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TITLE THREE-DIMENSIONAL PLASMA MEASUREMENTS FROM THREE-AXIS STABILIZED SPACECRAFT

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THREE-DIMENSIONAL PLASMA MEASUREMENTS FROM THREE-AXIS STABILIZED SPACECRAFT

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Abstract. Future planetary missions require that comprehensive three-dimensional measurements of electrons and mass-resolved ions be made from three-axis stabilized spacecraft. In order to make these measurements without requiring expensive and resource intensive platforms to scan space mechanically, we are developing various systems that are designed to scan space electrostatically. These systems also make it possible to circumvent the significant shadowing that would be present even with a scan platform, caused by necessary spacecraft appendages such as communications antennas and a power source (RTG or solar cell panels). The systems, which are axially symmetric, select particles arriving from 360° in azimuth along conical surfaces whose polar (or elevation) angles, referenced to the instrument symmetry axes, are determined by applying suitable deflection voltages to shaped deflectors. Particles thus selected in polar angle pass into spherically or toroidally-shaped electrostatic analyzers. After analysis, the 360° outputs of the analyzers are divided into discrete angular swaths to provide azimuthal angle resolution. In the case of electrons, the analyzed particles can be detected directly; in the case of ions, the particles in each swath can be counted directly, or further analyzed with time-of-flight or magnetic analyzers to obtain the velocity distributions of the separated major ion constituents. We present computer simulations of particle paths through the various analyzers of this type and show results from laboratory calibrations of prototypes.

Introduction

One of the fundamental realizations brought about by the planetary exploration program of the past two decades is the wide range of complex plasma physics phenomena that occurs in the vicinity of the terrestrial and Jovian planets, as well as comets. All of the solar system bodies which have been probed seem to exhibit strong and unique plasma and electrodynamic phenomena. However, in many cases the reconnaissance and exploratory missions which have been flown have left these phenomena only partially investigated and not completely understood. Two important limitations on the detailed understanding of plasma phenomena at other planets have been the incomplete coverage of plasma velocity distributions provided by previous missions and the absence of unambiguous composition measurements.

To obtain a quantitative understanding of the various plasma physical phenomena occurring in the vicinity of a planet or other body, it is important to have accurate measurements of the fluid moments, including the density, bulk velocity, temperature, and heat flux of each of the plasma components. These measurements must resolve the entire velocity distributions of electrons and ions with adequate temporal, angular, mass, and energy resolution. Full angular coverage is particularly important when the distributions are anisotropic in the spacecraft frame, either due to an actual pitch-angle anisotropy or to a significant flow velocity. Unfortunately, obtaining the requisite full velocity-space coverage is difficult because planetary missions typically use three-axis stabilized spacecraft in order to facilitate imaging experiments, and to maintain good telemetry links with Earth. Thus, one cannot take advantage of spacecraft spin to obtain full angular coverage of the plasma distribution. An additional problem exists even if a single scan platform is provided for plasma instrumentation. Necessary spacecraft appendages such as communications antennas and power sources (RTGs or solar cell panels), and the spacecraft itself block significant portions of velocity space.

Accurate measurement of plasma moments requires knowledge of the ion composition, the importance of which has only recently begun to be appreciated. This appreciation has been fueled by spacecraft observations of significant populations of heavy ions, with clear terrestrial origins, within the Earth's magnetosphere (see Young, 1983, for a review), and even more so by the discovery of major heavy ion components in the plasmas of the Jovian and Saturnian magnetospheres (cf. Lazarus and McNutt, 1983). Voyager observations at Jupiter

and Saturn suggest that the various satellites and rings within those magnetospheres may be the dominant sources of magnetospheric plasma. As a consequence, it is now clear that a knowledge of plasma composition is a first-order requirement for a proper understanding of the physics of various planetary magnetospheres.

The importance of understanding planetary plasma phenomena is now well recognized, and missions such as Galileo and Comet Rendezvous and Asteroid Flyby (CRAF) include comprehensive plasma and field instrumentation in their payloads. Two new missions now in the planning stages are the Mars Aeronomy Observer and Cassini, which is comprised of a Saturn Orbiter and Titan Probe. Fairly complete plasma instrumentation has also been recommended for these missions. However, the study reports for both missions assume that the needed instruments have already been developed for previous planetary or solar-terrestrial missions. Unfortunately, this is not the case. Previous plasma instruments on planetary missions have provided neither unambiguous mass analysis nor full velocity-space coverage. Furthermore, since for communication and imaging reasons planetary spacecraft are usually three-axis stabilized, plasma instrument of the present generation that make two-dimensional measurements, provide three-dimensional coverage of accessible portions of space only if mechanical scanning is available with scan platforms or separate spinning spacecraft sections. Even with such platforms, as mentioned above significant portions of velocity-space are blocked by spacecraft appendages.

