HIGH-ALTITUDE PLASMA INSTRUMENT FOR DYNAMICS EXPLORER-A

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Abstract. The Dynamics Explorer A High-Altitude Plasma Instrument (HAPI) will make differential measurements of the velocity-space distributions of electrons and positive ions over the energy/charge range of 5 eV to 32 keV. Five identical analyzers, each making simultaneous measurements of electrons and positive ions at 64 possible energy levels, will have viewing angles of 45, 78, 90, 102, and 135° relative to the spacecraft spin axis. The HAPI data will contribute to the overall Dynamics Explorer science objectives, particularly by providing information on the hot-plasma effects of the coupling of energy, mass, and momentum within the earth's atmosphere, ionosphere, and magnetosphere.

1. Introduction

The hot plasma populations of the magnetosphere play a central role in the coupling of energy, mass and momentum within the earth's atmosphere-ionosphere-magnetosphere system. For example, electrical energy is transferred between the magnetosphere and ionosphere by Birkeland currents, which are carried at least partially by hot plasmas in the energy range from a few eV to several tens of keV. Moreover, the direct coupling of energy from the magnetosphere to the ionosphere and atmosphere is dominated by the precipitation of hot plasmas caused by particle acceleration and wave-particle interactions. In addition, upward mass flow from the ionosphere proceeds partly via the acceleration of ionospheric ions and results in their introduction into the hot plasma populations of the magnetosphere.

The hot plasma measurements made by the DE-A High-Altitude Plasma Instrument (HAPI) will contribute to all of the major categories of objectives of Dynamics Explorer (DE)—electric-field-induced convection; magnetosphere-ionosphere electric currents; direct energy coupling; mass coupling; and wave, particle, and plasma interactions. In addition to the mass composition measurements to be made by the Energetic Ion Composition Spectrometer [1], the required hot-plasma data consist of the most complete measurement possible of the velocity-space distributions of electrons and positive ions, made at time and spatial resolutions appropriate to the specific study being conducted. Certain portions of velocity space are of prime importance in studies of ionosphere-magnetosphere coupling. Of particular significance to DE-A are the atmos-

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pheric loss cone and ionospheric source cone which, near the DE-A apogee, will each occupy pitch-angle ranges of less than 6° about the local magnetic field line. In addition to their roles as channels of plasma flow between the ionosphere/atmosphere and magnetosphere, the loss cone and source cone are dynamic regions of velocity space which typically contain strong plasma density and/or temperature gradients. These gradients are potential sources of free energy for plasma instabilities and wave-particle interactions. For these reasons the HAPI instrument was configured as an angular array of five electrostatic analyzers arranged such that pitch angles very near or within the loss cone and source cone will each be sampled by one of the analyzers once per spacecraft spin (every 6 s). In addition, the HAPI spinning detector array will have the capability of determining hot-plasma flow velocities with a sensitivity of ~ 50 km s^{-1}.

2. Objectives

The objectives of the High Altitude Plasma investigation are to contribute to the Dynamics Explorer mission goals by providing high-resolution phase-space measurements of electrons and positive ions over the energy range from 5 eV to 32 keV. These measurements, along with supporting measurements from other instruments on DE-A and DE-B, will primarily address the identification of the charge carriers of Birkeland currents, the nature of auroral particle acceleration mechanisms, substorm effects on high-latitude plasma populations, the transport of plasma through the mid-altitude cusp and into the polar cap, and resonant interactions between hot plasmas and natural and artificially-injected plasma waves and electromagnetic waves.

3. Instrument Description

3.1. Measurement capabilities

The HAPI instrument consists of five electrostatic analyzers mounted in a fan-shaped angular array lying in a plane containing the spacecraft spin axis. A sketch of the five viewing angles with respect to the spin axis is shown in Figure 1. The full width at half maximum response (FWHM) acceptance angles of each analyzer are 2.5° (in the plane of deflection) by 10° (polar angle), while the total acceptance angle is 5 by 20°. Owing to the nominally east-west orientation of the DE-A spin axis, the three analyzers viewing at 0°, + 12°, and − 12° will increase substantially the probability of sampling the loss cone and source cone on any given spin of the spacecraft. The 12° value was chosen to correspond approximately to the angle between the earth's spin and geomagnetic axes. The purpose of the ±45° viewing directions is to provide a measure of hot plasma flow velocities directed along the spin axis.

