plasma influences on the measurement of other parameters. The third reason is that one single mesh cannot guarantee uniform electric field inside the sensor.

In order to overcome the difficulties which spoil the measurement accuracies as described above, the RPA sensor needs to be composed of several stainless steel meshes and one stainless steel collector. The reason why we choose stainless steel for electrodes is because of its ability to prevent oxidized. An illustration of the RPA sensor is shown in Fig. 1 where G1-G4 indicate four different meshes and different potentials are applied to these meshes. In the ideal case, the potential is uniform on the mesh to allow ions penetrating though. Ions, which are selected, will be collected on the current collector (C). In reality, the potential on the meshes is not uniform because of the gap in the fine mesh structure. To form a more uniform electric field the mesh should have thinner pinholes or more grids. However, this will decrease the particle transparency and results in a smaller collected current. So we would better use as fewer pinholes as possible and try to form a uniform field at the most needed meshes in the sensor. A detailed discussion of the effects of the meshes is given in Section 4.

The ion flux measured by the collector at different retarding potentials \(V_a\) generates a current signals \(I_C\). The measured \(I_C - V_a\) curve is a function of the ion parameters \(V_a, n_i, v_D\), where \(n_i\) is the ion density, \(v_D\) is the bulk ion flow velocity, and under some assumptions and by curve fittings, the ion parameters can be obtained.

As shown in Eq. (1) we have neglected effects of the mesh geometry, the non-uniform potential field on the meshes, the ion acceleration by the potential inside the sensor, and the ion detention in the sensor, etc. This integral represents the ion flux seen by the sensor in the \(x\)-direction (normal to the mesh plane). To evaluate Eq. (1) we consider the ions with a normalized drift-Maxwellian distribution function given by

\[
f(\vec{v}) = \alpha \exp \left\{ -\beta (v_y - v_D \cos \theta_i)^2 + (v_y - v_D \sin \theta_i)^2 + v_y^2 \right\}
\]

where \(\alpha = (m_i/2\pi kT_i)^{3/2}, \beta = m_i/(2kT_i),\) and \(v_D\) is the ion drift velocity. Then, the integral in Eq. (1) can be carried out and the ion current is given by

\[
I_C(V_a) = \eta S n_i \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} v_x f(\vec{v}) dv_x dv_y dv_z
\]

where \(S\) is the surface area of the sensor opening, \(e\) is the ion charge and \(\eta\) is the grid transparency, and \(v_c\) is the critical velocity for ions to penetrate through the mesh at the retarding potential \(V_a\) and is given by

\[
e(V_a - V_S) = \frac{1}{2} m_i v_c^2
\]

Fig. 1. Principle of a planar gridded RPA and its operation potential profile.

Fig. 2. Illustration of the flowing of ions into the sensor.

\[
I_C(V_a) = \eta S n_i \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} v_x f(\vec{v}) dv_x dv_y dv_z
\]

\[
\exp \left\{ -\left[ \frac{m_i}{2kT_i} \left( v_D \cos \theta_i - \frac{2e(V_a - V_S)}{m_i} \right) \right] ^2 \right\}
\]

(3)
where \( \text{erf} \) indicates the error function. For ion measurements on sounding rockets, several parameters in Eq. (3) need to be measured by instruments. The particle incident angle \( \theta_i \) can be obtained by using the sun sensor and the magnetometer. The rocket velocity \( v_R \) can be calculated from the rocket trajectory which is obtained by the ground-based radar. Parameters such as the sensor entrance surface area \( S \) and the mesh transparency \( \eta \) should be checked in laboratory experiments. By putting these numbers, the ion parameters \( T_i \) and \( n_i \) at different heights in the ionosphere can be obtained by curve fittings. (Fitting methods will be described later.)

