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The Giotto Ion Mass Spectrometer

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Abstract

A wide range of ion species and velocity distributions are expected to be found as the Giotto spacecraft traverses the coma of Halley’s Comet. The outer coma is characterized by the interaction between solar wind and cometary plasmas, the inner coma by the outflow of cometary neutrals and their ionization products. The resultant demands on instrument dynamic range preclude use of a single sensor for measurements of ion composition. The Giotto Ion Mass Spectrometer (IMS) therefore consists of two sensors: one optimized for the outer and the other for the inner coma, with each obtaining complementary information in the region for which it is not optimized. Both sensors feature mass imaging characteristics, thereby permitting simultaneous measurements of several ion species by means of multi-detector arrays.

Resultant mass-per-charge resolution is >= 20. In addition to mass per charge, the energy per charge, the elevation and azimuth of incident ions are measured. Calibration and in-flight solar-wind data show that the IMS will meet its scientific goals for the Halley encounter.

1. Introduction

The interaction of a comet with the solar wind is fundamentally very complex and dynamic. Cometary material first makes its presence felt in the solar wind in the form of neutral gas photo-ionized and accelerated by the solar wind far upstream from the comet nucleus at distances > 10**6 km. Although their density is initially very low, these ’pick-up’ ions (e.g. H+, C+, O+, OH+, CO+, H20+) mass load the solar wind and begin slowing it. Nearer the comet a bow shock may form, but this is not certain. The solar-wind slowing process may also create a broad region of plasma turbulence as picked-up ions are thermalized and incorporated in the flow of solar wind around the comet. Implantation of cometary ions in the solar wind has the further consequence that the solar wind interaction with cometary material occurs far outside the contact surface that is expected at ~ 10**4 km from the nucleus (Ip, 1980). Once the contact surface is crossed the spacecraft is immersed in cold, low-velocity (~ 1 km/s) outflowing cometary ions. The region inside the contact surface, often called the 'inner coma', contains relatively high ion densities, and perhaps magnetic fields, which stand off the solar-wind ram pressure. Within the inner coma, at the latest, neutral gas and dust particles impinging on Giotto will create a plasma cloud around the spacecraft, giving rise to electrical charging and creating spurious ions (and electrons) detectable onboard by the Ion Mass Spectrometer (IMS). In this region some interference with the ion measurements is expected.

This thumbnail sketch of the flyby through Halley's coma illustrates the two primary science objectives of the Giotto IMS:

1. To measure accurately the relative abundances of both solar and cometary ions in the cometary coma, and
2. To determine ion velocity distributions as a function of position within the coma.

The design principles of one part of the IMS (the HERS, see below) have been described by Neugebauer et al. (1982). The complete IMS as adapted to the Giotto mission was discussed by Balsiger et al. (1981). The present paper documents the final instrument design as well as the successful implementation, calibration, and initial flight testing of the IMS sensors.

2. Approach

The ion composition of the outer coma is dependent upon details of the interaction of solar wind and cometary plasmas. In order to determine composition, we must obtain good measurements of the three-dimensional velocity distribution of individual ion species. From the latter we determine species flow velocities (speed and direction), temperatures, and number densities. Ion composition and velocity distributions are expected to be strong functions of radial distance from the nucleus (Fig. 1). Moreover, recent results from the electron plasma analyzer onboard the International Cometary Explorer (ICE) during its intercept of Comet Giacobini-Zinner indicate sharp variations in bulk plasma flow speed, density, and electron temperature (Bame et al., 1985).

Figure 1. Model of ion distribution along comet-Sun line in the coma of Halley. In this model the bow shock is at 4 x 10**5 km (Ip, 1980)

Based on the above discussion, an ion mass spectrometer suitable for high-speed flyby of Halley's comet near 1 AU must cover a wide range in particle phase space. At the time the Giotto instruments were designed, little was known about the cometary plasma environment. Today, following the successful ICE flyby of Comet Giacobini-Zinner, the impression remains that wide instrument response in angle, energy and ion mass will be needed for the Halley flyby. No single present-day ion instrument is able to cover this wide range of plasma properties while still providing the necessary mass resolution. We have therefore designed two different sensors specialized for measurements in these regions. The sensor for the outer coma is called 'HERS' (High-Energy Range Spectrometer) and the one for the inner coma 'HIS' (High Intensity Spectrometer). Their characteristics are summarized in Table 1.

Although energy and angular distributions are important parameters (and hence will be measured) the emphasis of IMS lies on an accurate determination of ion composition. Since not only chemical and elemental, but also isotopic, abundances are of high cosmogonic interest, good mass separation is required. Furthermore, mass analysis must be performed in such a way that prior knowledge of the ion velocity distribution is not assumed. Hence both components of the IMS are true mass analyzers using variable electric fields and static magnetic fields for determining energy per charge (E/Q) and mass per charge (M/Q), respectively. (In this paper M is ion mass in amu. Q is the ion charge state, and E is energy in eV). Both sensors have M/Q imaging capabilities that increase sensitivity and, because several ion species are detected simultaneously, increase the time resolution as well.

