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Bennett Ion Mass Spectrometers on the Pioneer Venus Bus and Orbiter

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Abstract

Identical Bennett radio frequency ion mass spectrometer instruments on the Pioneer Venus Bus and Orbiter have provided the first in-situ measurements of the detailed composition of the planet's ionosphere. The sensitivity, resolution, and dynamic range are sufficient to provide measurements of the solar-wind-induced bow-shock, the ionopause, and highly structured distributions of up to 16 thermal ion species within the ionosphere. The use of adaptive scan and detection circuits and servo-controlled logic for ion mass and energy analysis permits detection of ion concentration as low as 5 ions/cm^3 and ion flow velocities as large as 9 km/s for 0^+. A variety of commandable modes provides ion sampling rates ranging from 0.1 to 1.6 s between measurements of a single constituent. A lightweight sensor and electronics housing are features of a compact instrument package.

I. INTRODUCTION

Owing to the weak intrinsic magnetic field of the planet, direct interaction between the solar wind and the Venusian ionosphere creates a more complex and variable structure than encountered in the Earth ionosphere. As a result, theoretical predictions advanced prior to the Pioneer Venus (PV) mission set the requirement for instrument capabilities exceeding those previously demonstrated in extensive flight experience with the Bennett spectrometer in the Earth ionosphere on the Orbiting Geophysical Observatory and Atmosphere Explorer missions.

The primary objective of the PV Ion Mass Spectrometer (IMS) investigations has been to make global measurements of the composition of the ionosphere and, to the extent possible, measure ion drift with sufficient accuracy to contribute to the understanding of the solar-wind-induced dynamics of the ionosphere. Development of three unique measurement functions, 1) the step-dwell peak sampling technique, 2) the charge/velocity servo system, and 3) the explore/adapt ion mass sequencing system have proven to be essential for providing accurate ion concentration measurements compatible with both the data rate available from the spacecraft, and the high degree of variability encountered in the Venusian ionosphere.

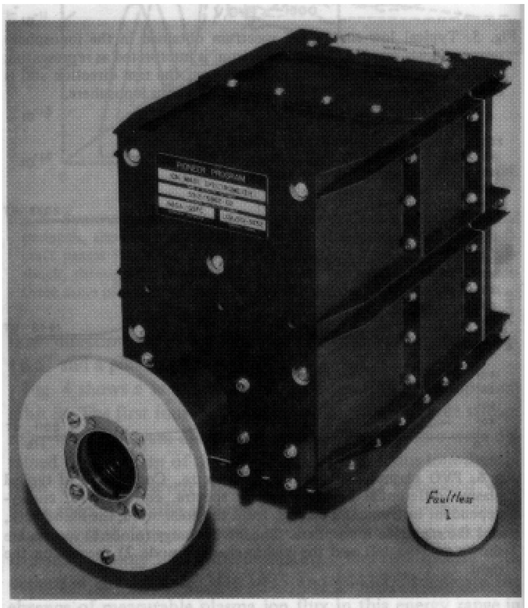

Fig. 1. The PV IMS instrument. Identical instruments were flown on the Bus (BIMS) and Orbiter (OIMS).

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II. INSTRUMENT DESCRIPTION

The Bus IMS (BIMS) and Orbiter IMS (OIMS) instruments are identical both electrically and mechanically, with the physical characteristics shown in Fig. 1. the instrument design and operational characteristics are similar to those of ion spectrometers flown on numerous rocket and satellite missions, including those on the Atmosphere Explorer-C and - E spacecraft [1]. The instrument consists of an analyzer tube and an electronics package. Ambient atmospheric ions sampled by the spectrometer enter the instrument through the analyzer orifice which is oriented as closely as possible in the direction of spacecraft motion, to enhance the collection of ions "scooped up" by the relatively rapid motion of the spacecraft through the thermal plasma. Both the

BIMS and OIMS instruments were mounted with the analyzer axis parallel to the spacecraft spin axis; this ensures a relatively small angle of attack throughout the periapsis pass and eliminates spin modulation of the ion currents.

A. Mechanical Configuration

The mass analyzer, shown schematically in Fig. 2, consists of a lightweight aluminum tube enclosing a series of grids, spacers, and long drift spaces. The grids are 0.001-in diameter knitted tungsten mesh with approximately 90-percent transparency. The intergrid spacers are machined from polyimide which has been baked to drive out volatiles. The drift spaces, which must be conducting, are made of gold- plated aluminum. Vacuum sealing of the tube, which is required only for the prelaunch calibration, is achieved by means of an O-ring in the collector area and by use of a low outgassing RTV sealant where the grid tabs protrude through the aluminum shell.

