THE RETARDING ION MASS SPECTROMETER ON DYNAMICS EXPLORER-A

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(Received 11 May, 1981)

Abstract. The thermal component of the magnetospheric plasma plays a key role in magnetosphere-ionosphere coupling processes acting as a strong influence on ionospheric structure at low altitudes and as a source and modifier of the hotter plasma population at high altitudes. The Retarding Ion Mass Spectrometer (RIMS) instrument on Dynamics Explorer-A is designed to measure this important thermal plasma component. Using a combination of retarding potential analysis and magnetic ion mass spectrometer techniques, the RIMS instrument will measure the bulk plasma parameters of ion density (0.1 to 10^6 ions/cm^3), temperature (0–45 eV), and bulk flow (>0.5 km s^{-1}) in the inner plasmasphere and ionosphere and the specific ion pitch angle and energy spectral characteristics in the outer plasmasphere and plasma trough for a mass range of 1–32 amu. The energy and mass spectral step sequences as well as the multiplexing of the resultant data can be tailored to accomplish a variety of thermal ion measurements throughout the inner magnetosphere.

1. Introduction

Since its original discovery through the measurement of lightning-induced whistler signals [1], the low-energy thermal component of the magnetospheric plasma has been found to play an increasingly important role in the coupling of the magnetosphere, ionosphere, and atmosphere. During this same period of study, the complexity of the distributions of thermal plasma has become more evident, and the role of this plasma not only as a modifier but also as a source of the more energetic magnetospheric plasmas has been realized.

Based on the assumption that the ionosphere must be the source of this low-energy plasma component, early instrumentation for the measurement of magnetospheric thermal plasma was patterned after ionospheric instrumentation. Thus, both retarding potential analyzers and ion mass spectrometers were designed for magnetospheric application [2, 3, 4]. The operation and interpretation of data from these instruments were dependent on the ramming or scooping effect of the instrument through a cold, well-behaved Maxwellian distribution of the plasma, such as exists in the Earth's ionosphere. This approach met with some success [3, 5, 6], but at high altitudes the higher plasma temperatures and flow velocities combined with the slower spacecraft velocities and higher relative densities of energetic particles introduced uncertainties into

Space Science Instrumentation **5** (1981) 477–491. 0377–7936/81/0054–0477 $02.25.

the acquisition and interpretation of the ,thermal plasma data. It was realized, for example, that the simple measurement of density was dependent on the simultaneous measurement of the plasma temperature and flow velocity, as well as information on the spacecraft potential and its effects on the ambient plasma distribution.

This realization led to the design and development of the multi-headed Retarding Ion Mass Spectrometer (RIMS) for Dynamics Explorer-A that combines the ion temperature-determining capability of the retarding potential analyzer with the compositional capabilities of the mass spectrometer and adds multiple sensor heads to sample all directions relative to the spacecraft ram direction. The multiple heads permit the determination of the thermal plasma flow characteristics. This instrument combination is also effective in eliminating the confusing effects caused by energetic particles impinging on the open collector of the retarding potential analyzer, since in this new instrument the detector element is well protected behind the baffled magnetic mass spectrometer.

In recent years several new characteristics of the thermal plasma distribution have emerged. First, it was discovered that in the outer plasmasphere and magnetosphere, the 'cold' plasma was much hotter than expected, reaching temperatures of one hundred thousand degrees Kelvin or higher [7, 8, 9]. This temperature is quite different from the few thousand degrees expected from an ionospheric source. Second, the thermal plasma has been found to exhibit a multitude of pitch angle distributions [10, 11, 12] including field-aligned, conical (peaked at 20–40° pitch angles) and trapped (peaked at 90° with respect to the magnetic field). Third, new compositional elements have been discovered [13, 14, 10]. These new ions, such as O^{++} and He^{++}, have broadened the view and complexity of the processes which populate the magnetosphere with low energy plasma and have added ion species to the list of those which should be routinely surveyed on the Dynamics Explorer mission.

In each observed case the ion pitch angle distributions seem to have a mass and energy dependence and the observer is led toward the idea of detailed plasma information more penetrating than can be adequately displayed by the simple bulk parameters of density, temperature,and bulk flow. In the ionosphere and inner plasmasphere, the RIMS data will be adequately interpreted using bulk parameters, but at higher altitudes the displays of flux versus energy, angle, and mass which are more characteristic of energetic plasma measurements will be required.

The RIMS instrument is designed to measure the details of the thermal plasma distribution. The multiple sensor heads containing retarding potential energy analysis and magnetic spectrometer mass analysis will permit the determination of bulk plasma parameters in the inner magnetosphere where such a characterization is appropriate. This will allow the exploration of the interchange of ions between the ionosphere and plasmasphere and determine, for example, the relationship between the plasmapause and the ionospheric light ion trough. The multiple heads will reveal the bulk flow vector of the plasma thereby contributing to our knowledge of the convective motion of the magnetospheric plasma and the filling processes through which the ionosphere acts as a source of plasma for the magnetosphere.

In the outer plasmasphere and plasma trough other RIMS features will be utilized.

The narrower angular acceptance of the radial head (±10 by ±55°) will permit the sampling of ion pitch angle distributions which when combined with the energy analysis capability permit the examination of ion energization processes. The programmable mass stepping of the spectrometer allows the surveying of different ion masses and energies to assess the ionosphere as a source of low-energy magnetospheric plasma. The above discussion represents a sampling of the science objectives which will be studied by the RIMS instrument that is described below. The specific geophysical parameters to be measured by the RIMS instrument are shown in Table I.

