Plasma Experiment for Planetary Exploration (PEPE)

DS1 Technology Validation Report

Prepared by:

David T. Young
University of Michigan
College of Engineering
Department of Atmospheric Oceanic and Space Sciences
Tel.: 734-936-7263
e-mail: dtyoung@umich.edu

Jane E. Nordholt
Los Alamos National Laboratory
Space and Atmospheric Science Group
NIS-1
Tel.: 505-667-3897
e-mail: jnordholt@lanl.gov

John J. Hanley
Southwest Research Institute
Space Research and Instrumentation Division
Tel.: 210-522-2884
e-mail: jhanley@swri.edu

Table of Contents

Section Page

Figures

Figure Page

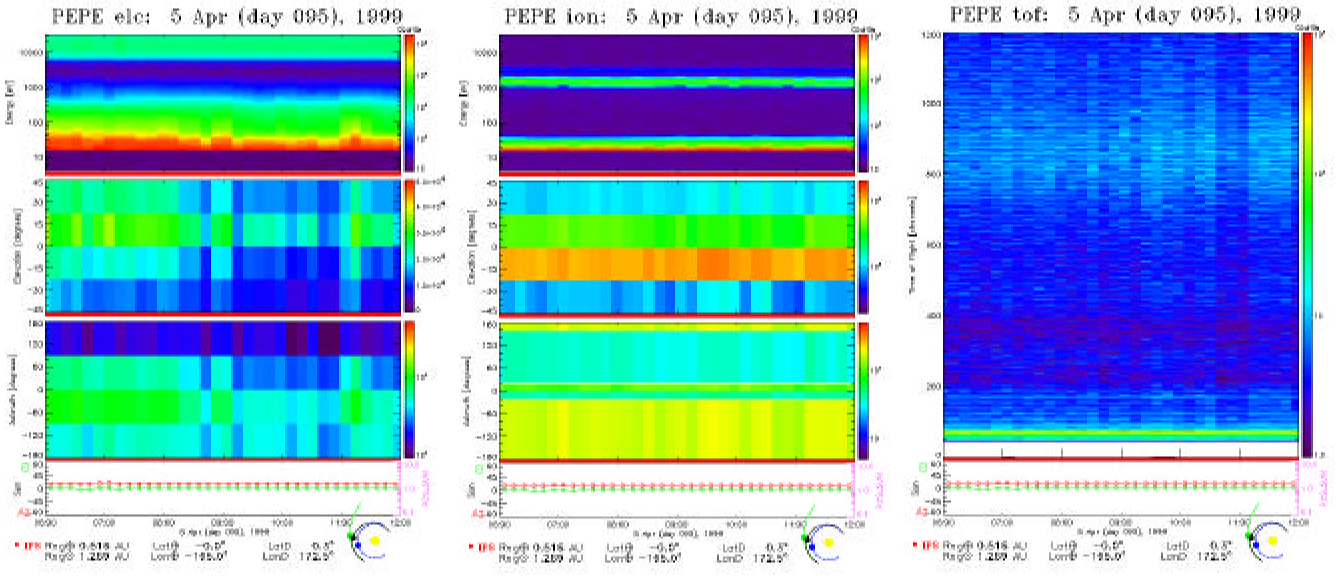
Appendices

EXTENDED ABSTRACT

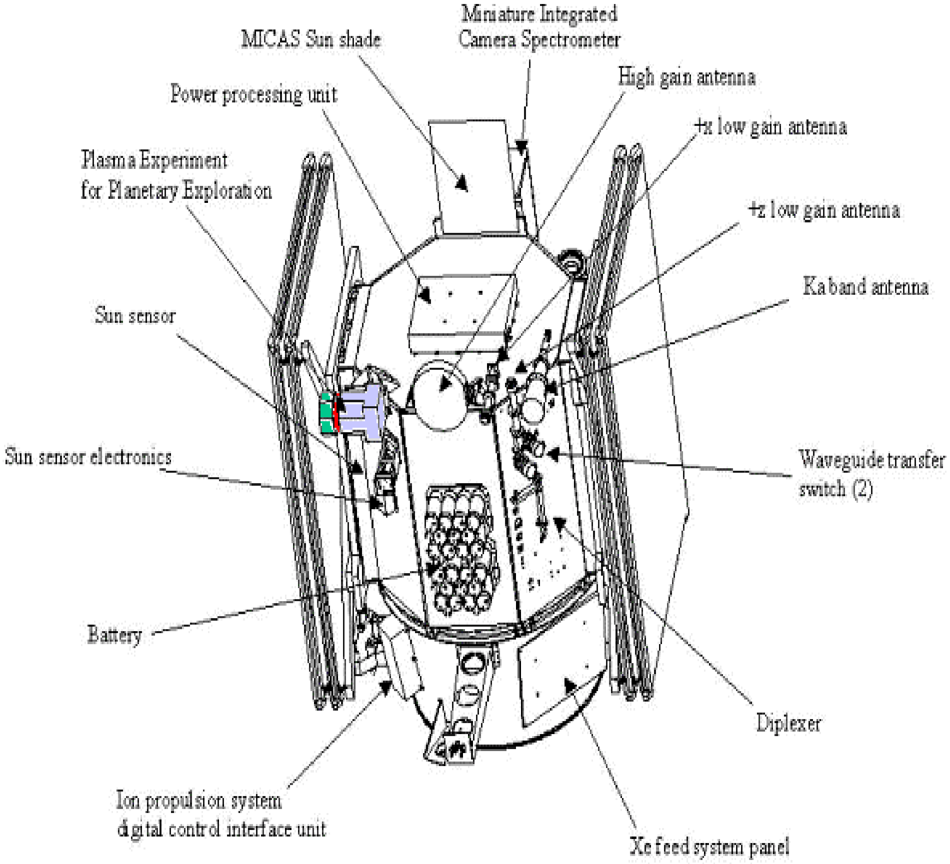
The Plasma Experiment for Plasma Exploration (PEPE) is a particle spectrometer capable of resolving the energy, angle, and mass composition of a wide range of plasmas found throughout the solar system. PEPE commenced successful operations on 8 December 1998. As a part of the Deep Space 1 (DS1) mission, the objectives of the PEPE investigation are to demonstrate new instrumentation technologies relevant to low-resource space plasma instrumentation, to show that such instruments can be operated successfully to obtain high-quality scientific data on a spacecraft employing an ion propulsion system (IPS), and to obtain new scientific findings related to the prime scientific targets of the DS1 mission. The three broad categories of new technologies demonstrated in the PEPE instrument include novel electron and ion optical systems, including an electrostatically swept field-of-view and time-of-flight mass analysis, that significantly reduce overall sensor mass and volume relative to performance; a compact, high-reliability, high-voltage system consisting of eight individual supplies ranging from ±3.6 to ±15.0 kV; and low-resource, high-performance electronics that perform sub-nanosecond measurements and provide very flexible data acquisition and processing capabilities.

Several categories of risk were associated with the PEPE program from its inception. Technological risks associated with the instrument manufacture included the use of novel materials and processing techniques that had no previous flight history. In particular, previously untried methods had to be developed to metal-plate and chemically etch low-outgassing exotic plastics. A second new process was required to vapor-deposit a variable-depth, extremely high-ohmic coating on high-purity ceramic cylinders. At the time we were assured by collaborating technologists that no one had ever tried to accomplish these tasks for ground applications, much less for spaceflight. A second risk category was overall system design. Although PEPE was based on previous experience and designs, the entire instrument was built without the benefit of a prototype or an engineering development unit for the optical subsystem, high-voltage subsystem, or for the system as a whole. A few selected subsystems were prototyped, primarily to develop and test digital interfaces. Schedule and budget comprised a third risk category: to our knowledge no instrument of this complexity has been built in a period of 26 months from the contract start date to delivery at the launch site. Schedule risk was managed largely through the contribution of prolonged work hours by a small and dedicated team.