(1) Sensor at rest relative to plasma:

$$M = \frac{K|V_a|}{S^2F^2}$$

(2) Sensor moving relative to plasma

$$M = \frac{K\left(|V_a| - 1/2mv^2 + \phi_{sc}\right)}{S^2F^2}$$

where
M = mass of ion (AMU)
V_a = accelerating voltage
m = mass of ion
v = sum of spacecraft and ion velocities
ϕ_{sc} = spacecraft charge
S = inter-grid spacing
F = RF frequency
K = constant

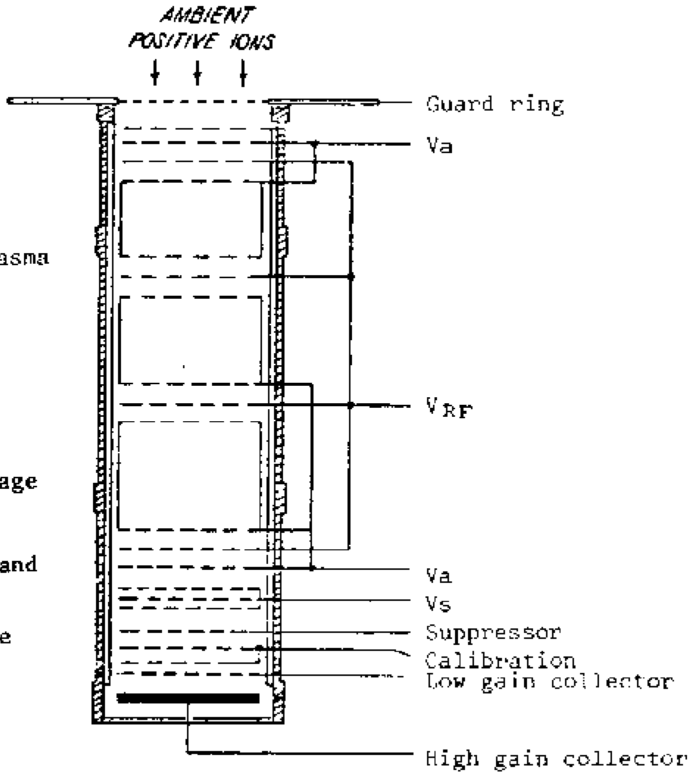


Fig. 2. Bennett mass spectrometer sensor and mass analysis equations.

The electronics housing is machined from magnesium. Component mounting in the printed-circuit boards utilizes both stitch-weld and solder techniques. All boards are conformally coated.

The total mass of the instrument is 3.0 kg.

B. Instrument Techniques

The system block diagram for the ion spectrometer is presented in Fig. 3. The instrument is powered by the +28 V spacecraft Bus and requires approximately 1.5 W of power in all modes of operation. The electronics system performs five major functions: 1) supplies required RF and dc potentials to the ion analyzer tube, 2) detects and amplifies ion current flowing to the collectors, 3) digitizes, processes, and formats data for telemetry, 4) automatically configures the sensor for subsequent measurements during a prescribed measurement cycle, and 5) decodes and implements instrument commands.

1) Ion Analyzer: Mass analysis of the spectrum of ambient thermal positive ions entering the Bennett RF spectrometer sensor (Fig. 2) is performed by 1) imparting incremental energy to those ions which are "resonant" as they traverse the analyzer, and subsequently 2) applying a retarding potential barrier which inhibits detection of ions except those which have gained the maximum energy with the analyzer. The instrument is identified as an RF spectrometer since the incremental ion energy is imparted by an RF potential (VRF) applied to each of four RF stages within the sensor. The sequencing of mass analysis within the chosen range of ion masses is accomplished by stepping the negative voltage (Va) which accelerates the positive ions down the longitudinal axis of the analyzer, through the four RF stages, and toward the retarding potential barrier established by the positive potential (Vs). For a particular value of the accelerating voltage (Va), the "resonant" velocity is imparted to ions of a given amu, such that these particles pass through each RF stage in synchronism with the phase of VRF. These ions receive maximum energy as they traverse the sensor, and are thus able to penetrate the retarding potential barrier and reach the collectors.

The barrier field established by the positive dc voltage Vs restricts the passage of all but the resonant ions, and thus acts as both an efficiency and resolution control for the analyzer. The gridded collector intercepts a small percentage of the total detectable ion flux and presents this current as input to a low-gain preamplifier. Ion flow to the solid collector surfaces serves as input to the high- gain preamplifier. Two additional grid structures within the tube suppress secondary electron emission from the collector surfaces and also induce (upon command) simulated ion currents into the detectors for end-to-end calibration of the electronic system.