Provision of a rotating platform introduces reliability problems, increases the cost of the spacecraft, uses limited spacecraft resources such as attitude control gas, and in any event does not solve the full accessibility to space problem caused by obstructions. Additionally, because of the need to conserve spacecraft resources, the measurement time resolution using a scan platform is necessarily constrained by the speed and number of operating cycles that can be allotted it.

The CRAF spacecraft presents a good example of the problems that arise when mechanical scanning is necessary to convert two dimensional measurements into three dimensional plasma distributions. CRAF, like Cassini, will use the Mariner Mark II spacecraft, which is three axis stabilized with scan platforms. The proposed instrument for providing composition resolved three dimensional plasma measurements has a two dimensional acceptance fan ($5^\circ \times 160^\circ$) and will need to rely on single axis mechanical scanning projected to be provided by the CRAF low precision scan platform

in order to obtain three-dimensional coverage. However, because of fuel limitations, scanning will be limited to a small fraction of the spacecraft operational time (less than 25%), a serious degradation of the measurement capability. Additionally, other experiments on the platform have pointing requirements that are incompatible with those of the plasma experiment, further reducing measurement capability.

Taking the lessons learned from CRAF and generalizing to future missions such as Cassini and Mars Aeronomy Observer as well as potential missions such as Lunar Polar Orbiter, Mercury Magnetospheric Orbiter, etc., it is important to examine how fully three-dimensional plasma velocity distributions might be obtained using fixed-attitude spacecraft. An optimum solution must avoid substantial blockage of velocity-space by the spacecraft and its appendages and should not require a scan platform. Search for an answer to this problem has been a major impetus for the work reported here that was carried out at the Los Alamos National Laboratory and the Southwest Research Institute (SwRI). As discussed in the following sections, mechanical scanning can be eliminated by the use of electrostatic scanning. Several candidate systems are presented. The problem of solid angle obscuration by the spacecraft and appendages can be overcome by appropriately locating two sensor heads on opposite sides of the spacecraft.

Measurement Objectives and Approach

As noted previously, the plasmas found within all of the planetary magnetospheres sampled to date are highly complex in makeup and in velocity distribution. Moreover, they are highly variable both spatially and temporally. For example, within the magnetosphere of Saturn plasma densities range from less than 10^{-2} up to $\sim 10 \text{ cm}^{-3}$, flow speeds range from ~ 10 to $\sim 200 \text{ km s}^{-1}$, and both ion and electron temperatures range from several electron volts to $\sim 1 \text{ keV}$ (e.g., Sittler *et al.*, 1983; Richardson, 1986). Comparable or greater variations are found within other magnetospheres.

In addition, in many situations of great interest more than one particle population is present. For example, both very cold (several electron volts) and very hot (several hundred electron volts) electron and/or ion components commonly coexist in the same region, and several different elemental or molecular species may be present (for example, H, N, O, H_2O , CO, etc.). Each elemental species may also occupy more than one charge state (for example, O^+ , O^{++}). Further, velocity distributions may be highly non-Maxwellian, and strong

anisotropies may be present. Often strong streaming along the local magnetic field is observed. The plasma flow may be supersonic and therefore appear as a beam (typically transverse to the field within the magnetospheres of the outer planets), or subsonic and therefore more nearly isotropic in the spacecraft frame.