An example of the relation between the applied retarding potential \( (V_a) \) and the ion current at collector \( (I_c) \) with different ion temperatures is plotted in Fig. 3, assuming the mass of Nitrogen ions \( (N^+_2) \).
Equation (3) suggests that when the ion temperature \( T_i \) increases, the width and height of the exponential part will be larger and the slope of the error function will be smoother. So as \( T_i \) increases, the I–V curve becomes smoother as shown in Fig. 3, and more ions are measured as the retarding potential is lower. When the ion drift velocity \( v_D \) increases, the center of the exponential part and the deepest position of the error function part will shift towards higher \( V_a \) region. When the ion drift velocity is high, we need to apply higher retarding potential to prevent ions from penetrating in. Higher drift velocity also causes larger ion flux measured at the collector. The I–V curve at different drift velocity \( (v_D)_i \) is plotted in Fig. 4.

For ions flowing into the sensor from different incident angles, the flow velocity in the normal direction is changed. The I–V curves at different incident angles \( (\theta)_i \) are plotted in Fig. 5.

### 3. Derivation of Ion Parameters

To obtain the ion parameters \( T_i, n_i, v_D \), we can fit the measured I–V curve by the theoretical I–V curve derived by assuming that the ions have a drift-Maxwellian distribution. However, we can obtain the ion distribution directly from the measured I–V curves. Eq. (1) can be rewritten as

\[
\frac{dI_C}{dV_a} = \frac{2e^2\eta S n_i}{m_i} \int_{V_a}^{\infty} f(V_a - V_S) dV_a
\]

(4):

\[
= -\frac{2e^2\eta S n_i}{m_i} f(V_a - V_S). \tag{5}
\]

Or, the measured ion energy distribution function is given by

\[
f(V_a - V_S)_{\text{experiment}} = -\frac{m_i}{2e^2\eta S n_i} \frac{dI_C(V_a)}{dV_a}. \tag{6}
\]

It is also easier to fit the measured distribution by a 1-D drift-Maxwellian distribution function or in combination with a high energy tail distribution. The 1-D drift-Maxwellian distribution function can be written in terms of the applied retarding potential by

\[
f(V_a - V_S)_{\text{theory}} = \sqrt{\frac{m_i}{2\pi kT_i}} \exp \left[ -\frac{m_i}{2\pi kT_i} \left( \sqrt{\frac{2e(V_a - V_S)}{m_i}} - v_D \right)^2 \right]. \tag{7}
\]

By fitting the measured distribution function (Eq. (6)) with a 1-D drift-Maxwellian distribution (Eq. (7)), we can get the ion parameters \( T_i \) and \( v_D \).

To determine the ion density \( n_i \), we compare the maximum value of the ion distribution function given by Eqs. (6) and (7). The maximum value of these two formulas should be the same if these two distribution functions are the same. Accordingly, we obtain

\[
f(V_a - V_S)_{\text{theory, Max.}} = \sqrt{\frac{m_i}{2\pi kT_i}} = -\frac{m_i}{2e^2\eta S n_i} \left( \frac{dI_C(V_a)}{dV_a} \right)_{\text{Max.}}. \tag{8}
\]
The ion density can then be calculated from the above equation by
\[ n_i = -\frac{1}{\varepsilon^2 \eta S} \sqrt{\frac{\pi m_i k T_i}{2}} \left( \frac{d I_C(V_a)}{d V_a} \right)_{\text{Max}}. \]  

4. Laboratory Experiments

In order to check the performance (e.g. gain of amplifiers, system stray capacitance effect, noise level ... etc.) of the RPA, we conducted laboratory experiments by using the Space Plasma Operation Chamber (SPOC) at the Plasma and Space Science Center, National Cheng Kung University. The dimension of the chamber is 2 m in diameter and 3 m in length, and the pressure inside the chamber reaches below \(10^{-6}\) Torr in a day without loading with one cryogenic pump and one turbo-molecular pump. The initial pumping is done by an oil-free mechanical pump, which means that experimenters do not need to worry contamination due
to the pumping system. The chamber is the second largest space plasma simulation chamber among Asian countries and has the highest performance in all aspects such as stable plasma production as well as the stability of vacuum pressure. Two back diffusion type plasma sources are attached at both ends of the chamber. The plasma sources can produce plasma conditions similar to the ionospheric plasma with density of $10^4$–$10^6$ els/cc, and electron temperature of 1000–3000 K. In the chamber there is a sensor moving system that can move instruments along the chamber axis as well as vertically by using two motors. The movement in the vertical direction is done by flexible metal tether. Motions for both directions are computer controlled, and the location of the sensor can be either programmed or manually controlled. The maximum weight of the sensors to be hung at the end of the wire is around 500 gm. A neutral mass spectrometer is also attached to monitor the neural gas residue.