TABLE I

Parameters measured by the RIMS instrument

	Range	Accuracy	Resolution
Principal apogee mode[a] *(> 1500 km):*			
Density H^+, He^+, O^+, He^{++}, O^{++}	$0.1 \rightarrow 10^6$ ions/cm^3	±10%	Nominally 1/2 s (1/64 s maximum) complete – 1 s/c spin (6 s)
Temperature H^+, He^{++}, O^+, He^{++}, O^{++}	$0 \rightarrow 45$ eV	±5%	1/2 s complete – 6 s
Bulk flow H^+, He^+, O^+, He^{++}, O^{++}	0.5 km s^{-1} and up	highly temperature dependent	6 s
Spacecraft potential	few V positive → 45 V negative	0.1 V	6 s
Principal perigee mode[a] *(< 1500 km):*			
Ion composition	1–32 amu $0.1 \rightarrow 10^6$ ions/cm^3	10 pts/mass peak	6 s

[a] These modes of operation are commandable. Either mode can be operated throughout the orbit.

2. Instrument Description

2.1. Heritage

The direct motivation for the RIMS instrument came from the Light Ion Mass Spectrometer (LIMS) that was flown on the OGO-5 satellite [4]. This instrument showed the value of the magnetic ion mass spectrometer technique in the measurement of magnetospheric low-energy plasma at high altitudes. The actual design of the RIMS spectrometer is based on the Magnetic Ion Mass Spectrometer (MIMS) which was flown on the ISIS and Atmosphere Explorer satellites [15]. The successful operation of this instrument served as strong proof of the reliability and desirability of this type of spectrometer.

The retarding potential analyzer section of the RIMS instrument was based on an earlier design that had been flown extensively during the OGO and Atmosphere Explorer series of satellites [16, 17]. Early engineering studies showed that these two techniques could be successfully mated. This combined approach was verified through flight on the

AF/NASA SCATHA satellite which returned data on ion composition, pitch angle, and energy characteristics [18].

The RIMS instrument for Dynamics Explorer has expanded on the capability of the predecessor SCATHA instrument through the use of a programmable memory which permits an in-flight choice of the mass, energy, and angle sampling scheme that is employed for each science problem.

2.2. Sensor Design

The RIMS instrument consists of a central electronics assembly and three separate sensor heads, one mounted viewing perpendicular to the spin axis and one each mounted with fields of view parallel and anti-parallel to the spacecraft spin axis. The sensors are controlled by the central electronics assembly, and all data are channeled through the central electronics into the spacecraft telemetry stream. Each sensor head consists of a retarding potential analyzer followed by a magnetic mass analyzer with two separate exit slits corresponding to two mass ranges in the ratio 1 : 4. The total mass range covered is 1 to 32 amu. Figure 1 contains a cutaway view of one of the three sensor heads showing the entrance aperture, which is mounted flush with a ground plane on the outer surface of the spacecraft, the RPA grids, and ion collector plate, followed by the mass analyzer.

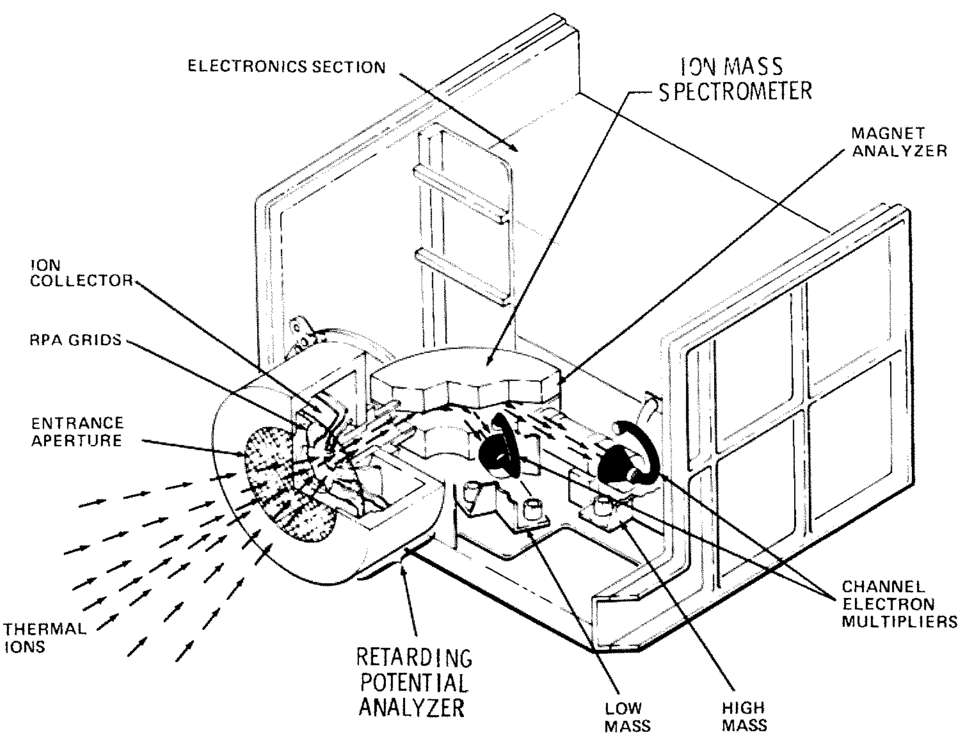

Fig. 1. A cut-away view of a RIMS sensor head showing the path of thermal ions through the analyzer. The arrows show the ions' entry through the retarding potential analyzer and ion mass spectrometer sections with detection by the channel electron multipliers.