Measurement objectives during upcoming planetary missions should therefore be directed toward resolving and distinguishing these complexities with a sensitive instrument placed on a three-axis stabilized spacecraft, and if possible these observations should be made without requiring a scan platform and in such a way as to avoid obscuration of significant portions of space by such mission-essential elements as the spacecraft antennas and the spacecraft itself. The plasma measurements should be fully three-dimensional or cover the pertinent portions of velocity-space required for the specific scientific problems of interest with adequate angular resolution to resolve moderately narrow beams independent of their flow direction or the spacecraft orientation. The instrument should be sensitive enough to measure densities of major ion species as low as 10^{-2} cm^{-3} on a temporal scale of several tens of seconds or less, and should have an energy range extending from near 1 eV to $\sim 30 \text{ keV}$ where energetic particle solid state detectors can take over. Energy resolution should be adequate for both cold supersonic and hot subsonic flows. Major ion species should be separated under all conditions; their separation should not be dependent on fortuitous combinations of ion flow speed and direction. To implement these objectives, the SwRI/Los Alamos joint program has two major goals: (1) to explore and develop instrument concepts aimed at providing fully three-dimensional ion and electron distribution measurements on three-axis stabilized spacecraft that might have large, blocking appendages, without requiring mechanical scan platforms or spinning sections, and (2) to develop an appropriate mass analysis system to be used in conjunction with the three-dimensional ion instrument to resolve all important ion species. Principal emphasis in this paper is given to goal (1). A parallel development of time-of-flight (TOF) mass analysis is being carried out; some results of this development have been reported by Young et al. (1989).

Our approach to the field of view (FOV) problem associated with fixed attitude spacecraft has been to develop the candidate electrostatic deflection systems described in the following sections. These systems scan a large fraction of the unit sphere with programmed deflection and analyzer voltages. The voltages required,

that are no higher than those that have been successfully used in some previous space flight plasma experiments, are shielded from the external environment by grounded enclosures. Combining a FOV scanning system with a high throughput, lightweight, high-resolution TOF system will provide high time resolution and M/q composition-resolved measurements of the three-dimensional distributions of the plasmas which surround planetary objects of interest.

Elevation Analyzers Under Development

In this section we describe five "elevation analyzer" concepts that achieve desired fully steerable FOVs. These elevation analyzers are in various stages of development at SwRI and Los Alamos. Each concept has been demonstrated to be viable, but some require further characterization with computer ray tracing studies and verification measurements on laboratory prototypes. Names given to the five candidate systems described below, in the order of presentation, are Beacon-C, Beacon-D, fast ion mass spectrometer (FIMS), gridded truncated hemisphere (GTH), and CRAF non-scanning platform (NSP).

Beacon-C Elevation Analyzer for Ion Composition Measurements

The Beacon-C elevation analyzer is one of two versions of a system called "Beacon" under development at Los Alamos. With a single Beacon sensor on a fixed-attitude spacecraft, particles can be resolved in energy, azimuth, and polar angle over all or most of a 2π steradian hemisphere. Fully three-dimensional measurements over the entire 4π steradian unit sphere can be implemented by placing diametrically opposed Beacon sensor heads on opposite sides of a spacecraft. A single set of power supplies and data processing and control logics can be used to operate both sensor heads. The Beacon-C is an ion composition version of Beacon designed to measure separately, but concurrently, the velocity distributions of the major ion species to be found in a planetary or cometary magnetosphere. Another version, Beacon-D, which is described in the next section, is configured to measure the velocity distributions of magnetospheric and solar wind electrons. It can also be employed to measure both electrons and ions (without composition) with a single detector system on missions with severely constrained spacecraft resources. Both the C and D versions make use of a Beacon system of rotationally symmetric electrodes shown in Figure 1, to deflect particles arriving along a conical surface into a toroidal elec-

trostatic analyzer for E/q analysis. The acceptance cone angle, equivalent to the polar or elevation angle as referenced to the symmetry axis, is selected by applying appropriate voltages to the deflector electrodes. Particles arriving from 360° in azimuth around the conical surface are accepted and can be resolved in azimuth by physically dividing the 360° range. This division is implemented in different ways for Beacon-C and Beacon-D as described below.

Figure 1 shows a schematic, cross-sectional view of Beacon-C. This instrument employs the specially shaped inner and outer deflector electrodes of Beacon to deflect incoming ions into a two-stage toroidal analyzer. The deflector shapes were empirically determined using a 2 1/2-dimensional ray tracing computer program. This program, which traces only those rays that pass through the symmetry axes of rotationally symmetric systems, was utilized to maximize the deflection sensitivity vs. voltage of Beacon-C while permitting the desired range of polar angle acceptance to be achieved. The inner deflector, as shown, can be entirely solid, while the outer deflector is made up of a solid section, where bending is strongest, followed by a conical section of wire or mesh that is largely transparent to incoming ions.

