Thermal Ion Instrumentation for CubeSat Missions
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ABSTRACT
Retarding potential analyzers (RPAs) have been built by the William B. Hanson Center for Space Sciences at the University of Texas at Dallas (UTD) and validated on a host of ionospheric science missions since the late 1960s. Recently the design has been adapted for accommodation on CubeSats and other small satellite platforms. These adaptations include redesign of the mechanical sensors and electronics to create a new instrument that is quicker and easier to assemble than the systems flown on previous missions, while retaining much of their functionality. The new RPA design has undergone limited environmental testing at the subsystem level, and is currently being readied for functional testing in a space simulation vacuum system using a new LabView controlled ion beam source. This paper describes the important design changes, validation tests, technical specifications, and performance metrics for the new instrument.

INTRODUCTION
Accurate specification of ion densities and temperatures is necessary for both military and civilian prediction/assessment of radio propagation and GPS navigation capabilities. Retarding potential analyzers (RPAs) are one of the oldest and most versatile approaches to measuring these fundamental characteristics of plasmas in the near-Earth space environment. Data provided by RPAs are therefore an essential part of space environment monitoring and modeling. In addition to providing synoptic data for seeding ionospheric models, RPAs can provide crucial information on ion density distributions relevant to DoD-mandated space situational awareness. The RPA technique is well suited to small satellite missions, where it may be feasible to fly several satellites simultaneously in order to provide data in multiple orbit planes, and thereby characterize ionospheric phenomena in a global context.

In this paper we describe the development of an RPA device for small satellite applications, including but not limited to CubeSats. We provide an overview of RPA operational principles, along with examples of flight data to illustrate typical RPA performance. Selected details of the mechanical and electrical designs of the CubeSat RPA are presented, based on developmental work over the past several years in the Center for Space Sciences at the University of Texas at Dallas (UT Dallas). Mission requirements for telemetry and attitude control are discussed in the context of reliable space-based measurements of several fundamental plasma characteristics. Measurement errors inherent in the RPA technique are also quantified and discussed.

RPA OPERATING PRINCIPLES
Figure 1 shows the basic configuration of an RPA instrument. The instrument faces into the ram, so that ions enter the aperture grid supersonically as the satellite flies through the plasma medium. Inside the instrument a flat current-collecting plate (the collector) is fronted by a series of electrically biased grids; most of these are held at constant potentials, but one grid (or in some cases a grid pair) is swept over a range of positive voltages to selectively reject a portion of the ion distribution. Current to the collector as a function of the voltage on the retarding grid(s) therefore yields a measurement that is representative of the distribution function of the thermal ion population in the medium. These measurements are subsequently used to determine the ion density, temperature, and composition of ions in the plasma. Under properly controlled circumstances the ion velocity along the

Figure 1 – A simplified schematic diagram of an RPA system showing the internal grids and the basic electronic functions.
orbit track and the spacecraft potential can also be determined.

Figure 2 – A typical one-dimensional ion velocity distribution in the spacecraft frame of reference. The red shaded region shows the fraction of the distribution collected for a retarding grid potential of +5 volts.

Figure 2 shows a one-dimensional velocity distribution function for a population of thermal oxygen ions moving at 7500 m/s in the spacecraft frame of reference. This distribution can be considered as a drifting Maxwellian in the spacecraft frame; the thermal velocity is assumed to be isotropic, but in the spacecraft frame the ions are moving toward the satellite at orbital speed. In this reference frame virtually all of the ions will be collected when the voltage on the retarding grid is zero, but as the voltage increases only those ions with sufficient ram energy to overcome the potential barrier are able to pass through the grid stack and be collected. The red portion of the distribution in Figure 2 represents the fraction of the distribution collected for a retarding potential of +5 volts.

From inspection of Figure 2 it should be clear that the number of ions collected decreases as the retarding voltage increases. Plotting the current collected in a plasma as a function of the retarding voltage yields a current-voltage (I-V) characteristic like the one shown in Figure 3. These data were obtained by the RPA aboard the DMSP F-15 satellite during sunlit conditions at a location near the magnetic equator. Because the satellite is at high altitude (near 850 km) it measures a two-species plasma. The portion of the I-V curve at retarding voltages less than ~2 volts is created by H\(^+\) and O\(^+\), while at higher retarding voltages the H\(^+\) energy is insufficient to pass through the retarding grids and only O\(^+\) is collected. The ion density, temperature, composition, and velocity along the orbit track can all be determined by analyzing these IV curves according to principles that have been well documented in the literature.\(^1\,^2\)

Figure 3 - A low latitude IV characteristic from the DMSP F-15 satellite near 850 km. Note the double humped signature caused by the two-species plasma.