2) Charge/Velocity Servo: The potentials Va and Vs work together to regulate the ion detection process with respect to the effects of 1) spacecraft velocity, 2) spacecraft skin charge, and 3) ion flow velocity generated by electric fields and/or solar-wind viscous interaction. For a sensor at rest relative to the

plasma, equation (1) of Fig. 2 applies, and the value of VA required to produce resonance for an ion of mass M is simply determined by the fixed coefficients K, S, and F. The potential Vs is set to provide nominal analyzer efficiency and resolution. Under flight conditions (equation (2) and Fig. 2) the sum of the axial components of spacecraft and ion drift velocities (v) results in a ram energy term for each ion mass, varying as 1/2 mv2. The servo system automatically compensates for this energy shift by appropriate adjustment of the Va and Vs voltages to maintain constant instrument efficiency and mass resolution. The effect of spacecraft skin charge is to add an energy offset proportional to phi sc, independent of ion mass. This additional term in the mass analysis equation is also automatically accommodated by the instrument servo.

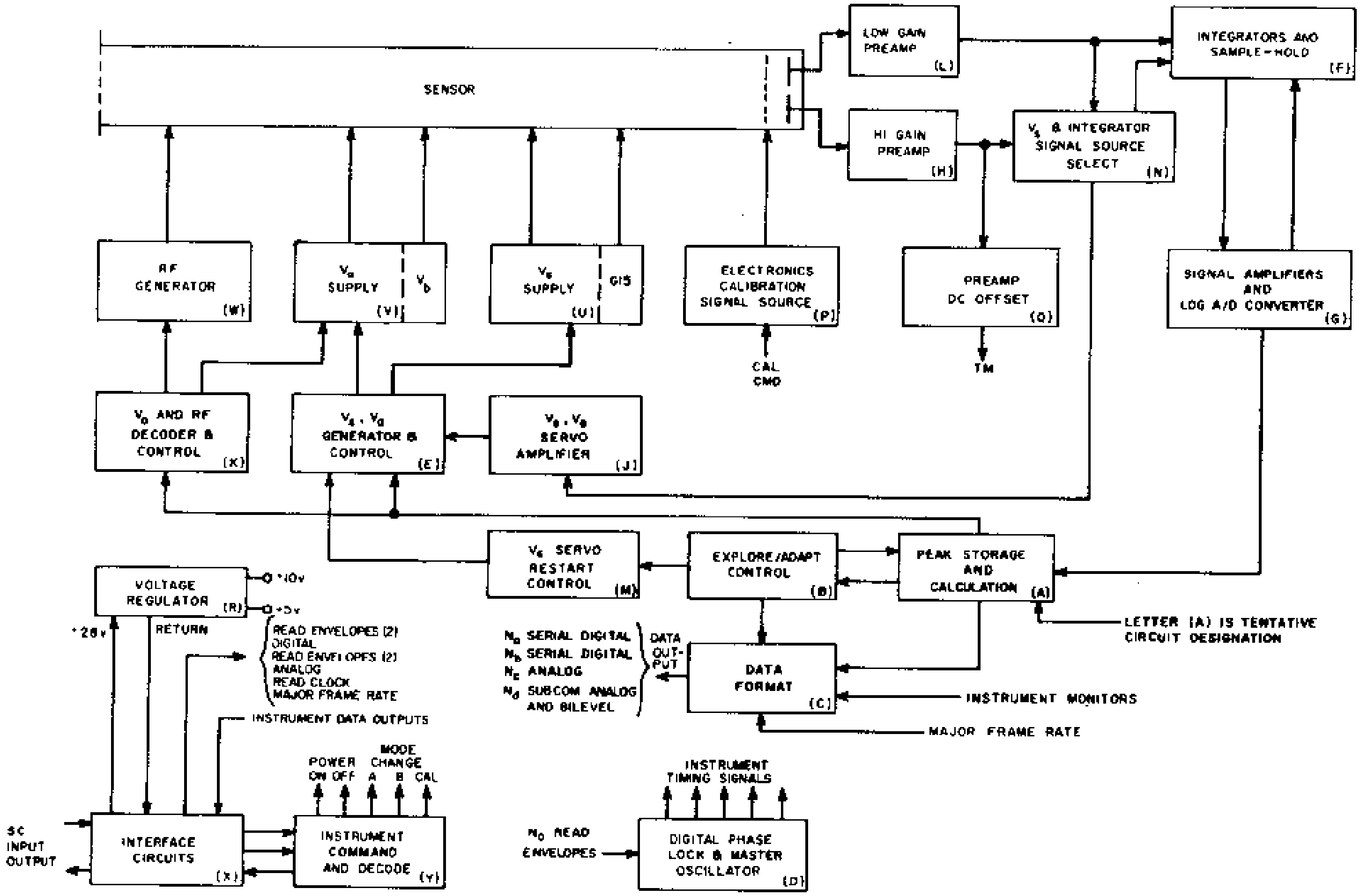


Fig. 3. System block diagram for the BIMS/OIMS instruments.