The purpose of the second reverse curvature stage of the compound toroidal analyzer is to extend the bending angle of the analyzer to provide adequate energy resolution and UV rejection and at the same time to bring the analyzed ions out along a cylindrically shaped surface centered on and parallel to the instrument symmetry axis. For mass per charge separation the ions are then post-accelerated by -15 kV and injected into a circular array of TOF analyzers such as the array with 22.5° azimuthal resolution described by Young et al. (1989). Mass resolution might also be provided by an appropriate magnetic analyzer system, or a combination of TOF and magnetic analyzers, as used for the C'RAF NSP instrument described in a later section.

Positive voltages are used on the deflectors and analyzer of the Beacon to avoid outward acceleration of the photo- and secondary electrons that will be produced on the instrument surfaces in space. The instrument is encased in a grounded outer container, as shown in Figure 1 to shield the instrument exterior from the interior voltages which may extend as high as 7 kV. (Such voltages have been successfully used in past space experiments and are not expected to cause any problems.)

Ray tracing with the 2 1/2 dimensional computer program has verified and characterized the capability of

the Beacon deflection system. The program calculates the electrostatic configuration of an axially symmetric system and then incrementally traces particles launched with given initial conditions through the system along a plane which contains the symmetry axis. Further characterization of the Beacon response is in progress using a program which tracks particles through the three-dimensional representation of the instrument without constraining them to any particular plane.

Results using the 2 1/2-dimensional program are given in Figure 2. The program calculates rays one at time; a number of them have been superimposed in the figure. With an appropriate positive potential applied to the outside analyzer plate, ions launched from deep within the analyzer follow central paths out through the analyzer entrance and the deflectors. For electrostatic systems the rays are, of course, completely reversible. The rays shown were traced for a selection of voltages on the deflectors. They exhibit a pattern extending from $\sim 1^\circ$ to $\sim 78^\circ$ in polar or elevation angle. (This pattern prompted the name "Beacon" for this elevation analyzer.) Rays at polar angles extending from 46° down to 1° , near the sensor equator, were obtained with outer deflector voltages extending from 0 V to +7000 V in 700 V increments. Rays from 46° up to 78° , 12° from a polar angle of 90° , were obtained with the same voltages applied to the inner deflector. In either case the opposite deflector is held at 0 V. For these calculations, the ion launch energy was 34.0 keV/q corresponding to an incoming energy of 35.5 keV/q. (The energy difference is $\sim 1/2$ the analyzer voltage.)

Figure 3 is a plot of ion deflection angle vs. deflection voltage applied to the inner and outer deflectors. The slope of the curve is a measure of deflection sensitivity, which increases from high to low polar angle. This is understandable from inspection of Figure 2 which shows that larger portions of the trajectories of ions deflected from low polar angles lie in regions in which the field strength is high and appropriately directed in comparison to the trajectories of ions deflected from high polar angles.

The ray tracing program has also been used to verify that the reverse curvature analyzer shown in Figure 1 performs as desired. A particle launched downward from near the entrance of the top toroidal section successfully passed into the lower section and exited with a trajectory parallel to the symmetry axis. Further simulations have shown that the Beacon can be configured to accept particles from an entire hemisphere. The version of Figure 1 accepts particles up to $\sim 78^\circ$ polar an

gle, which allows coverage of $\sim 98\%$ of the unit sphere with two sensor heads. Giving the outer deflector a more nearly cylindrical shape, coverage up to 100% has been calculated. The penalty for this small amount of additional spatial coverage is either a reduction of the maximum energy covered or a requirement for higher deflection voltages. For most applications the particle distributions to be encountered are broad enough that 98% coverage is quite adequate.

In order to verify that the Beacon operates as simulated and to further characterize its full three-dimensional behavior, a proof-of-principle test model was constructed at Los Alamos and taken to SwRI for preliminary tests in the SwRI calibration facility. A photograph of the test model is shown in Figure 4. It is constructed of aluminum alloy with Kel-F insulators in such a way that it can be assembled in both the Beacon-C and Beacon-D configurations. The figure shows it in the -C configuration without the external grounded container. The dome-shaped electrode in the center is the inner deflector; the outer deflector, visible above the inner, is extended by the wire cage continuation of the solid part of the deflector. The wire is 0.5 mm diameter BeCu which is relatively thick in comparison to the 1.5 mm analyzer plate spacing. Some of the Beacon response characteristics at low polar angle may have been affected by the thickness of the wire. We plan to do further tests with smaller wire or mesh.