Despite these similarities, the two sensors are different in many details (see next section), which leads to quite different properties. The range of energy and angle covered by HERS is large, although as one sacrifice in the tradeoff study the cometary direction could not be included in the field of view (Fig. 2). On the other hand, HIS has a more limited field of view, but concentrates on the cold cometary ions incident from the forward direction (Fig. 2). Both will be operated throughout the encounter measurement period. In the outer coma, two-thirds of the available data rate will be dedicated to HERS, one third to HIS. These ratios are reversed in the inner coma using a time-tagged command from the ground.

Because of the hazard of gas and dust impact that might lead to physical damage or a large background ion flux, neither sensor will view directly into the Giotto-Halley relative velocity vector (the ram direction). Protection of the sensors is achieved by mounting them within the spacecraft body and projecting their fields of view into the desired directions using electrostatic deflection devices.

Table 1. Summary of IMS chamcteristics

Parameter	HERS	HIS
E/Q range	10 eV/e to 2.0 - 4.5 keV/e depending on M/Q	300 to 1400 eV/e
M/Q range	1 to 35 amu/e in 4 groups	12 to 57 amu/e
M/Q resolution (M/delta M)	>= 20 at 20 amu/e	>= 20 at 20 amu/e
Elevation angle range	+15deg to +75deg	-3deg to +12deg (MA) -3deg to +22deg (AA)
Elevation angle resolution	7.5deg (15deg for H+)	5deg to 7.5deg
Azimuth angle range	360deg (spin-scanned)	30deg (spin-scanned)
Azimuth angle resolution	5.6deg	22.5deg
Spectral time resolution	16 s	4 s
Density range	10**-3 to 10**2 cm**-3	10**-2 to 10**4 cm**-3
Weight	9.2 kg	
Average power	8.5 W	
Telemetry, total	3253 bit/s	
Telemetry		
Outside contact surface	2169 bit/s	1084 bit/s
Inside contact surface	1084 bit/s	2169 bit/s

Figure 2. IMS angular coverage and fields of view for the HERS and HIS sensors. The more limited field of view of the HIS MA is shown shaded. The -z direction refers to the Giotto spin axis, which is directed towards the comet nucleus

3. Instrument Description

In order to simplify hardware interfaces, HERS and HIS were built as separate units, called IMS-1 and IMS-2, respectively. The interface to the spacecraft is provided by IMS-3, which includes low-voltage power converters and the common data-processing unit, whereas the high-voltage converters, preamplifiers, signal conditioning and test electronics are located directly in the IMS-1 and IMS-2 units. Figure 3 shows the principles of the IMS electronics, and Figure 4 shows the three IMS boxes laid out as on the spacecraft platform.

3.1 Sensor for the outer coma (HERS, IMS-1)

3.1.1 Objectives

The prime objective of the High-Energy Range Spectrometer is to measure the ion abundances and three-dimensional velociry distributions outside the cometary contact surface. The HERS sensor is designed to provide the mass resolution necessary to resolve the important cometary ion species over a wide range of temperatures and flow velocities within a field of view lying between 15deg and 75deg from the comet ram direction (including the solar wind direction, Fig. 2).

3.1.2 Main sensor components

The basic concept of the HERS sensor has been described previously by Neugebauer et al. (1981) and Balsiger et al. (1980). Referring to the schematic drawing of HERS in Figure 5, the main components of the sensor consist of (i) a curved electrostatic mirror, (ii) cylindrical accelerating/decelerating grids, (iii) a magnetic analyzer, (iv) an electrostatic deflector and (v) ion detectors. The electrostatic mirror compresses a 60deg external field of view to 30deg internal to the sensor with nearly uniform angular magnification over the full range. The mirror consists of a pair of nonconcentric, cylindrical, gold-plated high-transmission grids, the front one of which is maintained at ground potential, while the rear one is held at a potential positive enough to reflect the ions of interest in that portion of the measurement cycle (the cycling programme is described below.)

A photograph of the HERS instrument with the outer cover removed is shown in Figure 6.

3.1.3 The magnet

Two 3.60 mm high by 1.26 mm wide slits located symmetrically on either end of the 120deg sector magnet provide a constant normal-component-of-momentum filter over +/- 15deg angular acceptance in the plane of the magnet (Fig. 5). The samarium-cobalt magnet has a pole gap of 5 mm and a magnetic field strength of 0.335 T (uniform to 0.5% over the usable portion of the gap). The constant momentum per charge corresponds to an ion energy per charge of 7560/(M/Q) eV/e. The internal angular acceptance of the instrument out of the magnet plane (spacecraft azimuth) is an average of 2deg FWHM. This is determined by the slit height and separation and by the amount of vertical focussing in the magnetic fringing field. The external angular acceptance depends, of course, on the acceleration/deceleration voltage.