The axial component of ion drift velocity and the value of spacecraft potential are determined by analysis of the servo coefficients included in the BIMS and OIMS data stream.

3) Adaptive Mass Scan: A second unique feature incorporated in the BIMS and OIMS instruments is the explore/adapt logic sequence for regulating the consecutive measurements of individual ion species. This accomplished in two steps: 1) periodic exploration of all 16 preselected ion species, and 2) adaptive sequencing of repetitive ion measurements according to the relative significance of ion currents detected during the exploratory cycle.

Because of the significant variations in the distribution of the ions within the Venusian ionosphere, and the data rate limitations afforded by the PV mission, the explore/adapt measurement sequence was employed to insure the maximum possible repetition rate for sampling of species found to be prominent in a given altitude and/or local time range. Prompted by theoretical considerations, a total of 16 probable ion species to be identified in the Venusian ionosphere were selected and are identified in Table I. The sequence of ions listed in the table is sampled by stepping the accelerating potential Va to the appropriate value for each amu. The explore/adapt concept is shown in Fig. 4. The basic explore/adapt cycle is repeated every 6.3 s, and consists of an explore interval during which a sequential search is made for each of the 16 species, followed by a series of shorter adapt intervals during which repeated measurements of as many as eight prominent ions detected during the explore interval are performed. If eight or more ions are detected during the explore interval, adapt measurements of the eight most prominent of these will be repeated to fill out the remainder of the 6.3 s cycle as shown in the upper part of Fig. 4, thereby providing a total of six measurements of the eight prominent ions and one measurement of up to eight less prominent ions during the 6.3-s cycle. If less than eight ions are detected during the initial explore interval, the adapt intervals will contain repeated measurements of the most prominent ions detected up to the maximum number of eight. Thus, as shown in the lower part of Fig. 4, if only one ion is detected during the explore interval, forty repeat measurements of the same ion are made during the adapt interval, providing maximum temporal and spatial resolution for that single specie. The explore/adapt sequence thereby provides a spatial resolution of measurements inversely proportional to the number of ions encountered and thus automatically adjusts the measurement sequence so that information returned is optimized relative to the conditions encountered during the mission.

Several commandable options extend the flexibility and reliability of the explore/adapt system. As appropriate to conditions encountered, the instrument may be commanded to 1) explore only, and 2) adapt to less than eight prominent ions.

4) Step-Dwell Ion Current Detection: As an improvement over previous designs, the BIMS/OIMS ion spectrum scan is accomplished by a step-dwell sequence of ion detection, rather than the less efficient continuous sweep used in earlier instruments. The step-dwell sequence consists of a series of dwell intervals of approximately 0.1-s duration during which ion currents at each of the 16 mass positions are detected sequentially during the explore interval.