The chamber has a gas reservoir which can reduce the pressure from the original gas container cylinders. Two gas (normally nitrogen and oxygen) injection is available at the same time. The pressure inside the chamber is well controlled by the mass flow meter.

4.1 Experimental setup in SPOC

We assembled RPA instrument in the SPOC and the experimental setup is shown in Fig. 6. The RPA is placed on a rotation platform to change its look angle with respect to the plasma emitter. The pre-amplifier and the control board are put in metal boxes located right behind the RPA sensor. Outside the chamber is a data acquisition board similar to the one on rockets, with the same sampling rate and data resolution.

The plasma emitter used for plasma production in this chamber is illustrated in Fig. 7. The plasma is produced
Fig. 11. The measured ion temperature and ion density at RPA different look-angle with respect to the plasma emitter in the Space Plasma Operation Chamber.

Fig. 12. The sheath potential $V_S$ and the ion bulk drift velocity $v_D$ in the measured ion energy distribution function.

Fig. 13. Relation between the ion drift velocity $v_D$ and the plasma sheath potential $V_S$, and $V_S$ and the fitted ion temperature $T_i$.

Based on the principle of “back-diffusion plasma emitter.” By heating up the Nickel filaments with painted BaCO$_3$, thermal electrons with $T_e \sim 1000$–1100 K (≈melting temperature of Nickels) are emitted. Those electrons are accelerated by the electric potentials applied on a metal grid and a plate, and collide with neutral particles (N$_2$ or Ar) in the region between the grid and the plate. Then, the valence electrons of neutral particles are separated from the neutrals by high energy electron bombardments, and ions are generated. Then, ions are accelerated by the electric field from the difference of electric potentials applied on the grid and the plate, and they fly into the chamber and then electrons follow the ions into the chamber. Then, the chamber is filled with ions (N$_2^+$ or Ar$^+$), electrons and neutral particles (in the plasma generation period, the background neutral pressure is $\sim 2 \times 10^{-4}$ Torr), forming an environment similar to the Earth lower altitude ionosphere. (However, there is surely plasma beam component existing on the direction of plasma emitters in the chamber.)

4.2 Experimental results and data analysis methods

An example of the measured I–V curve by the RPA system is shown in Fig. 8, in which the red points are the measured data. It is clear that there are noises due to the electronics or other factors. To obtain the ion energy distribution function by differentiating the measured current (accumulated ion flux), we need to remove the noises.

Figure 9 shows the flow chart of the data analysis for data noise reduction and data processing results at each step. To
remove the noises, we first perform a band-pass filtering of the measured data to remove high frequency noises (those noises are amplified most in the differentiation). Then we perform a cubic spline fit to the filtered I–V curve, and the fitted spline function is differentiated to obtain the ion energy distribution function, which is then fitted with a drift-Maxwellian distribution.

In Fig. 9 the left bottom panel shows an example of the filtered ion current, and the right bottom panel shows the measured ion energy distribution function (red curve) and the fitted result (black-dotted curve). Following the discussion above, the measured ion energy distribution function is first shifted by a plasma sheath potential energy \(eV_s\), which is estimated from the Langmuir probe measurement, and then fitted with a drift-Maxwellian. The fitted result of this example is \(T_i \sim 310\) K and \(v_D \sim 2250\) m/s. For the chamber plasmas, since the neutral density is much higher than the ion density, \(T_i\) should be the same as the neutral temperature (\(\sim\)room temperature). From the Langmuir probe (with same electrode material as the RPA) measured data shown in Fig. 10, the plasma potential is \(V_{\text{plasma}} \sim 2.4\) V and the floating potential is \(V_f \sim 1.7\) V, so the sheath potential that accelerates ions \((V_{\text{plasma}} - V_f)\) is about 0.7 V. This corresponds to a drift velocity of 2200 m/s for \(N^+_2\) ions \((m_i v_D^2/2 = e(V_{\text{plasma}} - V_f))\), which is about the same as the fitted \(v_D\) value. This 2250 m/s drift is caused by the potential of the sheath around the RPA. (The potential differences in the region between “G1” and “sheath” in Fig. 1.) It is to be noted that for measurements on rockets, \(v_D\) is also caused by the rocket ram velocity in addition to the acceleration by the sheath potential.