Simultaneous measurements of electrons and positive ions in the energy/charge range of 5 eV to 32 keV are made by all five analyzers at a sample rate of 64 s^{-1}, with a nominal energy resolution of 32%. Energy stepping proceeds from high energies to low energies with a sample occurring at every 2^n ($n = 0$ to 5) steps out of 64 steps spaced loga-

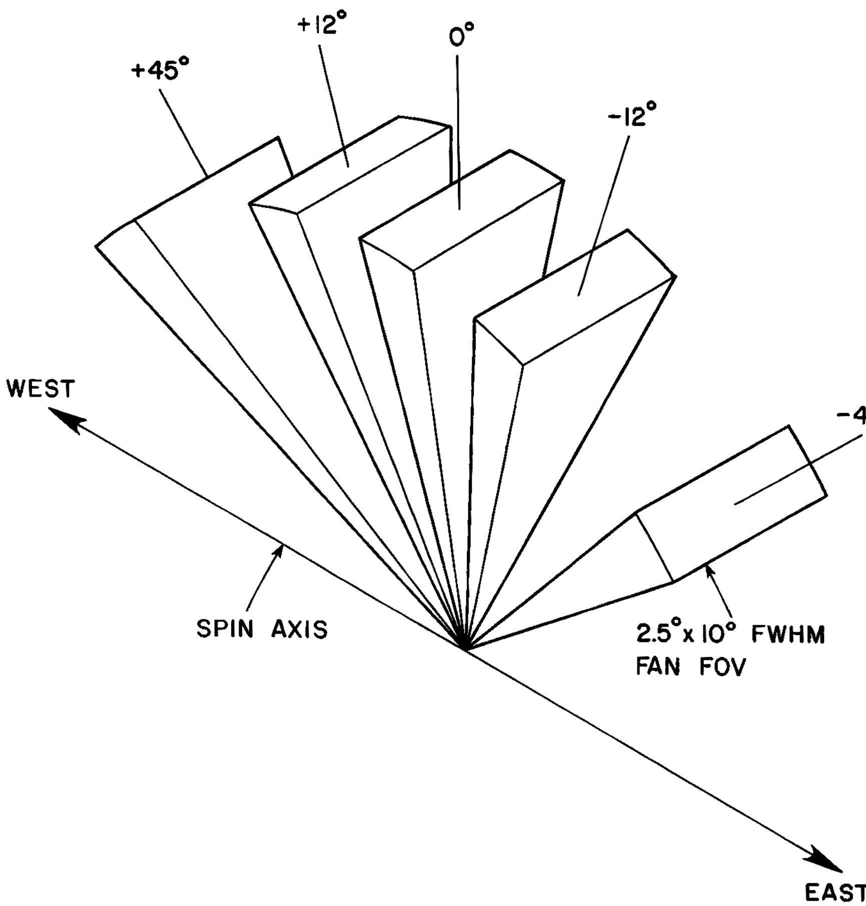

Fig. 1. Viewing angles of the five HAPI electrostatic analyzers.

rithmically over the total range of energies. Start and stop steps are selectable, as is the stepping rate of 2^n steps s^{-1} (n = 0 to 6). In addition, a one energy step per spin mode is available.