ERRORS IN RPA MEASUREMENTS

There are two main sources of error associated with the RPA technique. The first is caused by uncertainties in knowledge of the angle between the spacecraft velocity vector and the normal to the RPA aperture. Precise alignment of the instrument with the spacecraft coordinate system prior to launch mitigates this problem. On-orbit attitude control is required to maintain precise alignment of the aperture normal with the spacecraft velocity vector; pointing knowledge to better than ~100 arc-seconds allows excellent resolution and accuracy for all measured parameters.

A more subtle error arises due to distortion of the ion distribution when the particles flow through the grid stack. Two main problems arise: 1.) the potential in the open areas between grid wires is always less than the applied potential, allowing some particles to leak through the grid despite energies below the applied grid potential; 2.) velocity components in the plane of the grid cause some particles to be collected on the grid wires instead of passing through. Together these effects can produce surprisingly large errors in the densities, velocities, and temperatures inferred from the I-V curves. Quantifying the magnitude of these errors has not been possible in controlled laboratory tests, but has recently been the focus of numerical simulation studies by a number of authors.\(^3\,^4\)

The most recent simulation work on the RPA grid problem provides improved insight into how the
retarding grid design affects the accuracy of ion temperatures and densities inferred from RPAs. Using a commercial ion optics software package a flat, woven, and double thick flat grid are constructed in an RPA model assuming a single retarding grid. The flat grid is comprised of wires of square cross section, while the double-thick grids are twice as thick in the direction perpendicular to the aperture plane. In practice flat and double thick grids are created by electroforming, while woven grids are constructed from a commercially available window-screen wire mesh. In the simulations the potential distribution between the grid wires for each of these geometries is computed, and representative families of particles are allowed to traverse the resulting three-dimensional potential field. This method allows for the formation of simulated I-V curves and identification of errors introduced by specific grid geometries for a given set of inputs. N₂ ions are used in this study with velocities from 7 km/s to 8 km/s and temperatures from 300-1250 K. This range of inputs allows for future laboratory validation under controlled conditions, and the results can be extrapolated to spaceflight conditions.

Second order polynomial fits are shown for the simulation data presented in Figures 4 and 5. In Figure 4 all the errors are negative because the use of any real grid screens out more particles than is accounted for by ideal theory. The woven and flat grids show errors below the effective noise level for most RPA instruments over the entire range of temperatures studied. The double-thick flat grid causes errors in density roughly twice as large as the other two geometries. At the highest temperatures tested this grid geometry leads to density errors over 3%.

![Figure 4 - Simulation results showing simulated errors in density for three different grid geometries, along with second order polynomial fits.](image1.png)

![Figure 5 - Simulation results showing inferred temperature errors for three different grid geometries, along with second order polynomial fits.](image2.png)

Figures 4 and 5 show how the errors in the ion density and temperature inferred from the simulated I-V curves vary as a function of plasma temperature for all three grid geometries. An orbital velocity of 7500 m/s is assumed in this analysis for all cases. The simulations show that grid depth (thickness in the ram direction) has a major impact on the performance of an RPA. The single thick grid and woven grid, which have similar average thickness, display small temperature and density errors for the range of inputs simulated when compared to the double thick grid. With less transverse area these geometries minimize impacts on the sides of the grid wires, which is a major contributing factor to temperature and density errors. Although not shown here, the double thick grid provides the best accuracy for velocity measurements because the increased depth decreases the magnitude of the potential depletion between grid wires, and thus acts as a more accurate energy screen. Similarly, other simulation studies have shown that a single retarding grid geometry leads to better temperature measurements, while a double retarding grid enables more accurate velocity estimates.4

The results of these simulations show that grid geometry can play a major role in the accuracy of RPA measurements. We currently have CubeSat RPA designs for both the legacy woven-grid model with a
double retarding grid, and a new student-design that uses electroformed flat grids with a single retarding grid. The former is a scaled-down version of the instrument flying on the C/NOFS satellite, while the latter is an easy to assemble modular design. The simulations show that no one geometry is best in all cases, so when considering RPA grid design it is beneficial to account for the range of parameters the instrument is expected to encounter, as well as which inferred parameters need to be measured with the greatest accuracy. With the aid of simulation studies, future RPA experiments can be designed with grid geometries that most accurately measure the parameters deemed most important for the particular mission.