Since ions can be either accelerated or decelerated in the sensor due to many factors such as the potential difference between the floating potential \(V_f\) and the ground, the potential difference between the ground and the collector, the non-uniform grids on the meshes, the charge effects from ion detention, etc. Those factors can cause a shift in the measured ion distribution function and thus measurement errors. For example, because the sheath expansion effect can cause the mesh grid potential to leak, the measured I–V curve is not saturated even when the retarding potential is small as shown in Fig. 8. This makes the left part of the measured energy distribution function shown in the right bottom panel in Fig. 9 not well-fitted. So, we only fit the
right part of the distribution function (the “thermal” part) and obtain $T_i$. The sheath expansion effect as well as the potential leak effects caused by mesh grids will be discussed in details later.

Following the data analysis method described above, the measured ion temperature and the ion density at different look-angle with respect to the plasma emitter in the Space Plasma Operation Chamber is shown in Fig. 11.

When the RPA sensor opening is facing the plasma emitter (look-angle $= 0$ degree), both the ion temperature and the ion density become larger. It seems reasonable that the ion density is larger when the RPA faces the emitter, considering the wake effect caused by the sensor structure. The measured ion temperature is also higher when the RPA sensor opening faces the emitter. This might come from the high energy tail of ion energy distribution function in chamber beam component. Eventually the ions diffuse into the whole chamber, and they will be at the same temperature as the neutral particles at the room temperature. Note that when the RPA sensor opening faces the side-wall (look-angle $= -90$ degree), the measured $T_i$ is close to the room temperature.

The asymmetry of the measured $T_i$ on the look-angle may come from two reasons: (1) the plasma condition is changed after the IEA rotates from $-90$ degree to 90 degree; (2) the asymmetry of plasma condition caused by the experimental arrangements (the RPA structure, the chamber asymmetries, etc.).

4.3 Further considerations and discussions

In this Section, we will discuss the sources of errors of the measured ion parameters from the curve fitting. A 1-D drift Maxwellian energy distribution function is used to fit the measured ion energy distribution, which is expressed by Eq. (7). The unknown parameters in this formula are $V_s$, $v_D$ and $T_i$. To obtain $T_i$ by curve fitting, we first determine $v_D$ from the Langmuir probe measurements ($m_i v_D^2/2 = e (V_{\text{plasma}} - V_f)$), then we decide the sheath potential $V_s$, and then fit the measured ion energy distribution to get $T_i$. An example the fitted ion parameters are sensitive to the choice of $V_s$ value is shown in Fig. 12. The left curve in Fig. 12 shows an example of the drift-Maxwellian distribution versus the applied retarding potential that is obtained by choosing $V_s = 0$, $T_i = 150$ K and $v_D = 3500$ m/s. However, if we fit this energy distribution function by assuming that the plasma sheath potential is $V_s = 1$ V, we get $301 \pm 1$ K for $T_i$ and $2332 \pm 0.5$ m/s for $v_D$, respectively. This computer calculation shows that the fitted ion parameters are quite sensitive to the sheath potential $V_s$, and therefore we need to know the difference between the am-

Fig. 16. The RPA Measurement results by using meshes of different sizes.

Fig. 17. The fitted $T_i$ and $v_D$ values versus the plasma density for different mesh size.
bient plasma potential and the floating potential of the first grid accurately.