In most cases, validation of the PEPE concept and technologies is being obtained primarily by examining data obtained in space from the instrument and inferring subsystem performance indirectly. A number of subsystems, mostly digital electronics, were tested and validated during ground tests. However, our primary test case consists of the thoroughly studied characteristics of the solar-wind plasma that is simultaneously being observed by the Wind spacecraft and the Advanced Composition Explorer (ACE) spacecraft located near the Earth. Together with solar-wind instruments on other spacecraft located elsewhere in the solar system (Solar and Heliospheric Explorer [SOHO], Ulysses, Cassini), PEPE provides a valuable contribution to



***Examples of PEPE Data Returned on 5 April 1999 When the IPS Was Running.
The first two panels show the energy and angular distributions for electron and ions.
The third panel shows the time-of-flight spectrum summed over all energies and angles.***



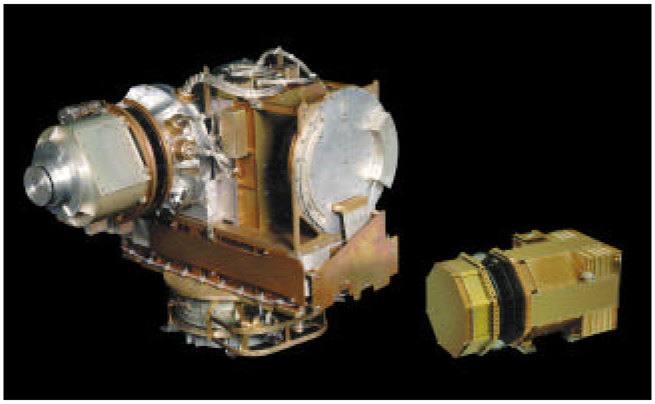
PEPE's Mounting Position on DS1. PEPE is color coded to show the electron section in green, the ion and data processing section in blue, and the aperture in red.

the study of large-scale solar-wind structures because of its location in a part of the solar system widely distant from the other spacecraft. Thus, a careful analysis of observations of solar-wind ions and electrons that have been collected since PEPE switch-on in December 1998 serve to validate the overall end-to-end performance of the optical design, high-voltage system, time-of-flight electronics, and other technologies. Particular details of the measured shape and intensity of the solar-wind velocity distributions give specific information about optical alignments, carbon foil and detector efficiencies, high-voltage system performance, and end-to-end system performance.

Although validation of the PEPE instrument and technologies is a primary concern of the program, it was realized early on that because of the compacted development schedule we would have to forgo a considerable amount of ground testing and calibration activities. Individual electronic subsystems received enough ground testing to validate their specified performance; however, combinations of subsystems often received little more than interface checks to validate their compatibility. Because the complete PEPE system came together only very late in the program, testing at the system level was minimal in the extreme. For example, the thermal vacuum test consisted of a single cycle that was combined with an attenuated calibration period lasting only 2 days! The hot part of the cycle also served as the bakeout period for the instrument prior to calibration. This deficit was to be made up in flight by accumulating a large number of operating hours in different environments and instrument operational modes and by in-flight calibration using targets of opportunity involving similar instruments on other spacecraft.

To a large extent it has been possible to gather the data necessary for validation. The data taken so far with PEPE compare very favorably with solar-wind data obtained by plasma instruments on the Wind, ACE, and Cassini spacecraft after allowances are made for the structure and evolution of the solar wind and the separation distances of the respective spacecraft from DS1. In addition, PEPE data have been used to demonstrate that high quality measurements of plasma at energies above roughly 50 eV can be made with the IPS operating. Below this energy PEPE has obtained measurements of xenon ions as well as secondary electrons related to both the IPS and SCARLETT solar arrays. These data can be used to map the previously unobserved local plasma environment of an IPS-driven spacecraft—a topic of considerable interest for future planetary and heliospheric missions.

PEPE technologies can be put to future use in two ways: as an entire sensor technology and as a set of subsystem technologies. As an integrated system, PEPE provides nearly the same capability as the state-of-the-art Cassini Plasma Spectrometer; however, at 5.5 kg and 9.6 W, it requires only 24% of the mass and 46% of the electrical power of the latter. In addition there are qualitatively different approaches used in PEPE that simplify its use in future missions. Typical planetary spacecraft such as Cassini and DS1 are 3-axis stabilized, which presents a problem for plasma instruments that typically need to view as much of the unit sphere as possible. The ideal is 4π steradian coverage, which presents a significant problem to both the spacecraft and instrument designers. On Cassini, this problem was solved by scanning the plasma instrument mechanically using a 3.6 kg motor with attendant problems related to magnetic cleanliness and mechanical stability needed for fine pointing of optical sensors (both problems were solved on Cassini). With PEPE, the problem was approached for the first time by employing an electrostatically scanned field-of-view using no moving parts or magnetic fields. Thus, the PEPE technology has wide appeal for future missions because it eliminates possible magnetic and mechanical interferences. Other PEPE subsystem technologies having wide future applicability include very low resource high-voltage power supplies and compact time-of-flight mass, spectrometer optics and associated electronics.