TABLE I
BIMS/OIMS DEDICATED ION MASSES

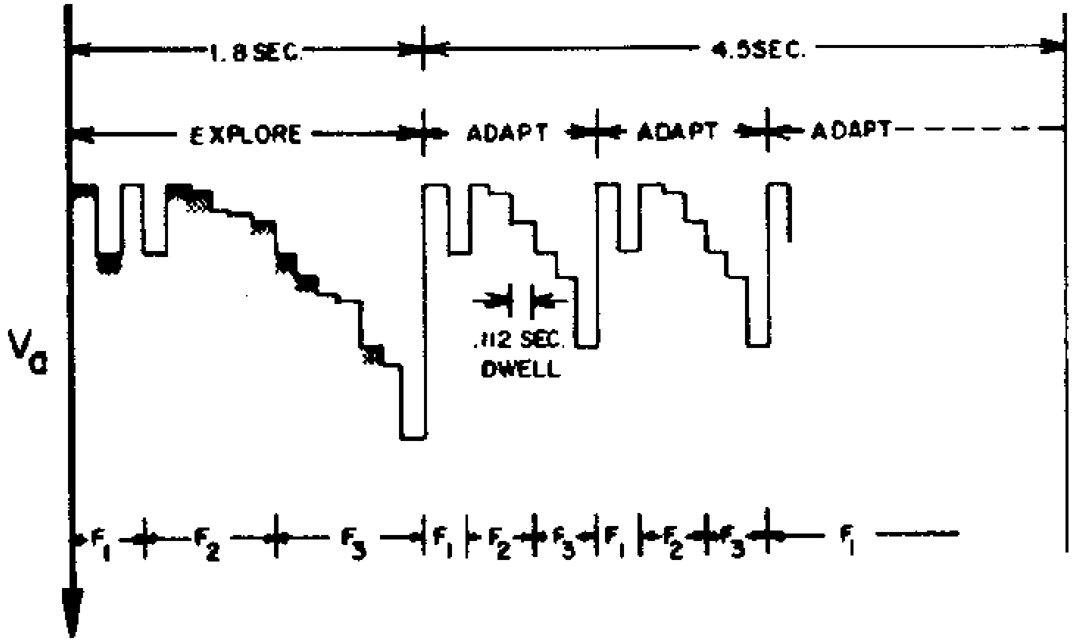
Measurement Sequence Position	Ion Mass (AMU)	Ion Species
0	1	H+
1	18	H2O^{+} ^180^{+}
2	12	C^{+}
3	32	O2^{+}
4	4	He^{+}
5	28	N2^{+}, CO^{+}
6	16	O^{+}
7	44	CO2^{+}
8	2	H2^{+}
9	24	Mg^{+}
10	14	N^{+}
11	40	Ar^{+}
12	8	O^{++}
13	30	NO^{+}
14	17	OH^{+}
15	56	Fe^{+}

At the onset of each of the 16 dwell intervals, the accelerating potential Va is stepped to the approximate value required for the resonant measurement of the specific ion. As the measurement dwell cycle proceeds, the values of Vs and Va are servoed to compensate for changes encountered in spacecraft charge and velocity, thereby ensuring mass resonance and constancy of sensor efficiency and resolution for the ion current measurement.

During the dwell cycle VRF is switched an and off at a 30-Hz rate so that intervals of ion current measurements are alternated with intervals of background (zero-level) collector current. These alternating cycles of signal and noise are integrated in a manner which cancels the zero level current. At the end of the dwell cycle, the accumulated ion current value is sampled and held for A/D conversion and subsequent transfer to telemetry storage registers.

In addition to providing for the servoing Vs, Va interval, the step-dwell feature of the mass scanning circuitry provides benefits for both the bandwidth requirements of the instrument and the system noise figure.

8 OR MORE IONS PRESENT
EXPLORE-ADAPT (8 MOST ABUNDANT IONS REPEATED 5 TIMES)



1 ION PRESENT
EXPLORE-ADAPT (1 ION REPEATED 40 TIMES)

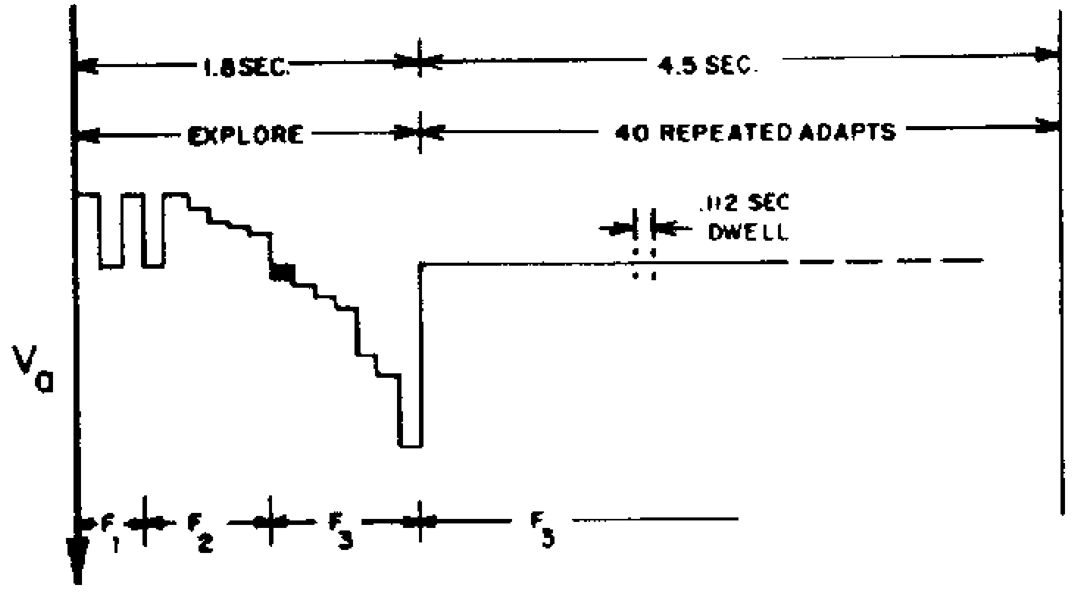


Fig. 4. Schematic representation of the explore/adapt mass sequencing system.