Figure 13 shows $v_D$ versus $V_S$, and $T_i$ versus $V_S$. Thus, we can obtain $T_i$ by fitting the measured data in Fig. 12 with different assumed values of $v_D$.

From Fig. 13, when $v_D$ has an error of 500 m/s (which is equivalent to an error in “$V_{\text{plasma}} - V_f$” of about 0.4 V measured by the Langmuir Probe), the fitted $T_i$ error is about 80 K.

Another important feature should be noted in Fig. 13 is that the fitted $T_i$ and $v_D$ have opposite tendency. In other words, if we get higher fitted $v_D$ values (e.g. due to plasma and floating measurement error), the fitted $T_i$ will be lower. We will see this effect clearly in the experimental results presented later.

5. Effect of Grid Mesh on $T_i$

5.1 Experimental arrangements

The experimental measurements by the RPA are performed to investigate the grid effects. We have used four different mesh sizes and performed ion measurements in the SPOC. Figure 14 shows the photos and dimensions of meshes with different sizes. Those meshes are manufactured by photo-etching processes with a tolerance of $\sim$0.02 mm.

Using the mesh structures shown in Fig. 15, we conduct
RPA measurements with two different sizes of mesh at the same time in the SPOC. The experimental arrangement is similar to the one shown in Fig. 6, and the sensors are placed on a rotation platform, and the circuit (including amplifiers and noise filters) is placed in a metal box located behind the sensor (Fig. 15).

Since we can only put two RPAs in the chamber at the same time, the RPA with mesh size 1 (the smallest mesh) is chosen as the reference, and we use a different size of mesh in the other RPA sensor in each experiment. Thus, we will conduct three experiments with mesh sizes 1 and 2, mesh sizes 1 and 3, and mesh sizes 1 and 4, respectively.

5.2 Experimental results

The measured I–V curves with different mesh sizes at similar plasma conditions are shown in Fig. 16. The green and yellow-dashed curves in each panel are measured with mesh size 1 (smallest), and the red and blue-dashed curves in the top, middle and bottom panels are measured with mesh sizes 2, 3 and 4, respectively. Although the results in these three figures are not measured in the same experiment period, but the ion saturation current (at retarding potential \( = 0 \) V) measured by the RPA with mesh size 1 in these three panels are quite similar, and thus the ion density is also similar in these three experimental measurements.

In Fig. 16, we can see that as the mesh grid size increases, the measured ion current (proportional to the incident ion fluxes) also increases. In comparing measurements with mesh sizes 1 and 4, there’s about a factor of two differences in the measured ion fluxes. The calculated optical transparency for mesh size 1 and 4 are 0.59 \((0.95^5)\) and 0.77 \((0.95^5)\), respectively. Although the ion optical transparency is higher for larger sized meshes, the main reason for the measured ion flux differences may not just come from the mesh transparency. The main reason of the difference in the measured ion fluxes may be due to the mesh alignment difficulty for meshes with smaller grid size. Besides the difficulty in manufacturing meshes with uniform grid for smaller grid size, it is also harder to align two meshes because of the grid differences between the smaller meshes. The orbit transparency decreases as a result of mesh non-alignments. Furthermore, the ion lensing effects may also become more serious for meshes with smaller grid-size be-
cause of the mesh non-alignments.

From Fig. 16, we note that the sheath expansion effect becomes clearer at small retarding potentials, and the measured I–V curve shifts toward higher energy for meshes with larger grid size. These two effects both come from the potential leak effect. For larger grid-sized meshes, it is more difficult to maintain the potential uniformity in the sensor. And, if we use meshes with larger grid size for the G1 of RPA, the potential of G2 easily leaks outside G1 into the plasma. Then, the ambient ions can be affected by the potential leakage from the sensor.

Following the data analysis procedure introduced previously, the ion energy distribution is fitted, and $T_i$ and $v_D$ obtained for each size of meshes for different plasma densities are shown in Fig. 17. The look-angle of the sensor opening with respect to the plasma source is 90 degree. To calculate $T_i$, we assume that the smallest mesh gives accurate $T_i$ of 300 K, and $V_1 - V_f$ is the same for all experiments.