Comparison Between the Cassini Plasma Spectrometer (CAPS) and PEPE.

ACKNOWLEDGEMENTS

The authors wish to thank the PEPE teams at Southwest Research Institute (SwRI) and Los Alamos National Laboratory (LANL) for their hard work during the development phase of the instrument. These scientists and engineers are: J. L. Burch[1], D. J. McComas[2], R. A. Abeyta[2], J. Alexander [1], J. Baldonado[2], P. Barker[2], R. K. Black[1], T. L. Booker[1], R. P. Bowman[1], P. J. Casey[1], L. Cope[2], J. P. Cravens[1], N. Eaker[1], H. O. Funsten[2], R. Goldstein[1], D. R. Guerrero[1], S. F. Hahn[2], B. P. Henneke[2], E. F. Horton[1], D. J. Lawrence[2], K. P. McCabe[2], S. Rogillio[1], R. P. Salazar[2], E. Santiago[2], M. Shappirio[2], S. A. Storms[2], and C. Urdiales[1]. We also thank the two institutions and the Department of Energy for their support and dedication to PEPE. We would particularly like to thank SwRI for investment of internal research support to help develop several of the PEPE technologies. Development and operation of PEPE would not have been possible without the support of members of the JPL DS1 team; in particular, L. Livesay, K. Cleven, D. Lehman, R. Nelson, K. Fleming, P. Chadbourne, M. Rayman, and P. Varghese. We particularly want to thank G. Withbroe of NASA HQ for his generous support of the PEPE instrument. We would also like to thank R. Christy and C. Gerber of TriboCoat Inc. for their willingness to try some new things. The development phase of PEPE was supported at SwRI by JPL contract 961207 and at LANL by NASA contracts WO-9049 and WO-9066; the mission operations and data analysis phase is supported at SwRI by JPL contract 960619 and at LANL by WO-9165 and WO-9138.