3.2. Electrostatic analyzers

The five identical electrostatic analyzers of the HAPI instrument are derived from the parabolic-plate analyzers which were developed for the ISIS 1 and 2 satellites [2]. A photograph of the −45° HAPI analyzer appears in Figure 2. The three-element rectangular collimator sets the 5 × 20° total viewing angle and acts as a baffle for sunlight incident from other angles. The geometric factor of the collimator itself is 3.0×10^{-4} cm^2 ster. The flared parabolic deflection plates ensure that no high energy particles or photons passing through the collimator can find a straight-line path to either plate. Instead, these potentially troublesome sources of background counts will enter the nearly totally absorbing light trap (see Figure 2). The light trap itself, which is designed

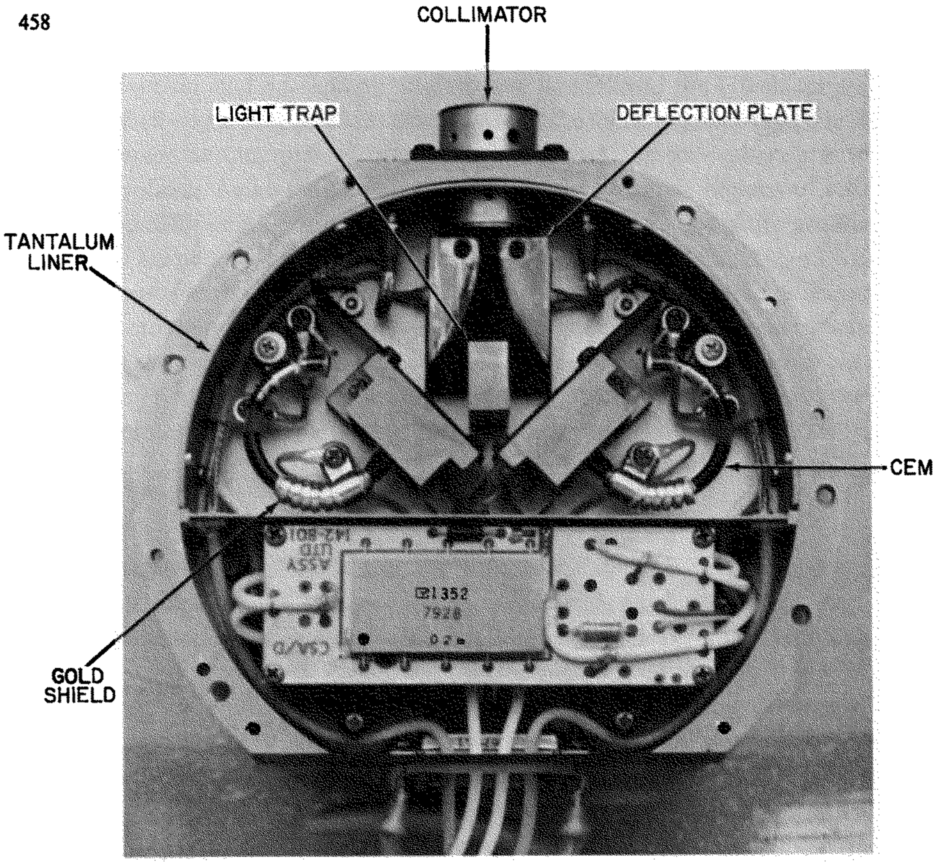

Fig. 2. Photograph of the HAPI −45° detector module.

to reflect photons into a curved funnel, is gold-plated. Other internal parts of the analyzer are gold-blackened to reduce scattering of ultraviolet light to minimum levels.

To reduce fringing-field effects, balanced deflection potentials are used, with equal positive and negative deflection voltages over the range from ±2500 down to ±0.33 V. Each voltage step is nominally 15.5% higher than the next lower step. In addition, a final step of 0 V is available for background measurements. The parabolic shape of the deflection plates allows electrons and positive ions to be detected with a single analyzer. For these analyzers the center energy in eV is approximately equal to 6.3 times the total deflection voltage. After deflection, the particles approach exit slits whose width determines the energy resolution of the analyzer (the five HAPI analyzers have $\Delta E/E$ in the range of 0.32 ± 0.02). The exit slits are covered with a 71%-transmission screen mesh which isolates the channel electron multipliers, and the potentials applied to them, from the deflection volume. Except for the attenuation caused by this screen mesh the transmission factor of the deflection system is very nearly unity over the 32% energy pass band. Therefore, each analyzer has a maximum physical geometric factor (not including particle counting efficiency) of 2.13×10^{-4} cm^2 ster.