The top (bottom) panel of Fig. 17 shows the fitted ion temperature $T_i$ (drift velocity $v_D$) versus the plasma density for 4 different mesh grid sizes (very small, small, large, and very large) described in Fig. 14. Note that the ion temperature is peaked at about 500 K at 0.5 plasma density (in arbitrary unit). From the experiments, we conclude that the potential leak effects will cause both higher fitted values of $T_i$ and $v_D$ because of the ion energy distribution expansion and shift. The tendency of the fitted ion drift velocity $v_D$ with respect to the plasma density is related to the floating potential which is influenced by the plasma density. As the plasma density increases, the plasma potential remains almost constant, while the floating potential increases. Then, from the relation $m_i v_D^2/2 = e(V_{\text{plasma}} - V_f)$, $v_D$ will decrease as the plasma density increases.

The variation of the fitted ion temperature $T_i$ with the changing plasma density shown in the top panel of Fig. 17 is not known yet. When the plasma density is high, the measurement results are consistent with simulations because those complicated effects are overshadowed by large ion fluxes in the sensor. But, the reason of the measured $T_i$
peaks in Fig. 17 is still unknown. To investigate this, we may need to perform more experiments with different mesh grid sizes to investigate this effect in details. The peak $T_i$ value seems to be lower for smaller grid-size meshes, so we need measurements between mesh grid size 1 and 2 in the future.

6. Instrument Design for Sounding Rocket Experiment

6.1 Retarding potential analyzer system for NSPO sounding rocket #10

RPA which we are going to install in the rocket has 5 meshes. G1, G2 and G4 are single-layered meshes, and G3 is a double-layered mesh. G1 is grounded to the rocket body and plays the role of sensor potential boundary. Grounding the G1 mesh is to make sure the sensor opening is at the same potential as the rocket body. This reduces leak of the internal potential to ambient plasma and the sheath effect from G1.

G2 is used for repelling electrons. The electron temperature at the sounding rocket height is about 0.2 eV, and G2 potential is chosen to be biased at $-4$ V with respect to the rocket body. This voltage level should repel most electrons during the rocket flight.

The positive potential applied to G3 serves as a potential barrier for ions. It is swept from 0 to 3 V (for ion mean energy of $\sim 0.1$ eV). Thus, G3 selects the incident ion energy in the sensor normal direction. This is an important part of the ion energy analysis in RPA measurements, so we use a double-layered mesh to produce more uniform potential field for clearer ion threshold energy determination.

The negatively biased ($-2$ V) G4 is used for repelling any possible secondary electrons caused by the bombardment of high energy ions or radiation at the collector. The secondary electron due to ion bombardment is negligible for the sounding rocket height because the work function of the stainless steel is much higher than the energy of most ions. But the solar EUV (Extreme Ultraviolet) radiation at the rocket height could be substantial since the launch time is at daytime, and the bombardment of EUV photons to the sensor wall and collector might produce significant secondary electrons. This produces an extra current at the collector, and so we design the additional G4 to repel the secondary electrons.

The gain of the amplifier of the RPA is designed based on the International Reference Ionosphere (IRI-2007) model, we can estimate the ion parameters in the height range up to 300 km.

In this height, ion density is in the range of $10^4$–$10^6$ cm$^{-3}$, and the ion temperature is about 300–900 K. For this comparatively high plasma density, the RPA current collector is designed without using particle multipliers. A normal stainless steel is used, which has a strong structure and is relatively free from surface contamination. Since the ion temperature is also not so high (the mean energy is less than 1 eV), there is no need to use high voltage devices for the ion energy analysis. Thus, we don’t need to worry about vacuum arc effects in the sensor.

To conduct experiments on rockets, we need to finish the basic data processing unit which performs the onboard data acquisition, data packaging and downlink to a ground-based site through telemetry. An illustration of the RPA system on rockets is shown in Fig. 18.

As ions hit the collector in the sensor, they generate current. This current will flow into the “pre-amplifier” circuit located right after the sensor. The pre-amplifier circuit is put in a small metal box and the current signal from the sensor flows in through short coaxial cables.