At SwRI the calibration tests were conducted by placing the Beacon-C in the calibration system beam, mounted to permit rotation in both the azimuthal and polar angle directions. A broad parallel beam of 1120 eV N_2^+ ions was used for all the tests and the analyzed ions were detected in an imaging microchannel plate (MCP) system which had adjustable spacing behind the test model. Figure 5 shows 12 MCP images of the spatial distribution of the output ions from Beacon-C as displayed on a storage oscilloscope screen. For this series the deflectors were at 0 V, the instrument was set so that the beam polar angle was 44° , and the analyzer voltage was tuned to 84 V. As the figure shows, the analyzed beam at this polar angle is bifurcated at close and distant spacings but has a broad, well-defined cross-over or focussed distribution at intermediate spacings extending from ~ 8 to ~ 21 mm. This bifurcation, which is under further study with fully three-dimensional simulations, is thought to result from transmission of those ions in the broad parallel beam which pass on either side of the region around the symmetry axis. Any of these intermediate focussed distributions would be suit

able for 15 kV post acceleration into a TOF system such as that described by Young *et al.* (1989).

Figure 6 shows count rate contours taken over a field composed of the relevant ranges of analyzer voltage and polar angle. Both deflectors were held at 0 V for this set of measurements. The contours show evidence of structure in the response peak which is probably caused by grid wire shadows; this will be investigated further using finer grid wires.

Significant responses were found for Beacon-C over a range of polar angles extending from 0° to 79°. At angles above 79° the outer deflector wire cage interferes with the incoming ions. Figure 7 shows photographs of MCP images for a beam at a polar angle of 16°, obtained with 84 V on the analyzer, 0 V on the inner deflector, and 150 V on the outer deflector. For this angle the beam is somewhat broader than for the previous case, but the image is still quite adequate between ~8 and ~20 mm to feed into a TOF system. Count rate contours over the relevant ranges of analyzer voltage and polar angle for 150 V on the outer deflector are shown in Figure 8. Multiple response peaks are not as prominent here as for the previous case. Count rate contours for 200 V on the inner deflector are shown in Figure 9, and again there seems to be only one principal peak, positioned at ~74° polar angle and 85 V analyzer voltage. Here the beam does not go through the wire grid.

As a final test of the Beacon-C capabilities, the analyzer voltage was set at 84 V and polar angle sweeps were made for deflector voltages set at 0, 50, 100, 150, and 200 V, first on one deflector and then on the other. The results, given in Figure 10, show clean separation of the polar angle deflection ranges, particularly at high polar angles. At low polar angles, fine structure in the response peaks, as mentioned above, appears to be real and repeatable. Again, we believe this structure is probably due to the relatively large deflector wire size in comparison to the analyzer plate spacing. Future tests using finer deflector grid wire or mesh should help resolve this issue and reduce the amplitude of the fine structure, if indeed the wire size is the source of this response.

Beacon D Elevation Analyzer for Electron Distribution Measurements

The Beacon D analyzer shown in Figure 11 is intended for measurements of the velocity distributions of electrons in planetary magnetospheres and in the solar wind. It has deflection optics identical to those of

Beacon-C, but instead of utilizing a compound toroidal analyzer, it uses a single toroid with a 133° bending angle. Analyzed electrons are post-accelerated, e.g., by +200 V, into an exit aperture housing where they strike a secondary emitter and create secondary electrons which are attracted into an MCP with its front face at +400 V. Since the azimuthal angle distributions of the electrons entering the sensor from outside are retained after deflection and electrostatic analysis, azimuthal angle resolution can be obtained by spatially resolving the electrons striking the MCP by employing a divided anode. For example, division of the anode into 16 parts would give 22.5° resolution.

As mentioned earlier, this configuration could be used to detect both electrons and ions for missions where both need to be measured, but spacecraft resources do not allow for flying independent electron and ion detectors. Referring again to Figure 11, ions as well as electrons can be analyzed if a second analyzer supply is provided. No additional deflector voltage supplies are required since the existing set serves to deflect both electrons and ions. To detect both electrons and ions after analysis, a programmable secondary emitter supply must be added to change the voltage configuration of the exit aperture housing/secondary emitter suitably. Computer simulations show this scheme to be viable; we plan to demonstrate it with a breadboard model as well. However, if resources permit, it is of course preferable to measure electrons and ions with separate instruments, to allow concurrent measurements.