In order to cover the 120-dB (106/1) dynamic range of output current from the ion analyzer, along with the desired current sensitivity, two preamplifiers are employed, each receiving its input from the appropriate collector surface within the sensor. Each preamplifier employs a low noise N- Channel field-effect transistor at its input and a high megohm feedback resistor to establish the gain. The current sensitivity provided by this system permits the measurement of ion concentrations as low as 5 ions/cm3.

5) Instrument Modes and Commandable Functions: The OIMS instrument has provision for sixteen commandable states, any one of which is selected by a serial 5-bit code, 4 bits containing the command information and one bit for initiating command. The instrument can be commanded to adapt to either the 8, 4, or 2 most prominent of the 16 ion masses. In each case, it will adapt to no more than the number commanded, but will adapt to a lesser number if

there are fewer masses present than the commanded number. In addition, an EXPLORE ONLY mode overrides the adapt interval and causes the instrument to continue scanning all 16 mass positions repeatedly; (the BIMS adapt command is fixed at 8 of 16). The sensitivity of the instrument may be modified by a GUARD RING command, which applies a dc potential of either 0 or -6 V to the circular guard ring surrounding the sensor orifice. This command may be used to increase the collection efficiency for ambient positive ions, thus increasing the sensitivity.

The operation of the charge/velocity servo system may be checked by use of the SERVO NORMAL/OVERRIDE command. In the OVERRIDE mode, the servo is disabled, and the Vs and Va parameters are set at nominal values predicted to be appropriate for periapsis. In this mode, the instrument is nonresponsive to changes in ion flow velocity and spacecraft charge.