The latter consists of an entrance (collimating) slit set, magnetic analyzer, collector slits and the high current channel electron multiplier detectors. The three sensor heads are identical except that the $\pm 55°$ conical field of view (FOV) of the $\pm Z$ sensors has been adjusted on the radial sensor to a rectangular angular acceptance of ± 10 and $\pm 55°$ in the planes perpendicular to and containing the spin axis, respectively (see Figure 2).

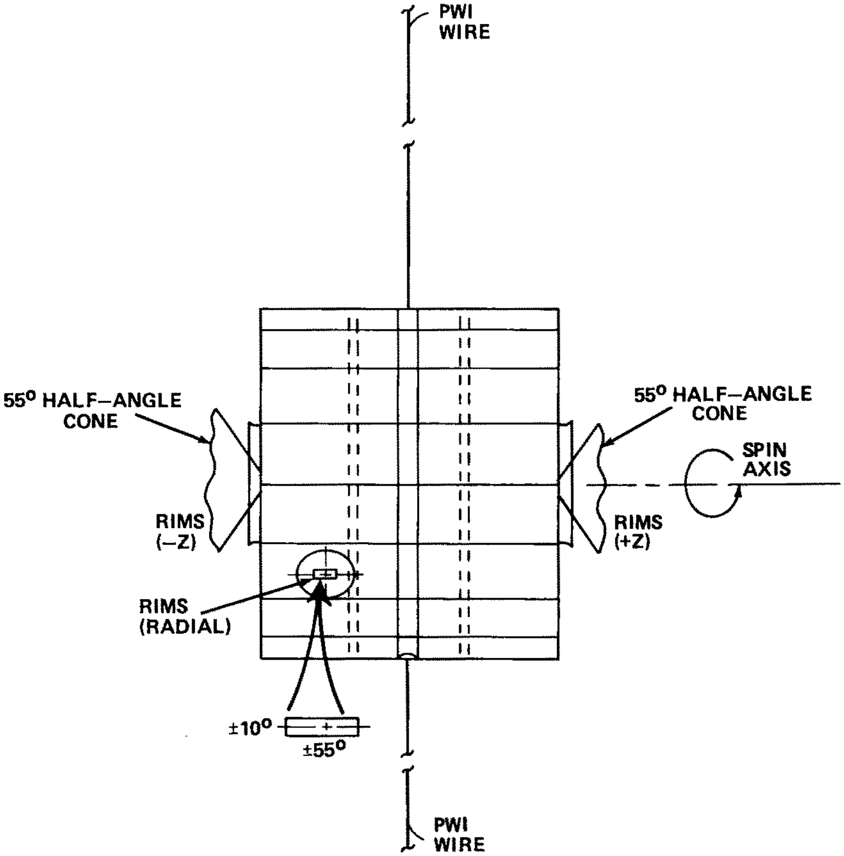

Fig. 2. A sketch of the Dynamics Explorer-A spacecraft showing the locations of the RIMS radial and $\pm Z$ sensor heads along with the angular field of view of each sensor.

As shown in Figure 1, ambient ions enter through the front aperture into the retarding potential analyzer section. The front aperture potential may be selected by command to any of four values as a bias for a non-zero spacecraft potential. Ions having sufficient energy to pass the retarding grid may either be collected on the ion collector plate or pass into the mass analyzer. As a practical rule, the ion collector currents will only be significant around perigee in the topside ionosphere where the electron multipliers will be shut off for protection from high counting rates. The RPA retarding grid voltage is programmable over a 0 to 51.2 V range, referenced to the aperture potential. Any 32 of 1024 voltage steps may be selected in increments of 50 mV.

The ions passing into the mass analyzer are accelerated and then sorted according to their atomic mass per unit charge. The proper combination of ion accelerating voltage and magnetic field strength produces an ion beam radius in the magnetic field which focuses a particular mass on each exit slit. Varying the ion accelerating voltage varies the ion mass detected. Ions of mass 1 to 8 amu and 4 to 32 amu can be focused on the low and high mass slits, respectively. Ions exiting the slits are counted with the channel electron multiplier detectors. The ion mass range is also programmable by a minor mode command. Any 32 of 4096 voltage steps may be selected in increments of 0.5 V. All 32 may be the same, in which case the mass analyzer will be locked onto a given set of mass peaks having the ratio 1 : 4.

Each of the sensor assemblies contains the necessary complement of electronics to operate the RPA sensor and the IMS sensor sections under the control of the central electronics assembly. The sensor head circuits are shown schematically in Figure 3 and include the following functions: an RPA logarithmic amplifier which generates a logarith-