At SwRI the Beacon-D configuration was tested in the same manner as Beacon-C with similar results. Polar angle sweeps for deflector voltages of 0, 50, 100, 150, and 200 V on the two deflectors, shown in Figure 12, demonstrate that the polar angle response of Beacon-D is similar to that of Beacon-C.

Fast Ion Mass Spectrometer (FIMS) Elevation Analyzer for Ion Composition Measurements

At SwRI, work has proceeded over the past several years on a class of gridded hemisphere elevation analyzers. This work was motivated by the need for three-dimensional, composition resolved plasma measurements on CRAF, coupled with a lack of sufficient availability of mechanical scanning because of fuel limitations. Three instrument concepts that have been investigated are described here, beginning with FIMS. A schematic cross sectional sketch of the FIMS is presented in Figure 13. This system, an outgrowth of an elevation analyzer system described by Wilhelm (1985), consists

of three parts, which for convenience have been called an "elevation" analyzer, an "energy" analyzer, and an "azimuth" analyzer. The system is designed to cover a hemisphere, like Beacon, and would require two sensor heads with opposed viewing axes to cover the 4π steradian sphere. For ion mass measurements, the "azimuth" analyzer could directly feed into a cylindrical array of TOF analyzers as described by Young *et al.* (1989).

The elevation analyzer consists of a hemispherical system with the outer hemisphere made of grid or mesh material. The inner elevation hemisphere consists of concentric conducting rings electrically isolated from each other. By programming the analyzer voltage onto first the bottom unshaded #1 ring, then the first two rings, the bottom three rings, etc., ions with polar angles beginning near 90° and extending down to near 0° can be accepted and further energy analyzed in the central truncated hemispherical analyzer. Particles then cross over from the energy analyzer into the azimuth analyzer which then brings them out in a cylindrical shell parallel to and centered on the instrument symmetry axis. By dividing the output of the azimuth analyzer into swaths, the azimuthal distribution of incoming ions, which is mirrored at the output, can be resolved, while polar angle resolution is achieved, as described, by programming the analyzer voltage on the rings of the elevation analyzer.

Figure 14 shows the results of a FIMS angular response measurement at SwRI. The instrument was placed in a 1 keV N_2^+ beam in the SwRI calibration chamber and the polar angle response was measured with 365 V on the various combinations of conducting rings. It is apparent that the FIMS can clearly resolve ion distributions in polar angle, as well as azimuth, thus facilitating three-dimensional determinations. By adding TOF units at the exit of the azimuth analyzer, the measurements of all major ion species can be made simultaneously.

Gridded Truncated Hemisphere (GTH) Elevation Analyzer

Another member of the class of gridded hemisphere elevation analyzers under development at SwRI is the GTH, shown sketched in Figure 15. The inner deflection plate consists of a hemisphere that is truncated and closed with a flat surface at a latitude of 60° ; i.e., it is a 360° by 60° hemispherical section, capped by a flat plate parallel to the equatorial plane of the section. The outer deflection plates are of similar geometry, but the flat plate is raised above the point of truncation. Both

are made of 85% transmission conducting mesh or grid. In essence, the GTH consists of a parallel plate deflector followed by a spherical section deflector. For selecting particles from high polar (elevation) angle directions, as illustrated in Figure 15a, only the spherical section deflector is used, with no deflection occurring in the parallel plate deflector. To select particles from low polar angles, as in Figure 15b, the hemispherical analyzer is set at a constant deflection voltage, while the voltage of the parallel plate deflector is varied. The polar angle, α , is defined in Figure 16.

The reason two deflector systems are combined for the GTH, rather than using a full hemisphere, is that laboratory tests and ray tracing results have shown that if a full hemisphere is used the angular resolution (as measured by $dV/d\alpha$, where dV is the change in deflection voltage and $d\alpha$ is the resulting change in polar angle) becomes very coarse for polar angles less than about 30° . Figure 15a shows how the angle for 1 keV ions is controlled by varying the deflection voltage on the hemispherical section. In Figure 15b we show how polar angles less than 30° are selected, with good angular resolution, by changing the voltage on the parallel plate deflector while holding the hemispherical section voltage constant. As shown in Figure 15b, good angular resolution is obtained even to polar angles beyond 0° , i.e., the instrument equatorial plane, with the circular parallel plate deflection system.