Figure 3. Block diagram of the IMS

Figure 4. The IMS boxes laid out as on the spacecraft platform, with (from right to left) IMS-1 (H

Figure 5. Cutaway view of the HERS sensor showing principles of operation

Figure 6. The HERS sensor with cover removed (for description see Fig. 5)

3.1.4 The electrostatic deflector (ESD)

The electrostatic deflector serves as an energy-per-charge analyzer, and since the normal momentum has been fixed by the magnet, it becomes a mass-per-charge analyzer. The electric field in the analyzer deflects ions out of the optical plane of the magnet towards the detectors. The ESD field is nonuniform in such a way that all ions of a given M/Q are focussed in the detector plane. The focal line for ions of different elevation is very nearly straight, and the position along this line maps out the angle that ion trajectories make at the entrance to the magnet slit S1 (Fig. 5). The higher the M/Q of the ion, the nearer to the ESD entrance slit S2 this line lies.

In Figure 6 the ESD is seen to the rear of the magnet. The structure on the topmost face supports some of the signal-processing electronics for the detectors. The microchannel plate (MCP) detector is hidden by this structure, but the four channel electron multipliers (CEMs) are visible at the rear top corner.

The nonuniform, approximately two-dimensional electric field is generated by applying voltages to a set of vane-like electrodes arranged appropriately in the analyzer. Figure 7 shows a cross section of the ESD, including the results of computer simulation of ion trajectories. The ESD entrance slit S2 is at the lower right corner with the vanes shown in projection. Voltages are applied to the vanes by taps on a resistive divider between two supply voltages. For the case shown, +4667 and -667 volts are used to bring ’light’ ions of M/Q = 2 to 4 onto the main detector area. The main detector, an MCP, allows two-dimensional imaging, and will be discussed in more detail below. Protons are focussed by the same voltages onto a separate set of CEMs. By switching to other voltage combinations, other mass ranges can be detected on the MCP. Since the ion energy entering the analyzer is inversely proportional to M/Q, higher mass ranges are detected with lower voltages on the analyzer. (The corresponding voltages are +770 V and -110 V for ’medium’ ions defined as M/Q=12-26, and +576 V and -82 V for ’heavy’ ions with M/Q=16-35.)

Figure 7. Cross-section of the HERS electrostatic deflector. Envelopes of ion trajectories are shown for the light ion range (M/Q=2 to 4 amu/e). Vanes behind slit S2 act as a particle trap (note trajectories for M/Q=12 amu/e)

For the case shown in Figure 7, all ions with M/Q>4 are deflected onto the region in front of the MCP. In order to minimize the effects of scattering, the vanes in this region are arranged to act as a particle trap (see M/Q= 12 in Fig. 7). Similarly, when heavy ions are being detected, the light ions pass nearly straight through the ESD and are trapped by the vane arrangement at the end opposite the entrance slit. The vanes in this far region are electrically split, with potentials arranged such that the electric field near the vanes retards the escape of low-energy secondary ions.

3. 1.5 Detectors

Only protons are detected on the CEMs at the appropriate voltage combination mentioned above. These separate detectors for the protons are used to avoid unreasonably high voltages necessary to deflect them onto the MCP, and because anticipated proton count rates are more easily accommodated with a CEM. A line of four 5x 12.8 mm funnel-type CEMs is used. Each covers an external elevation angle range of 15deg. Any loss of detector gain during flight is measured by test routines (see below) and can be corrected by selecting one of four high-voltage bias levels. We presently operate the CEMs at -2450 V with discriminators in the output pulse circuits fixed at a threshold of 0.1 pC.

All heavy ions (M/Q> 1) are detected on the 50 mm diameter (45 mm diameter sensitive area) curved-channel MCP, in each of three mass ranges set by the ESD voltages given above. As for the CEMs, the MCP high voltage is selected in flight from one of four levels. It is currently set at -1650 V.

In order to obtain simultaneous two-dimensional information (one dimension for mass and one for elevation angle), the MCP is equipped with two orthogonal sets of pickup anodes (Liptak et al., 1984). These produce electrical signals that allow a unique determination of the location of an event on the MCP. Figure 8 shows a photograph of the angle-sensing anodes deposited directly on the output surface of the MCP. Each of these eight anodes covers an external elevation angle of 7.5deg. The second set or mass-sensing anodes, consists of 40 gold-plated strips deposited on the face of a high-purity alumina plate. A photograph of the mass anode plate is shown in Figure 9. This plate is located parallel to and 0. l mm removed from the output face of the MCP. It is held 50 V positive relative to the MCP to attract the pulse of secondary electrons emitted by the latter. Thus, when an ion strikes the input side of the MCP, a positive pulse is produced on one of the eight angle anodes and a negative

Figure 8. The angle-sensing anodes deposited on the back of the HERS MCP detector

pulse on one of the 40 mass anodes. One of eight logarithmically spaced threshold levels is selectable separately for the discriminator of each type of pulse (i.e. mass or angle). We presently use 0.024 pC for the mass threshold and 0.012 pC for the angle.

For an ion to be registered by the encoding electronics, it is a prerequisite that it produces a charge pulse above the mass discriminator threshold. A coincidence (within 1 micro s) between both mass and angle pulses is required to produce a ’good’ event initiated by the arrival of an ion at the MCP. In such a case the event is defined by its location (angle anode and mass anode numbers) and a flag to indicate that a good event occurred. If the angle pulse is missing, or if more than one of either or both pulses occur within the allotted time window, the event is not discarded, but rather a 3 bit flag is used to indicate the pulse combination produced. Analysis of flagged versus unflagged events provides a quantitative assessment of the overall efficiency of the MCP system.