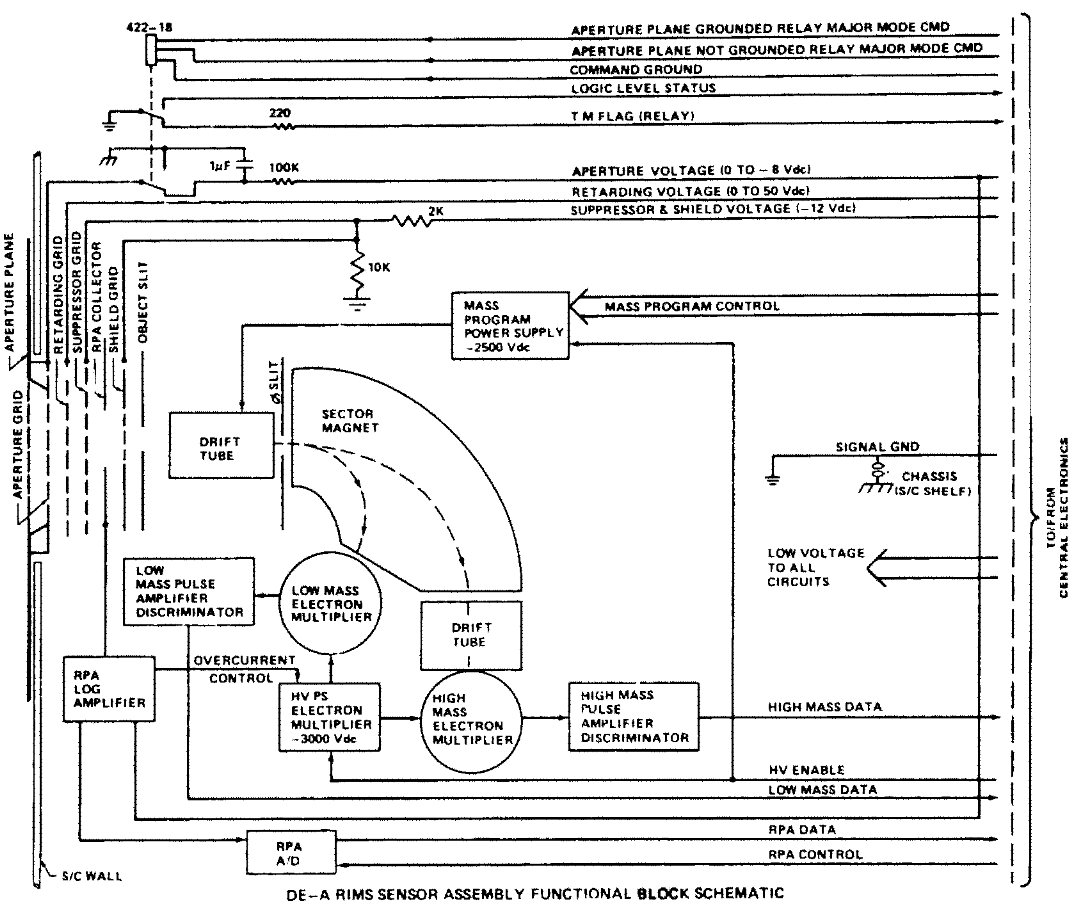

Fig. 3. A schematic block diagram of the RIMS sensor head electronics showing the control of the ion analyzer and interfaces to the Central Electronics Assembly.

mic output voltage in the range 0 to 10 V for an input ion current to the collector in the range 10^{-11} to 10^{-6} A, a mass sweep high voltage power supply which accelerates the ions prior to their entry into the magnet by generating a programmable voltage in the range -250 to -2250 VDC, a multiplier high voltage power supply which powers both electron multipliers and is capable of producing four selectable high voltage outputs, and a pulse amplifier/counter which discriminates and counts the voltage pulses which have been converted from the charge pulses of the channel electron multiplier output. The basic instrument cycle is 32 mass and energy steps over a period of 0.5 s with a basic data accumulation period of 12 milliseconds. More details of the instrument operations are given below.

2.3. Central electronics function

The three sensor assemblies are controlled by a Central Electronics Assembly (CEA). The particular RPA retarding sequence and mass stepping sequence are loaded into the central electronics assembly by minor mode ground commands. The sensor heads are then stepped through this sequence under the control of the central electronics. All sensor heads execute the same stepping sequences. The data from the three sensors are then routed through the central electronics assembly where they are multiplexed and fed into the spacecraft telemetry stream. The selection of data channels and the timing of data channel switching are controlled by the central electronics based on a minor mode ground command. This ability to control the energy step, mass steps, and data multiplexing assure maximum flexibility in instrument operation during the mission.

A functional block diagram for the assembly is given in Figure 4. This figure shows the interface signals with the DE-A spacecraft. The data outputs are synchronized to the telemetry minor frame rate. A short description of each circuit function is given below.

2.3.1. *Instrument Memory*

The instrument memory control assembly will do all read/write operations and monitor health of the memory. All minor mode 'B' commands will be received by this assembly which keeps the master sequencer updated as to its status and health. This assembly also generates the fixed scan address for the RPA sensor.

2.3.2. *Floating Point Converters/Counters*

There are six accumulators and holder registers associated with the six IMS channels. The data from each accumulator are multiplexed into the data compressor for compression into a 10-bit, base 2 floating point number (6-bit mantissa and 4-bit exponent) for outputting into the telemetry buffers. This assembly also contains the major mode command circuits and status bits.

2.3.3. *Housekeeping Multiplexer and Telemetry Buffers*

Sixteen instrument health and monitor outputs are received by this assembly and multiplexed into a single A/D converter for conversion to an 8-bit telemetry word.