[1] SwRI
[2] LANL

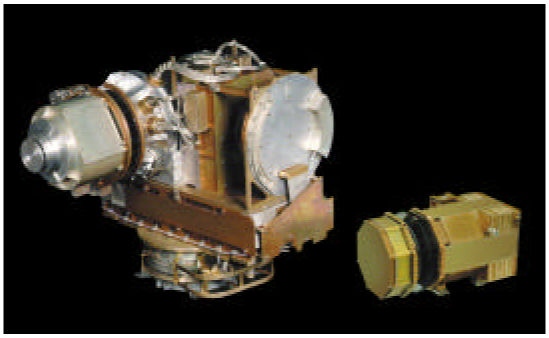
PEPE Fact Sheet

Parameter	Range/Resolution	Performance	Units
Sensor Type	Toroidal electrostatic angular scanning and energy/charge analyzers coupled to linear-electric-field time-of-flight ion mass/charge analyzer.		
Energy	Range	8.0 to 33,500	eV/eV
	Range scanned	120 steps, log-spaced	
	Resolution (ions)	0.046	ΔE/E
	Resolution (electrons)	~0.085	ΔE/E
	Analyzer constant (ions)	13.07	
Mass	Range	1 to 135	amu/e
	Resolution (medium mode)	~4	M/ΔM
	Resolution (high mode)	~20	M/ΔM
Angle	EL angle range (scanned)	–45 to +45	(°)
	EL analyzer deflection	6.7×10^5/(E/Q)	(°)
	Range scanned	16 steps, linear-spaced	
	AZ angle range (static)	360	(°)
	Solid angle coverage	8.9	sr
	Resolution (electrons)	256 pix @ 5 × 22	(°) × (°)
	Resolution (ions)	128 pix @ 5 × 5	(°) × (°)
	Resolution (ions)	32 pixels @ 5 × 22	(°) × (°)
	Resolution (ions)	96 pixels @ 5 × 45	(°) × (°)
Temporal	AZ angle × TOF	0.008/0.032	s
	AZ angle × EL angle × TOF	0.128/0.512	s
	AZ angle × EL angle × energy × TOF	16.38/65.54	s
Sensitivity	Electrons (5° × 22° pixel, ε ~ 0.5)	$\sim 1.5 \times 10^{-4}$	cm^2 sr × cts/el.
	Ions (5° × 22° pixel, ε ~ 0.5)	$\sim 8.0 \times 10^{-5}$	cm^2 sr × cts/ion
	(@8.0 kV TOF, ε ~ 0.2)	$\sim 3.0 \times 10^{-5}$	cm^2 sr × cts/ion
Dynamic Range	Electrons	0.1 to 10^6	Hz
	Ions (singles)	0.1 to 10^6	Hz
	Ions (TOF analyzed)	0.01 to 10^5	Hz
Resources	Mass	5.5	kg
	Power	9.6	W
	Volume	~7.25	liters
	Density	0.83	g/cm^3
	Telemetry (commandable)	1024, 512, 250, 100, 50, 25	bits/s
	Location on spacecraft	+Z edge of the +X-Y face of s/c	
	Operating range	–20 to +35	C
	Cover (with GN2 purge)	Remove before flight	
Performance	Operating time (as of 11/1/99)	~5600	hours

Contacts:
David T. Young
University of Michigan
Ann Arbor, MI 48109
dtyoung@umich.edu

Jane E. Nordholt
Los Alamos National Laboratory
Los Alamos, NM 87544
jnordholt@lanl.gov

John J. Hanley
Southwest Research Inst.
San Antonio, TX 78228
jhanley@swri.edu



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David T. Young, University of Michigan, College of Engineering
Jane E. Nordholt, Los Alamos National Laboratory, Space and Atmospheric Science Group
John J. Hanley, Southwest Research Institute, Space Research and Instrumentation Division

1.0 INTRODUCTION

Unlike all of the technologies onboard the Deep Space 1 (DS1) mission (except MICAS), Plasma Experiment for Planetary Exploration (PEPE) (shown prior to delivery in Figure 1) is both a spacecraft technology and a self-contained scientific instrument [1, 2]. PEPE itself incorporates a half-dozen technologies that are to our knowledge novel to space-plasma instrumentation. The technologies were developed in response to the need for greatly reduced resources relative to comparable instrumentation on other missions, such as Cassini. Because the two teams that built PEPE (Southwest Research Institute [SwRI] and Los Alamos National Laboratory [LANL]) had also designed and built much of the Cassini Plasma Spectrometer (CAPS) (see [3, 4]), a decision was made to design an instrument that would maintain the performance envelope of CAPS while at the same time reducing the resource envelope by a significant fraction. The PEPE resources were also dictated by their availability and allocation on the DS1 spacecraft.

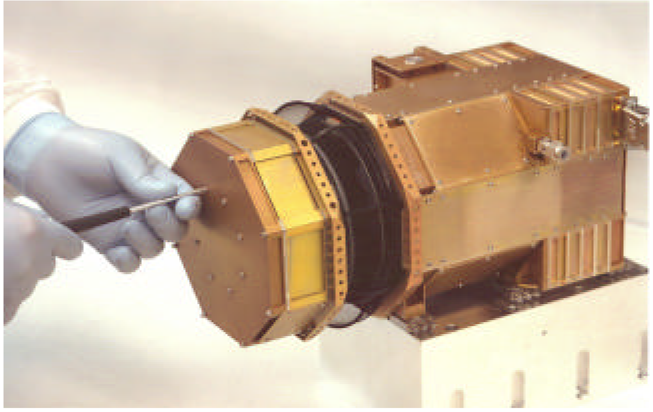

Figure 1. Photo of PEPE on the Bench Prior to Delivery

PEPE required a number of breakthroughs: a complete redesign of the CAPS particle-optics system, new ways of miniaturizing and incorporating the large number of high voltages required to drive the optics, and miniaturization of critical circuits needed for high-speed (~1 GHz) time-of-flight (TOF) measurements and for data acquisition and compression. Fortunately, the radiation hardness required of the DS1 program did not place any stringent requirements on the PEPE electronic-parts procurements. We also attempted several new materials treatments and processes, including depositing-uniform coatings of very high ohmic materials on ceramics, metal plating of relatively inert plastics, and complex, multi-layer electrical boards containing ion-optical components.