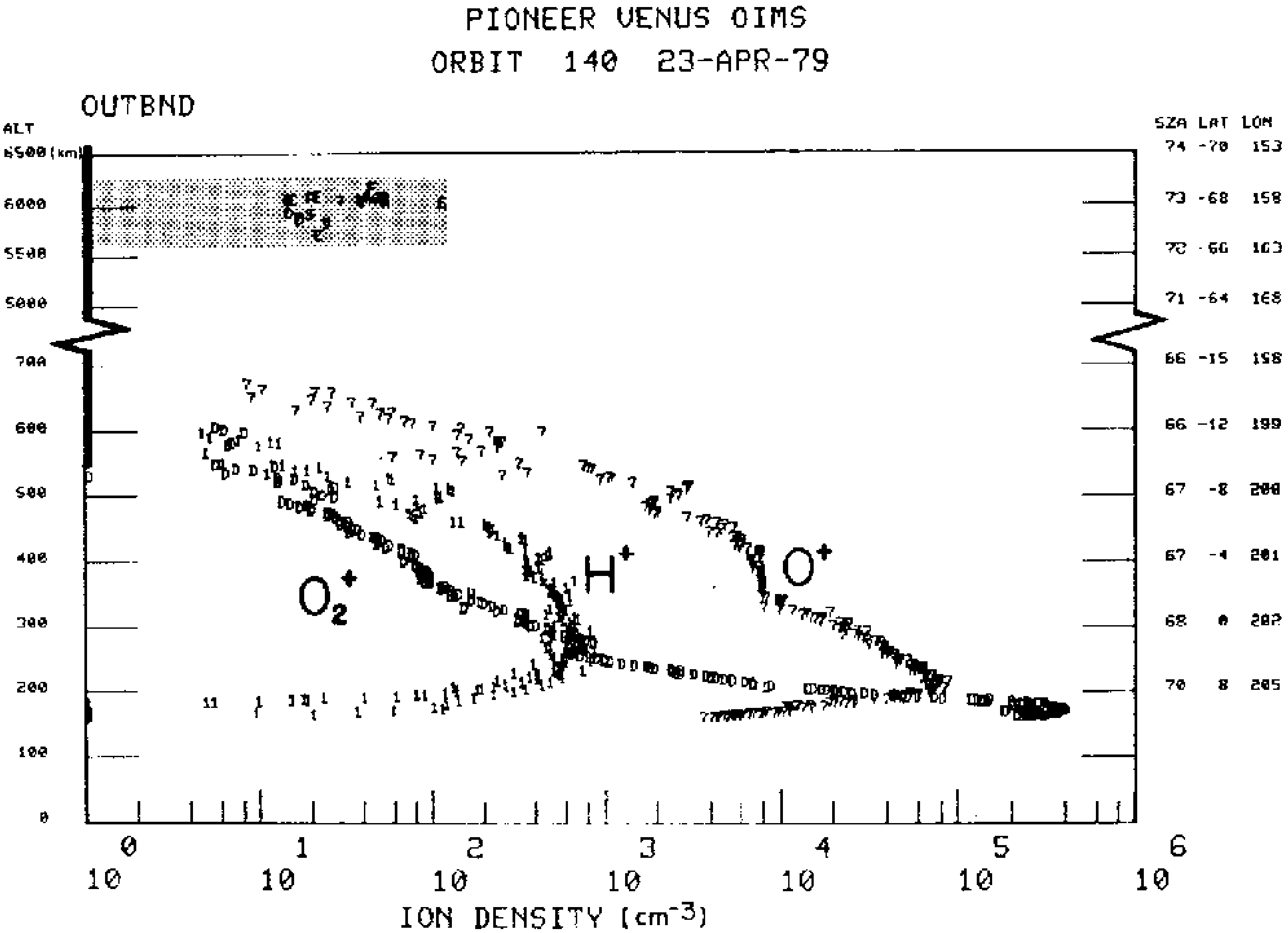
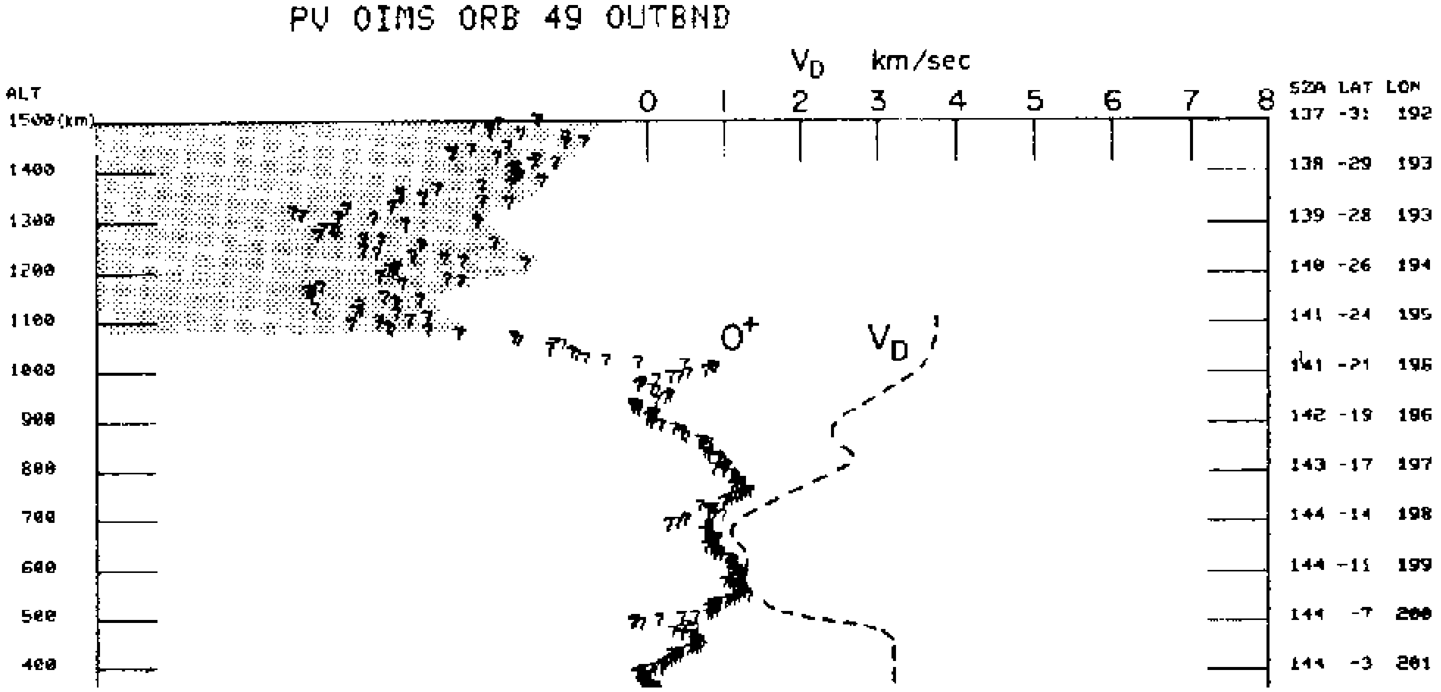


Fig. 5. An example of the scope and height resolution of measurements provided by the OIMS. For clarity only three of the 16 possible ion distributions are plotted. Measurements within shaded area result from the influx of superthermal particles of undetermined mass and concentration associated with the bow-shock region.