CUBESAT RPA DESIGN

Mechanical Design and Specifications

Figure 6 shows a photograph illustrating one possible mounting configuration for the UT Dallas CubeSat RPA. The electronics comprise two circuit boards that mount directly behind the RPA in a sheet metal box; one of these boards is shown in the figure. The four large screws visible near the corners of the instrument extend into the device to secure internal structures. The other screws cover access points that are used to test grid connections and to stimulate the collector for end-to-end tests. All of the screw heads are flush with the surface to create a flat, uniform potential surface.

Figure 6 - Photograph of the UT Dallas CubeSat-ready RPA with its protective aperture cover and analog electronics board

Figure 7 shows an exploded view of the RPA to reveal its internal structure. The design shown in the figure was created by students at UT Dallas during a one-semester class in satellite systems engineering. The students were advised to make the system modular and easy to assemble, and to randomize the alignment of the grids so that all optical paths through the grid stack are identical.

Figure 7 - Exploded view of the student-designed RPA, revealing some details of the easy to assemble modular structure.

The small size of the resulting RPA device allows it to be accommodated easily in a variety of spacecraft designs, leaving ample room for other satellite subsystems such as attitude control, solar panels, batteries, power regulation and telemetry circuits, and other instruments or electronics. The overall mechanical design specifications for the RPA system are summarized in Table 1.

Table 1: Mechanical Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Size</th>
<th>Mass</th>
</tr>
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<tbody>
<tr>
<td>RPA Sensor</td>
<td>9.6 x 9.6 x 6.3 cm</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>Electronic boards and connectors</td>
<td>9 x 9 cm</td>
<td>0.05 kg</td>
</tr>
</tbody>
</table>

Electrical Design and Specifications

UT Dallas has provided RPA instruments for a large number of ionospheric missions, including AE, DE, DMSP, ROCSAT-1, and C/NOFS. In these missions minimization of sensor size, weight and power (SWaP) at the expense of production simplicity, test or instrument functionality was not a main driver of the design. Because of this the Center has maintained a tradition of fully hand-built electronics using thru-hole mounted components to facilitate circuit board inspection, modification, testing and repair. As new flight opportunities have appeared that require SWaP minimization we have adopted some newer, more modern approaches to electronics design and assembly techniques. These practices are carefully balanced to achieve SWaP reduction without sacrificing reliability and versatility. Using these techniques the CubeSat RPA design described here achieves a 63% reduction in
PCB area relative to the RPA instrument currently flying on the Communication/Navigation Outage Forecast System (C/NOFS) satellite, while reducing power consumption by 75%.

The Center for Space Sciences produces a few ion sensors that have commonalities in their basic current-sensing electronics. Because of the commonalities of the sensor requirements for multiple sensors, the electronics design approach for the Cubesat RPA electronics also takes into account the variety of sensor applications. The resulting design is geared toward a flexible system architecture that can be simply modified to support other requirements.

The Cubesat RPA contains two square printed circuit boards (PCBs) connected with a single stackable internal connector, as shown in Figure 8. The circuits are partitioned into sensor specific analog circuits for the first board, with power, digital, and interface circuits on the second board. The PCBs mount behind the RPA baseplate, with board-mounted terminals that wire to the sensor elements from both PCBs. A single micro D-sub miniature connector serves as the interface to the spacecraft. A variety of electrical interfaces are possible, but at a minimum they include a single +5 V power input and some type of digital communication interface. The preferred digital interface includes a dedicated synchronization pulse input line and either a full-duplex custom digital interface or a standardized bus interface such as I2C.

![Image](image.png)

**Figure 8 – CubeSat RPA electronic boards with key functional areas identified.**

Power reduction is achieved by reducing power rails for most analog circuits, and using low power components throughout the design. An FPGA (3.3 V I/O, 1.5 V core) provides low power memory and allows reduction of analog circuitry by incorporating some analog functions. Board space is reduced by using multi-layer boards with surface mount components and compact connectors.