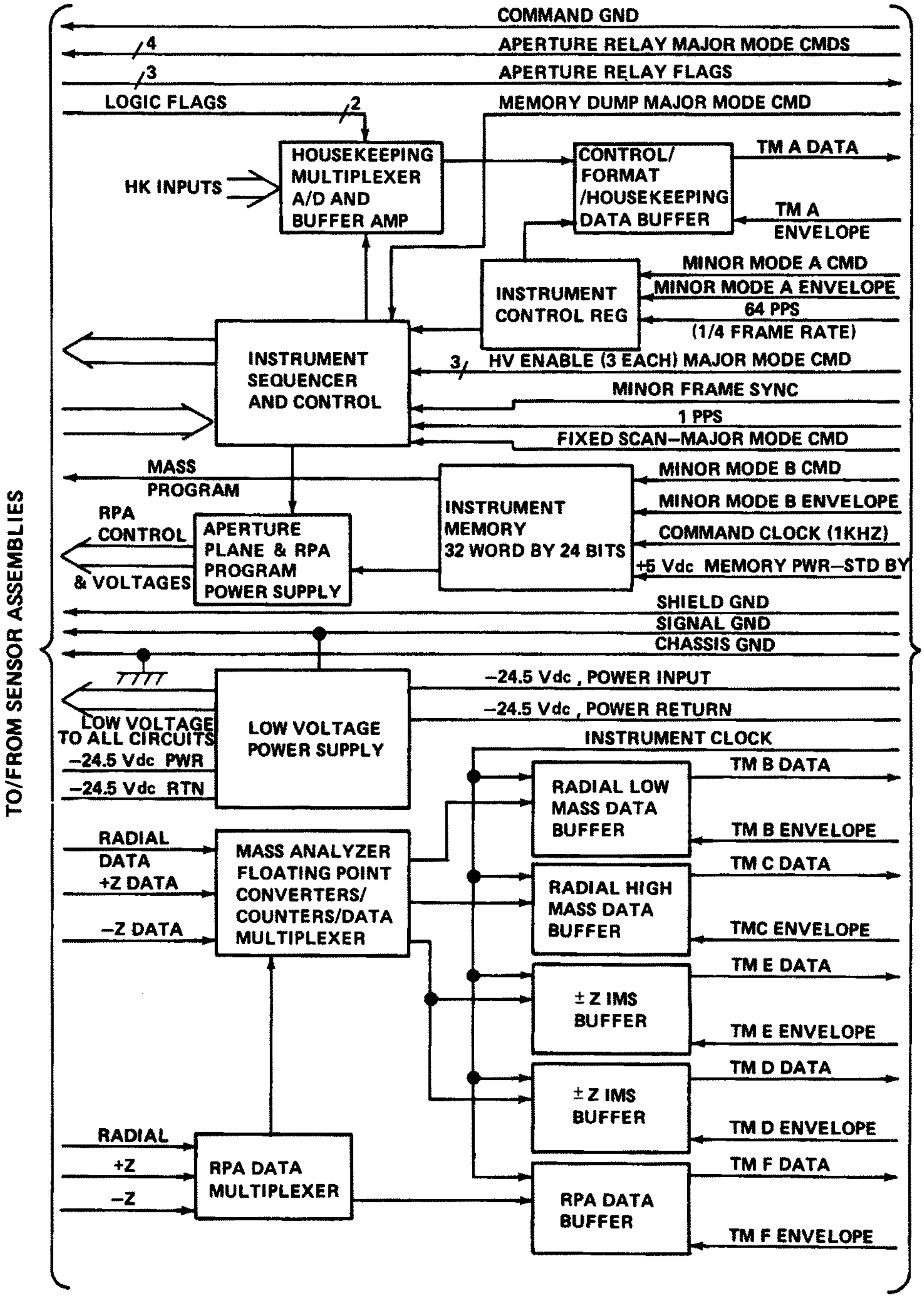

Fig. 4. A schematic block diagram of the RIMS Central Electronics Assembly showing the control elemen which drive the three sensor heads and the interface to the DE-A spacecraft.

2.3.4. *Instrument Control Register*

This assembly receives the minor mode 'A' command and stores it in the Instrument Control Register. This register contains all information needed to reconfigure the instrument and to select various combinations of data outputs to be loaded into the telemetry buffers.

2.3.5. *Instrument Sequencer and Control*

The instrument sequencer is the controller for the RIMS instrument. It sequentially determines when all circuits are to perform their various duties and keeps a status check on all commands and timing required to maintain instrument health and operation. All data collection and processing by the RIMS instrument are under the control of this assembly.

2.3.6. *Aperture Plane and Retarding Potential Power Supplies*

A two-bit input signal is used to command the aperture plane supply to one of four output voltages: 0, −2, −4, or −8 V. The output voltages are compared to a reference through selectable resistors to produce the four voltages. A high current output stage is used to provide a low impedance output, since other circuits are referenced to this supply output.

The output range of the retarding potential power supply is 0 to 51.2 V and is referenced to the aperture grid potential. Input control is a ten-bit word from the instrument memory. The output can be selected by command for either 50 millivolt steps from memory or 75 millivolt steps in the default mode.

2.3.7. *Low Voltage Power Supply*

The low voltage power supply provides the interface between the instrument circuits and the spacecraft primary power. The spacecraft primary power (−24.5 VDC, ±2%) is received by a filter and current limit circuit. A dc-to-dc converter operating at 20 kHz is used to generate the various voltages needed by the instrument electronics.

2.4. RIMS Operations

The RIMS operating sequence is controlled by an internal memory in the Central Electronics Assembly which is programmable by ground command. This feature is mandated by the versatility of the instrument and the intrinsic variability of the plasma it is designed to analyze. The memory itself is divided into two independent sections; one which controls the RPA grid voltages and one which controls the ion mass spectrometer settings. Each section contains thirty-two commands which are cycled sequentially in one-half second. This arrangement allows any combination of thirty-two mass and energy steps to be executed each thirty degrees of spacecraft spin.

In addition to the standard memory operation a selectable option has been included which can periodically override the contents of the mass spectrometer section of the memory and set the mass spectrometer to hydrogen and helium. This override occurs for eight seconds, each sixteen seconds, and effectively doubles the control capability on the mass spectrometer by freeing the memory to be utilized for a search of minor constituents with a periodic return to the major constituents occurring automatically. This feature of toggling every eight seconds between major and minor constituent settings can be utilized upon command from the ground. All three heads are under common CEA control.