3.1.6 Acceleration/deceleration system

Since the magnet is a momentum/charge filter, only a very narrow range of energies +/- 3% on average) for each M/Q is passed by the system. In order for the magnet to transmit a wider energy range, the acceleration/deceleration system accelerates or decelerates ions to a momentum range that the magnet will accept. This voltage is applied between the middle and innermost grids shown in Figure 5. (The outermost grid is at + 10 V to exclude spurious impact-produced low-energy ions from the system.) All parts of the optics downstream of the inner grid float at the accelerating potential. This floating ’platform’ can be seen in the centre of Figure 6, supporting the electrostatic deflector, magnet, and the innermost accelerating grid assembly. Several of the required high voltages must be generated at this floating level. Power is supplied through an isolation transformer, while data and telecommands are transmitted by means of opto-couplers.

Figure 9. The mass-sensing anodes for the HERS MCP detector. Forty gold-plated strips are deposited on a high-purity alumina plate which is mounted behind the MCP (see Fig. 7)

The accelerating potential is swept in a triangular waveiorm, relative to a selectable central voltage at a frequency of 8 Hz. This gives 32 complete cycles per 4 s spin period. The amplitude (peak-to-peak) is fixed at 4.35 kV, while the central value depends on which of the four mass ranges is being measured. The resultant voltage sweep ranges are -7932 V to -3580 V for protons, -3967 V to +385 V for light ions, -662 V to +3690 V for medium ions, and -500 V to +3852 V for heavy ions. Because the sweep is phase-locked to the spin period, two sweep phases, 5.6deg apart, are used in alternating measurement cycles. This avoids always measuring a given energy at the same set of azimuth angles. One waveform ramp is divided into 64 bins, spaced quasi-logarithmically to give roughly constant energy resolution (Delta E/E) over the full range. The energy bin number is telemetered as part of the address of each ion event detected.

The mirror voltage is swept synchronously with the accelerating voltage in such a way that its value approximately tracks the energy of the ions being measured.

3.1.7 HERS measurement modes

During each 4 s spin period, 64 complete energy scans are performed in one of the four mass ranges mentioned above. This yields one energy sweep for each of the 64 azimuth bins of 5.6deg for all ions within the selected mass range. (In two consecutive azimuth bins the sweep voltage runs up and down, respectively.) The basic HERS mode, used when HERS has priority in telemetry allocation, consists of four spin periods. (The HIS mode, used when HIS has priority, has eight spin periods.) These modes, selectable by telecommand, determine the mix of mass ranges in one instrument cycle. Modes include: l. protons only, 2. alternating protons and light ions only, 3. no protons (light, medium, heavy, medium), and 4. all masses (protons, medium, heavy, light). Mode 2 typically would be selected for measuring solar wind during cruise phase, while mode 4 is intended for encounter. Modes 1 and 3 have been included in case a detector deteriorates.

During cruise and passage through the outer coma, when HERS has priority, data are telemetered for each spin. In the inner coma, when HIS has priority, each mass range is held for two spins and telemetry is adjusted accordingly. Each ion event causes a 24 bit word to be formed containing the MCP elevation angle and mass anode numbers, the pulse coincidence flags, the energy and azimuth bin numbers during which the event occurred, and whether the voltage was sweeping up or down. Events are then placed chronologically into the telemetry queue. In the case of protons, a 24 bit word is also used, but instead of MCP location the total number of counts per energy bin for each CEM (along with the energy and azimuth information) enters the telemetry stream. A result of zero counts per bin is not transmitted. At very high count rates a data-compression scheme goes into effect to fit the measurements into the available telemetry rate.

3.2 Sensor for the inner coma (HIS, IMS-2)

3.2.1 Objectives

The High Intensity Spectrometer (HIS) is designed to complement HERS in the inner coma where we expect cometary ions at high densities, low temperatures, and with low bulk speeds relative to the nucleus. The composition of these ions will be determined between 12 and 57 amu per charge. Their velocity distributions will be measured in a limited range around the Giotto-Halley relative velocity of 69 km/s, both with respect to absolute speed and the angles of incidence. These data will be used to obtain the composition of the volatile fraction of the nucleus and ultimately the chemistry and dynamics of the inner coma.

3.2.2 Main sensor characteristics

The HIS contains two separate analyzers (Figs. 10 and 11), the Mass Analyzer (MA) and the Angle Analyzer (AA). The MA uses a combination of electrostatic and magnetic deflection systems designed to give good separation between adjacent masses near H2O+ (M/Q= 16-20). Its intrinsic field of view is 2deg X 15deg, including the direction of the spin axis (Fig. 2). Due to Giotto’s spin, the resulting field of view is conical, with a half angle of 12deg and slight overlap at the centre.