The RPA System analog circuits require both bipolar power for analog circuits and a +20 V Retarding Voltage generator supply. These are generated using a low power push-pull converter driven by the FPGA. The duty cycle and frequency are adjustable for maximum efficiency. The power supply generates ±7 V (nominal) with a tripled output of +21 V for the retarding voltage generator. Power for precision analog circuits is generated from three terminal DC regulators to reduce noise. To minimize total power digital circuits are powered directly from input +5 V supply. The total power estimate of 0.45 W is derived from a mixture of prototype PCB and breadboard tests.

**Telemetry Specifications**

Each IV sweep of the RPA yields twenty-four 16-bit samples plus one 16-bit status word. A typical operating mode might require downlinking one sweep every 4 seconds, providing ~30 km spatial resolution in low Earth orbit. If sufficient power and downlink capability are available the RPA can perform one such sweep per second to provide horizontal spatial resolution of ~8 km. This resolution is about an order of magnitude better than current global ionospheric models, allowing the models to ingest the data after averaging, while providing sufficiently high resolution to study small-scale irregularities that may be associated with radio scintillation at high frequencies. The maximum data rate is therefore 400 bits/second, or 2.16 megabits/orbit at a 100% duty cycle. The data rate for the lower resolution mode is 100 bits/second, or 504 kbits/orbit.

RPA sensors typically do not require complex computational or control functions, although uplink programmable retarding voltage steps are useful for post-launch versatility. For example, for sampling a plasma that is predominantly O⁺ it is useful to have the retarding voltages distributed non-uniformly over the sweep range, with the preponderance of samples taken between 4 and 6 volts where the current changes rapidly. If spacecraft charging changes the value of the ground potential it is useful to be able to uplink modified retarding voltage steps to mitigate the effects of charging on the I-V curve. Similarly, in a combined H⁺ and O⁺ plasma it is most useful to have a higher density of current samples in the 0-2 and 4-6 volts ranges, if charging is negligible or controlled. Based on the spacecraft configuration it is rarely possible to know the optimal distribution of samples before launch, so we prefer to be able to uplink specific sweep voltage settings depending on data received during the normal instrument check-out period.
TESTING

Full-system protoboards are currently under test to confirm breadboard results related to power consumption, analog performance, and system noise levels. Thermal tests over standard military temperature ranges have been performed to verify that the grids and other mechanical structures within the instrument are not warped or otherwise damaged by repeated temperature cycling. End-to-end functional testing in a space simulation vacuum system is scheduled for the summer of 2010. These tests will use a new LabView-controlled ion source to verify the results shown in Figures 4 and 5 for different grid geometries, and to demonstrate the sensitivity of the new RPA design.

REQUIREMENTS

As previously mentioned, a ram-pointing configuration is required for the RPA to function properly. This requires the satellite to have precise attitude control capabilities in either a 3-axis stabilized or spinning configuration. In the latter case the spin axis must be aligned with the velocity vector to yield valid RPA measurements. Table 2 lists the pointing and telemetry requirements for a successful RPA mission.

Table 2: Pointing and Telemetry Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>Pointing Accuracy (degrees)</td>
<td>±1 for temperature and density measurements</td>
</tr>
<tr>
<td>Pointing Knowledge (degrees)</td>
<td>±0.05 for velocity measurements</td>
</tr>
<tr>
<td>Spatial Resolution (km)</td>
<td>8-30 depending on bit rate</td>
</tr>
<tr>
<td>Required Downlink Bit Rate (bps)</td>
<td>100-400</td>
</tr>
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</table>

CONCLUSIONS

We have described the operation, requirements, limitations, and technical specifications for a new small-satellite RPA system. The instrument retains much of the design heritage of its predecessors, which have flown successfully on a number of important ionospheric missions. Typical flight data from one such experiment have been shown, and the magnitude and sources of the errors inherent in the technique have been identified and quantified.

If deployed simultaneously on multiple small satellite missions the new RPA system could economically resolve the spatial and temporal ambiguities that plague larger single-spacecraft missions. Alternatively, the low cost of CubeSats should allow them to be deployed for low-altitude, short-duration missions to study the dynamics of the lower F region in ways that larger, more expensive missions cannot. RPA measurements from such missions are poised to provide important contributions during this coming revolution in space science.

Acknowledgments

The authors acknowledge helpful inputs from W. R. Coley concerning flight RPA data from the DMSP instrument.

References