With three measurements available from each of the three heads (2 mass spectrometer channels and the ion collector), together with the sixty-four samples per second rate, the instrument is capable of producing a substantial number of measurements per unit time. To ease the burden on the spacecraft telemetry system, a multiplexing scheme has been incorporated which selects only two of the six measurements from the $\pm Z$ heads for transmission at any one time. Both the rate of the switching between $\pm Z$ head measurements and selection of specific data channel pairs are programmable. The two mass spectrometer data channels from the radial head are sampled continuously with the radial ion collector data available on command.

With this versatility of instrument operation, it is quite evident that the instrument can be configured to conduct measurements for a broad range of scientific problems with the data acquisition optimized to the specific needs of each problem. In a general sense the observer has a set of choices ranging from the extremes of high mass resolution or high energy/pitch angle resolution to survey modes which sample many masses and energies averaging over time and angle.

For preflight planning purposes, it is assumed that the measurement sequences which will be employed during the flight will be divided into three broad and mutually exclusive categories. These are: (1) a limited resolution-combined mass/energy survey which samples only the most probable mass species (for example, H^+, He^{++}, He^+, O^{++}, and O^+) using a minimum number of energy steps; (2) a comprehensive mass analysis of the ambient plasma in the range of 1 to 32 amu with no energy analysis, and (3) a high resolution energy/pitch angle analysis of a selected pair of ionic species.

It is anticipated that the first and second of these modes will be employed on a fairly regular basis in the earliest phases of the mission to obtain a general survey of the plasma. The third mode will be reserved for special studies such as those which might require particularly accurate density determinations or high time resolution information on ion pitch angle and energy spectral distributions. The RIMS operational flexibility will clearly permit the possibility of learning during early survey modes of the mission and modifying the instrument operation to optimize the observational approach for subsequent scientific measurements.

2.5. Calibration Approach and Results

The RIMS instrument was calibrated in the low-energy plasma calibration facility at the Marshall Space Flight Center. This specially-designed facility utilizes a large cylindrical vacuum chamber (1 m diam by 2-m length) which employs hydrocarbon-free pumping with sorbtion and ion pumps. The low-energy ion source is an ion gun designed at MSFC based on the principles utilized in the Kaufmann ion engine [19]. The neutral gases which

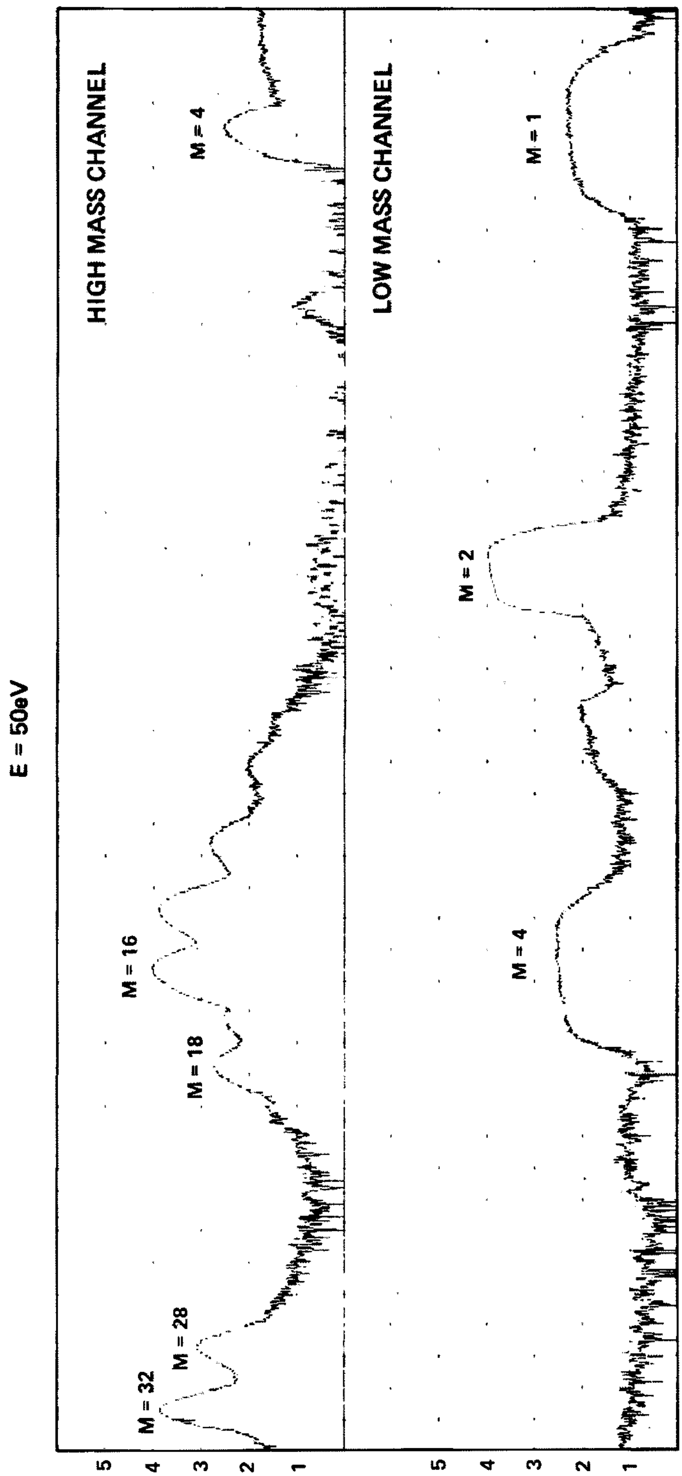

Fig. 5. A complete mass spectrum measured in the MSFC calibration facility showing a sweep of the low mass (1–4 amu) and high mass (4–32 amu) channels.

are bled into the source are controllable to permit the measurement of different composition ratios. The ion beam energies can be varied from a few eV to hundreds of eV. The beam diameter is approximately 6 cm for beam energies of tens of eV. Typical beam currents range from 5×10^{-12} to 1×10^{-10} A. The beam current is measured by a small faraday cup which can be moved into the beam on a swing arm. The RIMS instrument is mounted in the beam on an angular motion device which permits the two-dimensional measurement of instrument angular response.