All of these technologies and their attendant risks are discussed in detail in Section 2. The reference point for much of the discussion is the Cassini Plasma Spectrometer described in [2, 3]. Validation of the instrument technologies has required careful analysis of their performance in a number of situations using the ambient solar-wind plasma, the spacecraft-photoelectron sheath, and the products of the xenon ion propulsion system as test opportunities. Unfortunately, the time-of-flight system has not been able to operate at its planned high-voltage level. This topic will be discussed along with other validation topics in Sections 2.7 and 3. In Section 4 we will discuss the use of PEPE and related technologies for future missions. Appendices A and B give technical details on the PEPE data channels and data collection periods.

2.0 TECHNOLOGY DESCRIPTION

2.1 Overview

PEPE is a charged-particle spectrometer capable of measuring and resolving the velocity distribution of electrons and ions and the mass composition of ions that make up the wide variety of plasmas found in the solar system. In order to coincide with the scientific objectives of the DS1 mission, the particular design chosen for PEPE focuses on measuring solar-wind plasma and the plasma populations resulting from solar-wind interactions with intrinsic plasmas associated with the outgassing of asteroids and comets. However, the general concepts and technologies used in PEPE can be adapted readily to a wider variety of objectives and missions, in particular missions to study planetary magnetospheres. A major driving factor in the design of PEPE was to reduce its resource requirements relative to those of instruments with comparable capabilities. In this case, we turned to the Cassini Plasma Spectrometer, a very high capability instrument presently operating on the Cassini-Orbiter spacecraft. Because the core design teams of the two instruments are the same, the goals for the PEPE design consisted of trying to duplicate the main performance features of the Cassini instrument in a much lower resource instrument. It was recognized at the outset that PEPE could not exactly duplicate these features because the DS1 mission did not require it and because performance compromises would have to be made in some areas in order to meet resource targets.

With reference to the cross section of the PEPE instrument assembly shown in Figure 2, PEPE is made up of four functional components that are integrated using a novel architecture: (1) a series of charged-particle optical elements; (2) a system of high-voltage supplies that establish bias voltages needed for particle-optical elements and detectors; (3) high-speed pulse electronics that make timing measurements used to discriminate ion mass; and (4) digital electronics that provide data-acquisition and instrument-command-and-control functions. These are integrated using a packaging architecture that draws the subsystems together in a single, compact, low-resource instrument. The functional components of PEPE make use of several technology applications that are either newly developed for PEPE or are new applications of existing technologies, such as the system of Field Programmable Gate Arrays (FPGAs) used to make up PEPE's powerful and flexible data-acquisition system.