Figure 10. Schematic of the HIS sensor

Figure 11. The HIS sensor with cover removed
(for description refer to Fig. 10)

The AA is an electrostatic quadrispherical analyzer. Five miniature CEM detectors at its exit allow for a resolution of 5deg to 7.5deg within the fan-like field of view of 2deg X 25deg total width. Here the resulting conical field of view has a half angle of 22deg (Fig. 2). This viewing fan contains five elevation-angle ranges, which are split up electronically into 16 azimuthal segments each. For five major ion species, the angular velocity distribution around the ram direction can be inferred (see 3.2.5), which is important for interpreting the MA’s results.

Both HIS sensors are mounted in such a way that their viewing directions are nearly identical. Their measurement programmes are stepped in parallel and in part they use common supply voltages. An external electrostatic plane-plate deflector bends the ion trajectories out of the dust particle path and into the shadow behind the spacecraft dust shield, where the main part of the IMS is located.

3.2.3 The Mass Analyser (MA)

The basic principle of this mass spectrometer can best be understood with reference to the classical optical analogy sketched in Figure 12. The entrance slit S1 is located in the focal plane of the first convex lens L1 and a parallel beam of light leaves L1. A prism provides dispersion, while the lens L2 focusses the image of S1 onto the

Figure 12. Optical principle of the HIS sensor:
(a) classical optical analogue,
(b) ion optics of the HIS

image plane P, forming a spectrum of the source. In the MA the role of the lens L1 is played by the quadri-spherical analyzer L1: it transforms an incoming divergent particle beam into a parallel beam. Of course, only those particles with the appropriate energy per charge given by the applied voltage (0 to -200 V on the inner plate) are transmitted. The permanent magnet (0.19 T) acts like a prism, with dispersion depending on the particles' momentum per charge. Lens L2 (+/- 66 to +/- 333 V) images S1 onto the plane P, providing a momentum-per-charge spectrum there. At a certain position on P we will find particles with both identical energy per charge and momentum per charge, and thus with identical mass per charge. The spectrum formed in plane P is therefore interpreted as an M/Q spectrum. Computer modelling was used to optimize the optical system described above, details of which will be published separately.

If a given detector on the image plane is to be dedicated to a specific M/Q value, the principle of the HIS as explained so far would not allow any scanning of the E/Q range of incident ions. Ions are constrained to arrive at the detector with a fixed E/Q value given by the magnet field strength and its length, and by the position of the detector. In order to scan the E/Q distribution of incoming ions, the entire section of the instrument beyond L1 must be biased (Fig. 3) such that

$$U(1) - U(\text{bias}) = U(\text{const.})$$

where U(1), denotes the central energy per charge of ions transmitted by the first electrostatic analyzer L1, U(bias) (-1400 to +1050 V) is the voltage applied to float the rest of the analyzer, and U(const.) is the energy per charge the ion of appropriate M/Q must have in order to hit the desired detector.

One of the main boundary conditions for designing the MA sensor was the goal of optimum mass separation in the water ion group. Therefore, separate dedicated detectors for ion species 16-21 were placed in the image plane. At the positions of the virtual masses 17.5, 18.5, and 19.5, additional detectors were installed in order to monitor possible interferences between neighbouring masses.

For some of the ion species, e.g. H_2O^+, count rates in excess of 1×10^{6} s^{-1} are expected on detector areas as small as 2 mm^{2}. This prevents the use of MCPs and rather suggests the use of CEMs. The distance between images of adjacent mass numbers in the water-ion group is only 1.2 mm, however, and intermediate detectors are needed for masses 17.5, etc. These small spacings therefore required development of a special CEM-based miniature detector system.

Central to this miniature detector system is a prism-shaped activated lead-glass block (made of material similar to MCPs and CEMs) with gold-plated surfaces where high conductivity is required (Fig. 10). The block's front surface, which lies in the image plane, has nine rectangular holes roughly 0.6x2.0 mm, the bottoms of which are connected by a 0.4 mm diameter straight channel to the back side of the prism. The channels are drilled at different angles such that their exits are spread over a larger area than the entrances in the image plane. Funnels of specially fabricated CEMs are directly attached to the block's exits using conductive epoxy. Both the front and back surfaces of the glass prism are gold-plated. A voltage of 700 V applied between then, lets the activated channels act as preamplifiers for the ions hitting holes in the image plane. Because the completed detector array is reminiscent of a hedgehog, it is referred to as an 'Igel', which is the German name for this animal. For the CEMs four different HV levels between 2.5 kV and 3.4 kV can be selected by telecommand.

3.2.4 The Angle Analyser (AA)

The main purpose of the AA is to extend the MA's angular field of view and to allow for some resolution in elevation. This capability of the AA is important for interpretation of MA data in the case of high ion temperatures or of some ion bulk motion relative to the nucleus. Thus, to some extent, the AA bridges the gap in angle and energy coverage between the HIS and the HERS.

The AA is equipped with a detector system consisting of five CEMs (operated at one of four selectable HV levels between 2.5 kV and 3.1 kV) and appropriate amplifiers capable of handling count rates in excess of 2x10**6 s**-1. The CEMs are not hit directly by the transmitted ions but rather by secondary electrons produced on aluminium dynodes. The quadrispherical AA plates have the same R/deltaR values as the lens L1 in the MA and thus are connected to the same voltage supply.