The RIMS calibration activities were conducted in three increments: initial calibration in the MSFC facility, a comparative calibration in the University of Bern plasma facility [20], and a final calibration using the flight multipliers in the MSFC facility. These three tests had the goal of determining the instrument mass resolution, the angular response, and the absolute sensitivity.

Figure 5 shows a typical mass spectrum taken in the MSFC chamber during the bleeding of multiple gases into the ion source. Note the excellent mass resolution

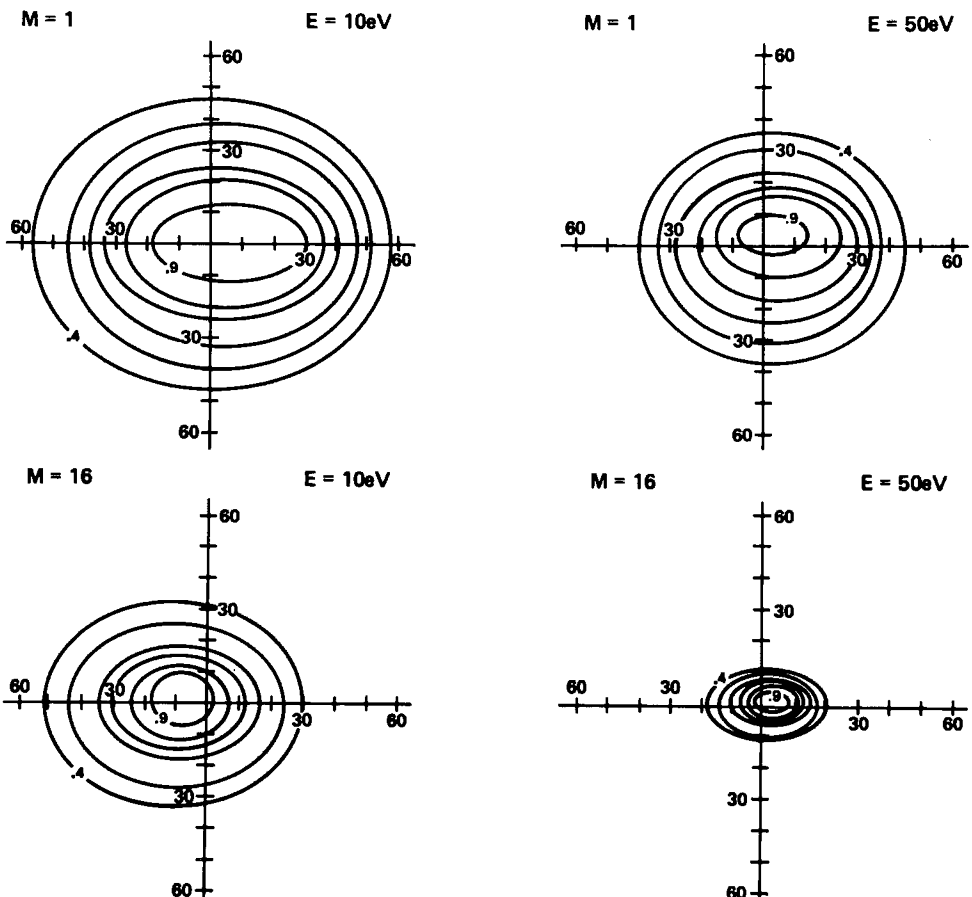

Fig. 6. Examples of the angular response of the + Z RIMS sensor head showing contours fitted to measured responses along the X and Y axes of the sensors. The angular response for different ion beam energies and masses is shown in the four panels.

throughout the mass range of 1–32 amu. The mass peaks are clearly separated and defined with a possible inflight sample density of greater than 10 points/mass peak at the high masses to hundreds of points/mass peak at the low masses.

Figure 6 shows a typical angular response of the + Z sensor head for two energies and two masses. The angular response is determined by the physical collimation of the apertures for low energies and low masses. As the beam energy and mass number increase, the angular acceptance becomes increasingly affected by the angular acceptance of the magnet assembly. This results in a narrowing of the angular acceptance for higher energies and masses. The radial sensor angular response is sharply rectangular because of the narrowed aperture collimation of ± 10 by $\pm 55°$ (not shown here).

The RIMS absolute sensitivity was determined by comparisons of counting rates from the channel electron multipliers in the mass spectrometer section with a simple measure of ion beam current from a faraday cup that is moved into the beam at the sensor head entrance aperture. The knowledge of the beam current and composition combined with the spectrometer multiplier response determines the instrument transmission factors and establishes the instrument absolute sensitivity. The sensitivity determination was done both in a multi-component beam at MSFC and in a single component, mass-analyzed beam in the University of Bern facility. Calibration activities in the University of Bern facility also gave an intercomparison with the Energetic Ion Composition Spectrometer [21] on DE-A which was calibrated in this facility.