Galileo 4800-series high-current channel electron multipliers (CEM's) with 6×20 mm input apertures are used for electron and positive-ion detection (see Figure 2). An operating potential of 2400 V, yielding gains of $\sim 10^8$, was chosen for initial operation. This voltage can be increased to 2700 V by ground command if required for a CEM gain increase. Post-acceleration potentials of +200 V for electrons and −2400 V for positive ions are applied between the analyzer exit slits and the CEM entrance apertures to increase counting efficiency for low-energy particles. Electron and positive-ion counting efficiency measurements now being made on prototype CEM's are generally consistent with previously published data on the older type CEM's. Output pulse rates from the CEM's and their thick-film hybrid charge amplifiers are equal to the input rates up to $\sim 2 \times 10^6\ s^{-1}$ and are correctable to true input counts up to a maximum output rate of $\sim 6 \times 10^6\ s^{-1}$, corresponding to input rates of $> 10^7\ s^{-1}$.

3.3. System description

A block diagram of the HAPI instrument system is shown in Figure 3. Separate power on/off commands control the low-voltage power supply (LVPS), the CEM high-voltage power supply (HVPS), and the deflection-plate program power supply (PPS). Instrument modes, including the PPS stepping sequence, the HVPS level, and the analyzer readout scheme, are controlled by two 32-bit minor-mode commands [3]. The minor-mode commands are retained when the main instrument power is off by a keep-alive voltage provided by the spacecraft.

Output pulses from the charge amplifiers for the electron and positive-ion channels of each analyzer are processed by a hybridized dual data processor. For each channel the output pulses are accumulated in an 18-bit register over a fixed accumulation interval of 12.7 ms. The contents of the 18-bit register are then compressed to an 8-bit word which gives the total counts for the 12.7 ms interval, N, as follows:

$$N = [(D + 16)\,2^{S-2}] + 2^{S-3}, \qquad \text{for} \qquad S > 0;$$
$$N = D/2, \qquad \text{for } S = 0; \tag{1}$$

where D and S are the least significant and most significant 4 bits respectively.

In each one-quarter minor frame of spacecraft telemetry any eight of the ten HAPI electron and positive-ion data channels plus a digital word indicating the PPS level are read out. During the PPS transition from the lowest commanded step back to the highest (or starting) step the data words in the quarter frame contain identification of the data channels assigned to them instead of the actual counting rates.

The four-second and eight-second subcom words which are available in the DE-A telemetry format [3] are used quite extensively in the HAPI instrument to measure various low-voltage and high-voltage levels, temperatures, and currents within the total system. The particular quantities being measured, and the measurement ranges, are controlled by the HAPI minor-mode commands.

3.4. Radiation shielding

The fluxes of penetrating high-energy electrons and protons are high enough along portions of the DE-A orbit that special precautions were required to prevent damage to CMOS and other sensitive electronic components and to avoid an unacceptably high