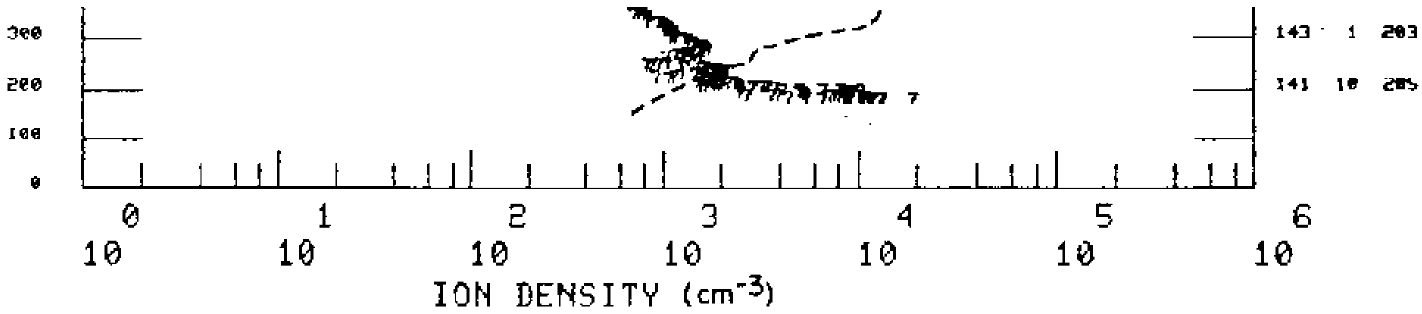


Fig. 6. Simultaneous measurements of irregularities in the concentration of O$^+$ and associated variations in the ion drift component V_D along the spectrometer axis. Shaded area indicates region of superthermal plasma encountered just above ionopause.

In addition to the foregoing, the BIMS/OIMS instruments have a POWER ON/OFF command and an internal CALIBRATION command. The CALIBRATION command couples known currents into the two preamplifiers equivalent to ion currents detectable within the dynamic range of the instrument. These simulated ion currents provide an end-to-end calibration of the electronics.

III. INITIAL FLIGHT RESULTS

Both the BIMS and OIMS instruments have performed accurately and reliably in flight. With repeated orbits, the OIMS has answered several basic questions which motivated the PV mission. In particular, the identity of the dominant ions O+ in the upper ionosphere and O2+ in the lower ionosphere was established immediately.

In addition to the determination of the dominant ion, the OIMS also identified H^{+}, H2^{+}, He^{+}, O^{++}, C^{+}, N^{+}, 18O^{+}, and/or H2O^{+}, CO^{+}, and/or N2^{+}, NO^{+}, O2^{+}, and CO2^{+} in the Venusian ionosphere. Data analysis currently in progress shows positive indications that the ion energy servo system will contribute to understanding the complex dynamic nature of the ionosphere, as well as the detailed composition.

In addition to the early results from OIMS and BIMS already reported [2] - [4], several examples of in-flight results are included here to illustrate the fulfillment of the instrument design goals. First, the sensitivity and temporal resolution of the ion measurements have permitted detection of numerous plasma signatures, including the bowshock region, complex ionopause structure, and pronounced irregularity in the ionosphere, as shown in Fig. 5. In Fig. 6, the capability is shown for simultaneous detection of axial ion drift velocities of the order of km/sec along with associated extreme structural variations in the ion concentration. Together these measurement tools provide a mean for detailed exploration of both the composition of the Venusian ionosphere and the complexities of its dynamic interaction with the solar wind.

Acknowledgement

The performance of the countless engineering tasks contributing to the successful operation of the Pioneer Venus Ion Spectrometers deserves special acknowledgement. Particular among the many contributors are J.S. Burcham, B.D. Gagnon, and M.W. Pharo of GSFC, D.E. Simons, R.C. Maehl, J.T.C. Coulson, D.E. Tallon, L.T. Fry, R. Madaris, P. Lepanto, and W. Heflin of Norlin Communications, Inc., and A.A. Stern of CSTA, Inc.

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