The pre-amplifier circuit is to amplify the small current signal from the collector to a larger voltage signal. The output of the pre-amplifier circuit will be again processed at the “control board” circuit. Signals from the pre-amplifier circuit are large enough, so the cable between the pre-amplifier and the control board boxes can be longer. The reason of separating the electronic circuits into two boxes is because the control board circuit is larger and we placed it in the lower space of the rocket to allow more upper space for the other payloads. The control board is to convert the measured analog signals to digital signals, produce the data packages which will be sent to the ground, and control the applied potential through the pre-amplifier to the sensor. When signals pass to the overall electronic unit (EU) by the control board, they are ready to be sent to the ground. The EU also applies the needed power to the pre-amplifier and control board circuits. Before RPA starts the measurements, EU will generate a signal to a cutter to open the sensor top cover.

6.2 Sensor design and fabrication

The dimension of the sensor is 100 mm in diameter, 57 mm in height excluding the vacuum port and valve. Total weight of the sensor is 1.5 kg.

6.3 Electronics design and fabrication

From the plasma conditions (based on the IRI-2007 model) in the rocket height and the RPA sensor dimension, the ion current is considered to be in the range of 5~500 nA. So the RPA pre-amplifier circuit gain is set to be $10^7$ V/A. The circuit diagram of the pre-amplifier is shown in Fig. 20.

When the collector current flows to the pre-amplifier circuit (Fig. 20, “SENSOR_IN”), it first flows through an inverting amplifier. The resistor at the negative feedback of this amplifier determines the gain. Then, the signal passes through a differential amplifier which amplifies and inverts the signal again. This signal then flows to the “control-board” circuit part (Fig. 20, “PRE_OUT”).

In addition to amplifying the collector current, the pre-amplifier circuit also contains several buffers to deliver potential to each mesh. The outermost mesh (G1) is directly grounded through a large resistor. The voltage output signal from the pre-amplifier (Fig. 20, “PRE_OUT”) flows to the control board box. The circuit diagram of the control board is shown in Fig. 21.

The FPGA in the control board circuit is in charge of packaging the pre-amplifier output signals, and G1~G4 monitor and pass those data packages to the overall electronic unit (EU) on the rocket. It also produces time-varying retarding potential to G3.

To reduce the circuit size, we manufactured all circuits with multi-layer printing boards and SMD (surface mount device) components.
6.4 Additional technical considerations and environmental tests

The process of cleaning the RPA sensor is shown in Fig. 24. An infrared light beam shines through the glass window to the sensor top is used for evaporating the water molecules on the collector and meshes. At the same time, the sensor is evacuated through the valves on the bottom. After the sensor is cleaned, dry N$_2$ gas is injected into the sensor to about 0.5 atm. pressures. The procedures are to open the valve 1 and the valve 3, evacuate the sensor with infrared light irradiation, then close the valve 3, open the valve 2, and inject dry N$_2$ gas, then close the valve 2 and the valve 1, and finally the RPA sensor is cleaned and ready for deployment.

To make sure that the sensor is maintained at 0.5 atm. pressure before deployment, a vacuum test is performed (Fig. 25). Since the rocket vibrates while launching, to make sure that the sensor will not be broken under this violent vibration, a vibrational test is also performed (Fig. 26).

6.5 Future works

In the near future, more investigations of mesh transparency and mesh alignments should be done. Although meshes with small grid sizes show better measurement accuracy, the small grid structure may produce rather serious mesh structure effect. To eliminate this, we need to try some special mesh structures to conduct measurements.

Besides the discussion in Chapter 4, more simulations and experiments are needed to investigate the grid effects in more details of a “planar-gridded retarding potential analyzer”.

For the RPA measurements by using sounding rockets during daytime, the effects of the secondary electrons from the collector should also be carefully checked because the solar EUV radiation produces the secondary electrons from the collector and the grid mesh in front of the collector. The check can be done by using a Deutrium lamp, which is commercially available.

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