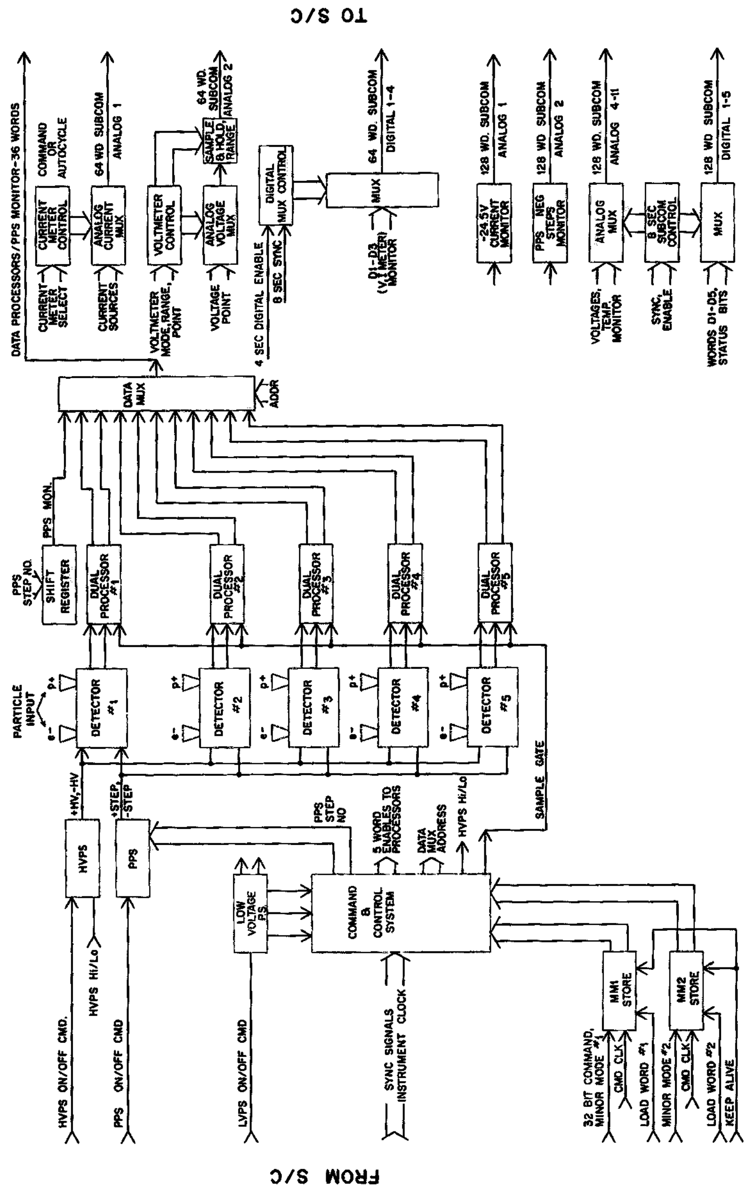

Fig. 3. Block diagram of the HAPI electronics system.

background counting level. A general philosophy of using outer layers of low-density material (aluminum and magnesium) for charged-particle absorption plus inner layers of high-density material (tantalum and gold) for bremsstrahlung X-ray absorption was employed in the sensitive HAPI subsystems. Visible in Figure 2 are the 1 mm thick tantalum liners in the electrostatic analyzer housings and the 1 mm thick gold foil which is wrapped around each CEM body for the first one-third of its length. The minimum shielding in any direction from the CEM apertures and any CMOS circuitry amounts to greater than 18 mm equivalent thickness of aluminum. The additional shielding provided by adjacent HAPI subsystem housings, and the spacecraft itself, all add to this minimum shield thickness.

3.4.1. *Operational modes*

As noted in the preceding section, a fixed data accumulation period of 12.7 ms is used, while a choice of eight of the ten analyzers to be read out in any one-quarter minor frame must be made. Another important constraint on possible data-acquisition plans is the fixed DE-A spin rate of ~ 10 rpm. With the above limitations in mind, it is evident that the PPS stepping sequence primarily determines the major operational modes of the HAPI instrument. Since the maximum stepping rate of the HAPI PPS is 64 steps s^{-1}, each HAPI analyzer can acquire electron and positive-ion data at 384 energy/spin-angle combinations during each spin of the spacecraft, with successive measurements occurring at 0.93° increments of spin angle. Normally, operational modes will be selected to emphasize either high angular resolution or high temporal (and spatial) resolution.

3.5. High angular resolution mode

In the High Angular Resolution (HAR) mode, the PPS is stepped each time a nadir pulse is received from the spacecraft. That is, a single energy is sampled every 0.93° for an entire spacecraft spin period. As noted in the previous section, any of the 64 HAPI energy steps can be chosen as start and stop steps, with every 2^n (n = 0 to 5) steps sampled between these two limits. This mode will be used primarily near apogee for studies of the loss-cone effects of wave-particle interactions (including the Siple wave-injection experiments) and for detection of ion beams produced by the upward acceleration of ionospheric ions.