With the type of analyzer shown in Figure 15, it is necessary to have additional energy filtering because a large matrix of energies and elevation angles can enter the elevation analyzer at different locations along the entrance grid and pass through the analyzer exit. For this reason, the GTH deflector system is fitted onto a second hemispherical-section analyzer for energy analysis. Similarly to the FIMS, shown in Figure 13, these first two stages are referred to for simplicity as the elevation analyzer and the energy analyzer, respectively. Again like the FIMS, a third analyzer, which is referred to as the azimuth analyzer, is added to provide a relatively large annular output aperture which can be segmented to obtain good azimuthal angle resolution. The complete GTH stack is shown in Figure 16, which also shows the computed tracks of two ions passing through the entire system. The azimuth analyzer also provides a nearly parallel output beam, which can then be mass analyzed with high resolution using either a magnetic or a TOF mass analyzer, not shown in Figure 16.

CRAF Non Scanning Platform (NSP) Elevation
Analyzer for Ion Composition Measurements

A recent addition to the SwRI candidate elevation analyzers for flight on the CRAF spacecraft, called CRAF NSP, would not require placement on the low resolution scan platform. Shown schematically in Figure 17, it is composed of three truncated hemispherical analyzer sections in a stack with an additional deflection system on top. The top two truncated hemispheres comprise an energy analyzer which is followed by an azimuth analyzer. The upper elevation analyzer is no longer a hemisphere, but instead is composed of two curved deflector plates with rotational symmetry. The deflectors are enclosed in a grounded toroidal section of screen to isolate the deflection voltages from the spacecraft exterior. A distinct advantage of this geometry is that, like the Beacon geometry, particles entering into the deflector stage from outside pass through the screen almost normally, while with the FIMS and the GTH they pass through almost tangentially so that transmission is substantially reduced by the screen.

The energy analyzer for the CRAF NSP is composed of two near-hemispheres fed by the elevation analyzer. Referring again to Figure 17, ions from the energy analyzer cross over into the azimuth analyzer which separates them again to provide a nearly parallel output beam for mass analysis. In the present example, analyzed ions passed into a magnetic analyzer for mass analysis. Laboratory measurements with a prototype show that this system provides high-resolution separation of singly charged molecular ions of nitrogen and oxygen.

A TOF mass analyzer array like that described by Young et al. (1989) could also be used to mass analyze the ions passing out of the azimuth analyzer, or a combination of TOF analyzers and magnetic analyzers could be used.

Tests and ray tracing results show that the practical polar angle range that the CRAF NSP can cover is about $\pm 45^\circ$ from the instrument equator. This range constitutes more than 70% of the full 4π steradian sphere and may provide sufficient spatial coverage for the CRAF mission.

Summary

The Los Alamos National Laboratory and the Southwest Research Institute are cooperating in a program to develop instruments capable of making three-dimensional measurements of space plasmas without requiring access to a spacecraft scan platform or spinning section. Such instruments could greatly reduce spacecraft requirements, simplify the acquisition of plasma

data on planetary missions, and substantially increase the useful operating time of a plasma experiment. Importantly, the obscuration problem caused by spacecraft appendages such as antennas, RTGs, other instruments, and by the spacecraft itself can be circumvented by placing two 2π sensor heads on opposite sides of the spacecraft.

Five different instrument concepts have been explored. Instruments based on all five of these have the ability to select plasma particles from all pertinent directions in space by using electrostatic deflection techniques. In a continuing joint program these instruments will be investigated and tested further with the goal of developing one or more of them to a state of readiness for an appropriate planetary mission.

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Figure Captions

Fig. 1. The Los Alamos Beacon-C ion composition elevation analyzer, shown in a schematic cross-sectional view.

Fig. 2. Beacon coverage of the hemisphere. 35 keV ions with polar angles extending from $\sim 0^\circ$ to $\sim 78^\circ$ are deflected into the analyzer with voltages extending from 0 to 7000 V.

Fig. 3. Beacon deflection angle vs. voltage. Voltage is applied to one deflector at a time holding the other at 0 V.

Fig. 4. Photograph of the Beacon proof-of-principle test model, with the outer grounded enclosure removed.

Fig. 5. Photographs of the spatial distributions of ions striking the imaging MCP taken at various MCP positions behind Beacon-C with the beam at a polar angle of 44° and deflectors at 0 V.

Fig. 6. Count rate contours taken over the relevant ranges of analyzer voltage and polar angle with both deflectors at 0 V.