3.2.5 HIS measurement modes

The basic HIS program consists of a 64-step energy scan repeated 16 times per spin period. During each scan, voltages for deflection, acceleration/deceleration and on the lenses Ll and L2 are swept in a rather complicated way depending on the measurement mode. The actual step values of the sweeps are stored in a PROM in IMS-3. Per spin, the 14 CEMs yield a total of l4 366 individual count rates. The 14 366x16-bit words are reduced by onboard compression to an array of 1004 8-bit words. Compression is achieved by: (i) summation of related count rates, (ii) omission of insignificant channels, and (iii) quasi-logarithmic compression of the remaining count rates. After the end of a cycle (1,2, or 4 spins, depending on telemetry rate and IMS mode), the data are processed further, then compressed and finally telemetered during that same spin. The actual time delay between a measurement and its transmission at nominal encounter conditions will not exceed 4 s. This fact may become important in the innermost coma where the end of the mission can be expected at any time.

The data scheme of the AA is rather simple: only for those E/Q channels in which the most abundant ions (M/Q= 18, 19, 20, 28, 44) are expected are the counts of all five CEMs behind the AA transmitted separately for each of 16 azimuthal bins per spin. For all other 59 E/Q channels, counts are integrated over a full spin for CEM 1 only (this is the CEM that looks in the forward direction). The remaining four CEMs are summed together over a full spin period and a single number sent back.

In order to understand the MA’s data scheme, one must be aware of a basic property of this instrument: by choosing the proper post-acceleration or deceleration and making corresponding adjustments in the L2 voltage, each mass species can be directed to any desired position on the Igel, and hence to any CEM. This property can be used to set up two distinct modes: the so-called ’N- and H-programmes’.

In the N-programme each species has its own dedicated detector within the appropriate E/Q regime. Any velocity value of a given species causes the particles to hit the same detector. To make optimum use of the focussing properties at the Igel’s centre and to keep the Igel’s size and number of detectors within reasonable limits, the whole range of masses is split up into seven groups. For example, in the ’water group’, mass 18 will always be registered by CEM 4, the peak of its nominal velocity distribution occurring at E/Q channel 14 corresponding to 69 km/s. For this mass channel as well as for mass channels M/Q= 14-17, 19-21,26-29, 32, and 44, all 16 azimuthal channels during one spin are transmitted individually, while in the other cases they are just summed over. Both flanks of the nominal mass-18 velocity distribution, which is focussed on a central CEM, are covered quite well. Other ions, e.g. mass 16 or 32 (focussed on CEMs I and 9, respectively), yield only one flank of their distributions. This scheme assigns best coverage to the expected most-abundant ion species. Less abundant species will not yield enough counts to measure their angular and velocity distributions.

The detector pattern on the Igel has been designed such that it fits best the requirements for resolving the water group. This pattern does not necessarily fit other groups equally well. In the latter case, some ion species will not be focussed at the centres of the detectors, but rather at their edges or even on the rims in between them. Therefore, at heavier masses (above 46), the group scheme was dropped and replaced by the same scheme as in the H-programme described below.

In the so-called H-programme individual detectors are not dedicated to fixed M/Q values but rather to fixed velocities centred on the nominal encounter velocity of 69 km/s. In other words, the peak of the velocity distribution of any species will be seen at CEM 6 as E/Q is scanned, provided only that the plasma is truly at rest in the comet frame of reference. In this programme the same ion species will appear on different detectors, according to its velocity distribution.

Each programme has its special merits: the H-programme is better suited to measuring relative abundances of different species because each is measured with the same detector (CEM 6). The N-programme allows better determination of the velocity distributions of several ion species because they are measured for each selected ion with a single CEM. Use of a single CEM for either mass (H-programme) or velocity (N-programme) distributions takes account of any variations in individual CEM sensitivities.

Via telecommand we can select either N or H programmes only, or N and H alternating every spin with a 3:1 or 1:1 ratio. If the latter mode is used, an additional ’wobble’ voltage is applied to the outer plate of the external deflector, which in all other modes is grounded. The voltage follows a sawtooth pattern (0 to -15 V) with a frequency of 1 kHz and effectively expands the field of view of both the MA and the AA in the direction away from the spacecraft (by 2deg for mass 12 or 0.5deg for mass 57). This feature becomes useful in case the whole spacecraft charges up negatively.

3.3 Common power and data-processing unit, IMS-3

The common electronics box for the HERS and the HIS links the IMS to the Giotto telemetry and telecommand subsystems and to the power bus. IMS-3 contains all the low-voltage electronics, including an isolating power converter. It supplies all voltages necessary to drive the various detector amplifiers, the logics and the high-voltage power circuitry.

Two microprocessors, together with their peripheral logic elements, receive and compress digitized data from the sensor boxes. One microprocessor, aided by two 64 kbit memories, is assigned to mode control and data compression for HERS. The other, together with another 64 kbit RAM, governs the HIS instrument, its modes and data handling, as well as all general IMS command, telemetry and housekeeping interfaces with the spacecraft. Digital-to-analog converters with PROMs at their inputs provide the necessary control voltages for all high-voltage stepping in both instruments.