These calibration results on mass and angular resolution and absolute sensitivity will be incorporated in the data reduction software which will convert count rates to equivalent ion fluxes as functions of energy and angle.

2.6. Data reduction and anticipated results

As was mentioned in the introductory sections, the thermal plasma characteristics can be quite variable in the different magnetospheric locations sampled by the DE-A spacecraft. The frequent non-Maxwellian character of the plasma prohibits the routine reduction to bulk parameters and leads to data displays which are more characteristic of energetic particle measurements such as energy-time and pitch angle-time spectrograms. In the inner plasmasphere and ionosphere where Maxwellian characteristics are more common, simple algorithm and curve-fitting routines will be employed to derive the bulk parameters of ion density, temperature, and bulk-flow. However, RIMS operations around apogee will be characterized by pitch angle and energy spectral distributions.

Figure 7 illustrates RIMS operational modes which can be used to study specific thermal plasma phenomena. At low altitudes ion composition would be measured using both the RPA and mass spectrometer capabilities. In this region mass spectra versus time, latitude, and local time are shown. As the spacecraft moves over the pole, pitch angle measurements of different ion species are measured to search for polar wind effects. In this region a pitch angle-time spectrogram is utilized for data display. Moving towards apogee the spacecraft can examine the plasmasphere filling and energization processes. Here, both pitch angle-time and energy-time spectrograms are employed. DE-A then

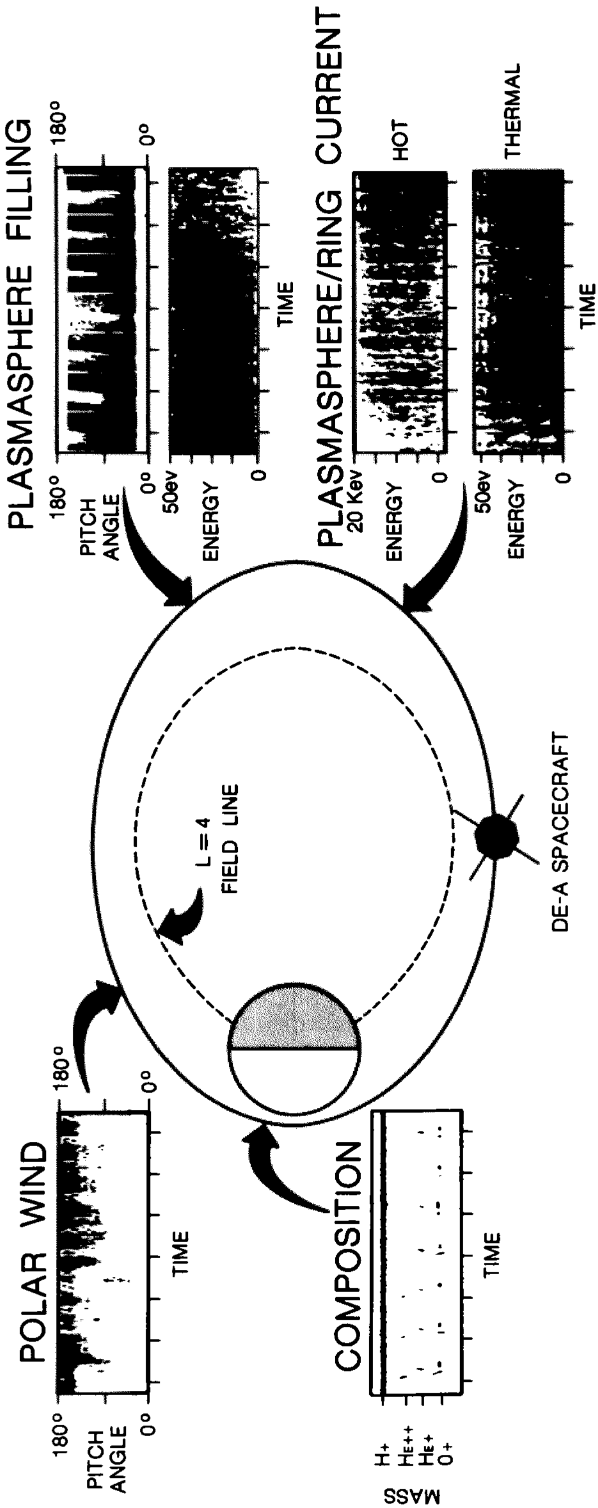

Fig. 7. A variety of RIMS operating modes which address different science problems of interest in thermal plasma studies.

moves through apogee to higher latitudes where the interface between the thermal plasma of the plasmasphere and the hot plasma of the ring current can be studied simultaneously. The effects of the low-energy ions on the hot ring current ions are traced using simultaneous energy-time spectrograms for hot and cold plasma as a function of time, L-shell and local time. The Retarding Ion Mass Spectrometer is a flexible and unique instrument which will furnish extensive new knowledge on thermal plasma dynamics in the ionosphere and inner magnetosphere.

Acknowledgments

It is a pleasure to acknowledge the excellent accomplishments of the instrument development staff at the University of Texas at Dallas, particularly Messrs Delaine Tipton, Al Blevins, Larry Brooks, William Lane, and Ron Lippincott for their efforts in the conceptual design and development of the RIMS instrument. We are also indebted to Messrs John Reynolds and Roy Hunt at MSFC for their dedication and long hours during the calibration activities. The RIMS instrument development was funded through the NASA/Goddard Space Flight Center Dynamics Explorer Project Office under Contract NAS8-32831.

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