Fig. 7. Photographs of the spatial distributions of ions striking the imaging MCP at various spacings with the beam at a polar angle of 16° .

Fig. 8. Count rate contours taken over the relevant ranges of analyzer voltage and polar angle with the outer deflector at 150 V.

Fig. 9. Count rate contours taken with 200 V on the inner deflector, resulting in high polar angle response.

Fig. 10. Polar angle response of Beacon C, measured at SWRI, for the various deflector voltages on the inner and outer deflectors shown above each peak.

Fig. 11. Beacon D configuration for detecting magnetospheric and solar wind electrons. The deflection optics are identical to those of Beacon C.

Fig. 12. Polar angle response of Beacon D, measured for the deflector voltages shown above the response peaks.

Fig. 13. Cross sectional schematic of the FIMS electrostatic analyzer system.

Fig. 14. FIMS polar angle response. The colatitude elevation or polar angle is used in this plot.

Fig. 15. (a) Cross-sectional view of the ion optics of the GTH elevation analyzer. Ions are shown entering from high polar angles through the outer walls of the parallel plate and curved plate deflectors which are made of screen or mesh. (b) Ions shown entering from low polar angles.

Fig. 16. View of the GTH stack, assembled with elevation, energy, and azimuth analyzers. Computed tracks of two ions are shown passing through the entire system.

Fig. 17. Cross-sectional view of the CRAF NSP detector.

Figure 1. The Los Alamos Beacon-C ion composition elevation analyzer, shown in a schematic cross-sectional view.

BEACON DEFLECTION OPTICS AND COMPUTED ION TRACKS

- ANGLE AROUND SYMMETRY AXIS SELECTS AZIMUTH ANGLE
- DEFLECTORS SELECT POLAR ANGLE

Figure 2. Beacon coverage of the hemisphere. 35 keV ions with polar angles extending from $\sim 0^\circ$ to $\sim 78^\circ$ are deflected into the analyzer with voltages extending from 0 V to 7000 V.

Figure 3. Beacon deflection angle vs voltage. Voltage is applied to one deflector at a time holding the other at 0 V.

Figure 4. Photograph of the Beacon proof-of-principle test model, with the outer grounded enclosure removed.

BEACON-C
MCP IMAGES AT VARIOUS MCP POSITIONS
1120eV NITROGEN IONS

Figure 5. Photographs of the spatial distributions of ions striking the imaging MCP taken at various MCP positions behind Beacon-C with the beam at a polar angle of 44° and deflectors at 0 V.

Figure 6. Count rate contours taken over the relevant ranges of analyzer voltage and polar angle with both deflectors at 0 V.

BEACON-C MCP IMAGES AT VARIOUS MCP POSITIONS

1120eV NITROGEN IONS

Figure 7. Photographs of the spatial distributions of ions striking the imaging MCP at various spacings with the beam at a polar angle of 16°.

Figure 9. Count rate contours taken with 200 V on the inner deflector, resulting in high polar angle response.

Figure 10. Polar angle response of Beacon-C, measured at SwRI, for the various deflector voltages on the inner and outer deflectors shown above each peak.

BEACON-D
ELECTRON (AND/OR ION) ELEVATION ANALYZER

- DIVIDED ANODES GIVE AZIMUTHAL ANGLE RESOLUTION
- DEFLECTORS GIVE POLAR ANGLE RESOLUTION

Figure 11. Beacon-D configuration for detecting magnetospheric and solar wind electrons. The deflection optics are identical to those of Beacon C.

Fig. 12. Polar angle response of Beacon-D, measured for the deflector voltages shown above the response peaks.

FIMS ELECTROSTATIC ANALYZER

Fig. 13. Cross-sectional schematic of the FIMS electrostatic analyzer system.

Fig. 14. FIMS polar angle response. The colatitude elevation or polar angle is used in this plot.

Fig. 15. (a) Cross sectional view of the ion optics of the GTU elevation analyzer. Ions are shown entering from high polar angles through the outer walls of the parallel plate and curved plate deflectors which are made of screen or mesh. (b) Ions shown entering from low polar angles.

BOTTOM HEMISPHERE FEEDS INTO AN ARRAY OF TOF UNITS

Fig. 16. View of the GTH stack, assembled with elevation, energy, and azimuth analyzers. Computed tracks of two ions are shown passing through the entire system.

Fig. 17. Cross-sectional view of the CRAF NSP detector.