In the event of microprocessor failure, all software controlled logic can be bypassed such that hardwired logic feeds the contents of the various counters directly onto the telemetry bus. However, in this emergency mode the sampling rate would be highly reduced. Finally, in-flight test modes enable us to verify the proper functioning of all electronics, including monitoring of high voltages and detector thresholds as well as the contents of the RAMs and PROMs.

4. Instrument Calibration

The entire IMS was calibrated in the ion-beam calibration system at the University of Bern. This facility has been used to calibrate mass spectrometers on Geos and several other spacecraft (Ghielmetti et at., 1983). The ion species used for IMS calibration were H+, H2+, He+, CH3+, CH4+, Ne+, N2+, Ar+ and CO2+.

The flight and flight-spare units of the HERS and HIS sensors were tested using two methods. The so-called ’dynamic calibration’ was performed under the control of the IMS-3 unit, with fast linear sweeps of deflection and acceleration potentials and the usual data encoding. Dynamic runs yielded low detector count rates because the acceleration voltage sweeps through a wide range compared with the sensor energy window and hence the duty cycle is very low. Such runs are, however, needed for the allocation of voltage sweep bins to ion energies.

In addition to the dynamic calibration, a ’static calibration’ was performed in which IMS-3 was replaced by ground-support electronics built specifically for these tests. With the static method, only DC levels of the instrument potentials could be commanded, but this allowed us to step each voltage through any arbitrary range of values. In this way, the optics of the sensor were investigated, and voltages were optimized (e.g., the HERS ESD and acceleration ranges). Moreover, response as a function of the energy and direction of the incoming ions could be measured in a very short time for each selected level of the acceleration/deceleration potential.

During static calibrations, the beam energy was linearly wobbled over the energy windows of the two sensors. The wider of the two orthogonal angle windows (Fig. 2) was scanned linearly by rotating the turntable on which the sensor was mounted. The narrower of the angle windows was stepped through in a sequence of runs.

Figure 13 shows the angular response of the HERS for H2+ ions with a mean energy of 2420 eV (i.e. with 1330 V acceleration), integrated over the energy window. The sensor response function was found to depend on the direction of ion incidence in a well-behaved manner. The modulation of the response function in Figure 13 is produced by potentials from the individual acceleration grid wires. High deceleration voltages tend to cause stronger modulation.

The angular response of the HIS mass analyzer for 20Ne+ ions is shown on Figure 14. The ion energy was wobbled with an amplitude of 13 eV (corresponding to a rather cold ion beam in the case of the rammed cometary ions for which HIS is intended). The average energy corresponded to the relative velocity during encounter. This run was performed in order to simulate the response of CEM 4 (nominally allotted to 18 amu/e) for water ions. Counts in CEM 5 adjacent to CEM 4 can be seen at the extreme epsilon angles.

Figure 15 demonstrates the mass resolution of the HERS for CH3+ and CH4+ ions. The figure shows the distribution of CH3+ and CH4+ counts over mass anodes 1 to 40 for one angle anode. With the ion beam filling the energy and angle windows, the mass peak width is approximately two anodes (FWHM). This width is nearly constant for all ions in all mass ranges and our estimate of the HERS mass resolution is M/deltaM=25. Note that the contribution of one peak to the centre of the neighbouring peak is less than one percent.

The mass resolution of the HIS is illustrated in Figure l6. This display of several dynamic runs shows counts accumulated in each mass/energy bin when unidirectional beams of CH2+, CH3+, CH4+, 20Ne+, and 22Ne+ arrived at the HIS from the ram direction with the encounter velocity. Each peak appears in its predicted bin. Counts are normalized to the same peak value, whereas no counts were obtained in any of the blank areas. The latter symbolize mass/energy bins transmitted, whereas shaded areas indicate bins not transmitted (see Section 3.1.5 for the data-compression scheme). Mass resolution is clearly sufficient to identify, for relatively cold ion

Figure 13. Angular respnose of the HERS MCP for H2+ ions. The beam energy of 2420 eV is wobbled to flll the energy window. This run simulates the response to 4He**2+ ions of 4840 eV. Contours in the lower panel show 20, 40, 60, and 80% of maximum response. Phi (azimuth) and lambda (elevation) angles correspond to the narrow- and wide-view angle shown in Figure 2 for the HERS. The upper panel gives the MCP response integrated over eight angle anodes and phi. The integrated response over both angles (geometric factor) is ~ 9 X 10**-3 cm**2 ster eV/e for this acceleration voltage

Figure 14. Angular response of the HIS mass-anlyser for 20Ne+ ions. The beam energy was 440 eV with a wobble of 13 eV (peak-to-peak). Contours are plotted at logarithmic intervals over two decades. Alpha and epsilon correspond to the narrow- and wide-angle of the shaded field of view of the HIS in Figure 2. The origin (alpha, epsilon = 0) is the cometary ram direction

Figure 15. HERS mass separation: composite spectrum for CH3+ and CH4+ measured in sequence. The integrated response of all 4O mass anodes is shown for ion beams filling the energy and angle windows. Thin and dashed lines show the response from the two individual runs