3.6. High temporal resolution mode

In the High Temporal Resolution (HTR) mode, multiple energy spectra will be acquired during each spacecraft spin. Typically 24 16-point energy spectra, each covering 15° of spacecraft spin will be measured during each spin period. An increase to 32 energy steps, covering the full energy range of the instrument, will decrease the angular resolution to 30° of spacecraft spin.

4. Calibration

The individual HAPI analyzers were calibrated separately using laboratory high-voltage supplies in place of the HVPS and PPS. The calibration was carried out jointly with the calibration of the Low Altitude Plasma Instrument (LAPI) analyzers [4]. The detailed description of the LAPI calibration technique which appears in reference [4] applies equally to HAPI. Briefly, an omnidirectional mono-energetic electron flux was simulated by rotating each analyzer about two perpendicular axes passing through the collimator entrance slit. The procedure yielded the angular response in the planes both parallel and perpendicular to the plane of electrostatic deflection.

The entrance slit was positioned on the central axis of an electron beam with intensity uniform to better than 1% across its 2 cm diam. The electron beam was produced by single-step acceleration of photo-electrons emitted from a 400 Å thick gold cathode deposited on a quartz UV window. With this arrangement it is possible to keep the UV lamp outside the vacuum enclosure, and to avoid almost entirely any background contamination due to UV photons. The energy-angle responses of the five HAPI analyzers were found to be essentially identical. This property will greatly facilitate intercomparison of data from the various analyzers. As noted in the Instrument Description section, the calibration procedure confirmed the $2.5 \times 10°$ FWHM angular response, the $32 \pm 2\%$ energy pass band, and the 6.3 eV/ΔV deflection constant of the five analyzers.

5. Data Formats and Analysis

The basic element of information provided by the HAPI instrument is total accumulated counts in a 12.7 ms period for one of 64 possible energy steps. When combined with spacecraft orbit/attitude data, magnetic-field data from the DE-A magnetometer, and the known properties of the analyzers themselves, this information can be converted through relatively simple algorithms to the velocity-space distributions of electrons and positive ions. There exist numerous graphical means of displaying these data for comparison with other measurements and with theories or models of the particular phenomena being studied. In the case of the DE-A summary plots [5], the HAPI data will be displayed as grey-scale spectrograms of electron and ion energy flux for pitch angles near 90° plotted versus energy and time for a one-hour interval. In addition, line plots of total electron and ion particle fluxes at pitch angles near 0° will be displayed on the same time scale.

The next step in the processing of HAPI data, as with the other DE instruments, will be the generation of mission analysis files [5] and graphical data plots such as energy-time spectrograms for selected time intervals; sequences of particle energy spectra, pitch-angle distributions, and velocity-space densities versus energy or velocity; and two-dimensional contour plots of velocity-space density in selected planes of velocity space. These plotting formats will be available to all DE investigators through their interactive graphics terminals.

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References

1. Shelley, E. G., Simpson, D. A., Sanders, T. C., Hertzberg, E., Balsiger, H., and Ghielmetti, A.: *Space Science Instrument.* **5**, 443 (1981) (this issue).
2. Heikkila, W. J., Smith, J. B., Tarstrup, J., and Winningham, J. D.: *Rev. Sci Instr.* **41**, 1391 (1970).
3. Hoffman, R. A., Hogan, G. D., and Maehl, R. C.: *Space Science Instrument.* **5**, 349 (1981) (this issue).
4. Winningham, J. D., Burch, J. L., Eaker, N., Blevins, V. A., Hoffman, R. A.: *Space Science Instrument.* **5**, 465 (1981) (this issue).
5. Smith, Paul H., Freeman, Clyde H., and Hoffman, R. A.: *Space Science Instrument.* **5**, 561 (1981) (this issue).