Figure 16. HIS mass separation: composite spectrum of five ion species with beam energies of 24.5 eV/amu (i.e. encounter energies). Energy wobble was 13 eV (peak-to peak, equivalent to one energy step). Counts are normalized to the number counted in the nominal E/Q bin of each ion species. No data are transmitted for the shaded areas

Figure 17. Colour spectrogram of solar-wind data collected on 24 October 1985 summed over 128 spins in the light ion range (i.e. data were averaged over a total period of 34 min). The frame on the left of the figure is a plot of energy channel number (vertical axis, with ion energy increasing downward) against mass channel number (horizontal axis), with the count rate indicated by the colour scale shown to the right. The mass scale corresponds to the light ion range (M/Q=2 to 4 from left to right). The black curved lines are lines of constant velocity over the mass range and correspond (from top to bottom) to 70,200, 400, and 600 km/s. These same velocities are separately marked for the protons (the left-most band labelled P) with crosses. The right panel shows the ion angular distribution excluding protons. Note the proton (red and black) and 4He2+ (blue and green) peaks at about equal velocities of 540 km/s

beams, ions in the water range separated by 1 amu/e.

These static and dynamic runs define the IMS response functions for the ion species and acceleration/deceleration levels actually tested. For other species and for beam energies and directions not measured directly, we are developing simplified physical models to predict the response functions for both instruments.

5. In-Flight Performance

The first in-flight operation of the IMS occurred on 7 September 1985 and showed nominal performance. At this time the solar aspect angle at the spacecraft precluded solar-wind measurement by the HERS, so that only the general health of the IMS could be assessed. Operation on 9 October 1985 showed the solar wind beginning to enter the HERS field of view (with nominal solar aspect angle 105deg). Both protons and He++ were observed by the HERS.   Owing to its more restricted energy and mass ranges, the HIS sensor does not respond to the solar wind. By 24 October the solar wind was well within the HERS field of view (solar aspect angle was 120deg), and we present results of preliminary analysis of HERS data from this day. The HIS sensor electronics were fully exercised during several periods and performed well. Detector background is low and calibrations showed both detector thresholds and analyzer plate voltages to be nominal.

Figure 17 is a colour spectrogram of data collected during 128 spins (512 s). The flux peak (blue and green) at the lower left shows the presence of ions with M/Q = 2, which we identify as solar wind 4He2+. The maximum count rate averaged over the 128 spins was about 32 s**-1 at an energy corresponding to a velocity of 540 km/s for M/Q=2. The width of this peak corresponds to five mass channels, as was the case for the laboratory calibration spectrum shown in Figure 15. The vertical extent is a measure of the energy distribution, i.e. temperature, of the ions. Note that the high-velocity tail of the distribution is apparently cut off at the high-energy limit of the

HERS.

The instrument is programmed in such a way that integration times for high energies (above E/Q channel 32) are longer than for low energies. In the colour plot this produces a systematic energy dependence in the appearance of the background count rate.

The vertical band on the left labelled ’P’ shows proton count rates averaged over the 128 spin period. Protons (collected by the CEMs) are not on the same mass and velocity scales as the other ions (collected by the MCP), but are shown together for convenience. The averaged maximum proton count rate is > 1.6 X 10**4 s**-1; the peak instantaneous count rate was, in fact, about 2.5 x 10**5 s**-1. The peak of the distribution occurs at an energy corresponding to a proton velocity of about 500 km/s.

The frame to the right in Figure 17 shows the ion count rate in angle space, with 32 azimuth bins on the vertical axis and 8 elevation angle bins (each 7.5deg wide) on the horizontal axis. It can be seen that the ions are contained within three azimuth bins and are fully within the elevation angle field of view.

On 31 October, the solar-wind velocity had decreased to ~400 km/s, and thus ions up to M/Q ~3 arrived in the HERS energy range. Figure 18 is a mass spectrum measured on this day, showing the total raw counts accumulated in the angle range containing elevation channel 1 and azimuth channels 15 to 17. The spectrum has not been corrected for background (corresponding to an average of about 3 counts per mass channel), nor was the response function of the instrument taken into account.

The theoretical positions of the most abundant solar-wind ions in this M/Q range are indicated. The spectrum fully agrees with previously obtained solar-wind M/Q spectra, even in detail (Kunz et al., 1983). The valley between He2+ and O7+ corresponds to the resolution expected from HERS calibration data. Whereas O6+ is clearly isolated, the O7+ peak shows the well-known shoulder that is composed mainly of C5+ and Ne8+.

Figure 18. Solar-wind mass spectrum from 31 October 1985 taken with the MCP detector (light ion range). Counts are integrated over 500 spins (i.e. the total sampling period was 130 min) for one elevation and three azimuthal channels. Raw data, uncorrected for background, are given

Figure 18 demonstrates that the HERS can meet its scientific goals, namely those of measuring solar wind and hot cometary ion composition with good mass resolution. It is important to note that this resolution is maintained for high ion temperatures, similar to those expected in the interaction region of the comet. Although no scientific data has yet been returned from the HIS, engineering and calibration data lead us to expect that the HIS scientific goals will be met as well.

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