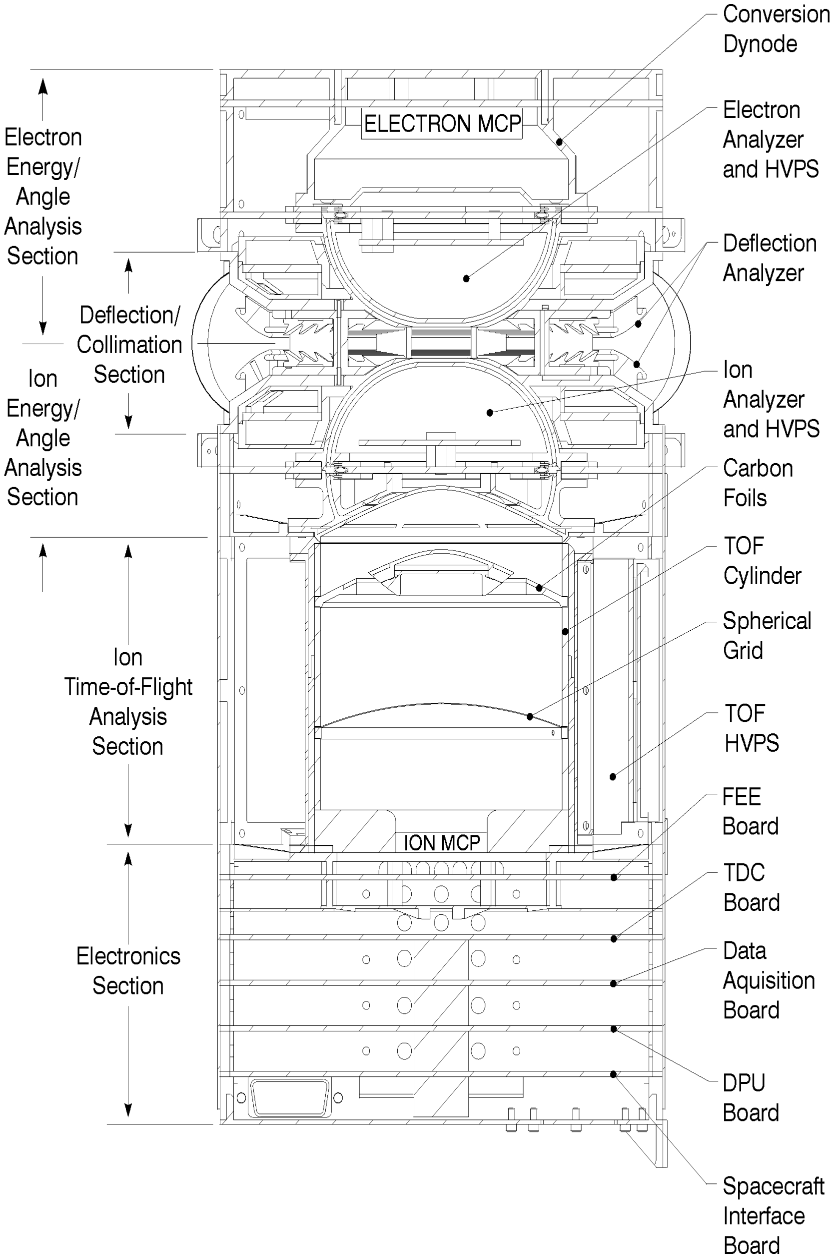

Figure 2. Cross Section Illustrating the Location of PEPE Subsystems and Layout of the PEPE Ion/Electron-Optical System

2.2 Key Technology-Validation Objectives at Launch

The primary-validation objective for PEPE, can be summarized as end-to-end functionality that meets requirements for scientifically useful data products. The objectives of developing a reduced resource instrument can be validated by simple measurement of volume, power, mass, and data rate if the functionality requirement is met. Each of the PEPE technologies can be analyzed and validated against the descriptions and requirements that will be described in the following sections. However, the paramount issue in validating PEPE is the contribution of each technology to overall performance. With that overarching goal in mind, we can reconsider each of the 6 PEPE technologies.

2.2.1 Miniaturized 3-dimensional Linear Electric Field (LEF3D) Time-of-flight (TOF) Optics—The LEF3D-conceptual design is based on that of the LEF3D used in the CAPS instrument's Ion-Mass Spectrometer (IMS) [5, 6, 7]. The cylinder technology rests primarily on the use of high-resistance surface coatings in place of a set of discrete-ring electrodes on the CAPS/IMS. A second departure was to re-design interfaces between the high-voltage supplies and the LEF3D's optical elements. Validation objectives include being able to apply the target ±15 kV high voltage to the cylinder without high-voltage breakdown and operating the cylinder stably for a period comparable to typical mission lifetimes of ~2 years. The LEF3D optics should deliver TOF spectra with mass resolution equivalent to $M/\Delta M$ ~20 based on ray-tracing and experience with the IMS. Resolution and mass range as well as species rejection of the LEF3D optics must also be validated.

2.2.2 High-Speed TOF Electronics—The TOF electronics consist of a high-speed front-end electronics (FEE) that includes amplifiers, discriminators and logic, and a time-to-digital converter circuit with associated logic. The TOF electronics should deliver performance with ~1 GHz bandwidth that is consistent with the TOF resolution required of the cylinder. This performance should be nearly identical with that of the IMS [6, 7] although the resources required should drop by ~50%. Built-in test functions and in-flight validation of the FEE and time-to-digital converter (TDC) will be carried out using TOF data from the LEF3D.

2.2.3 Integrated Ion/Electron Optics—Using the solar wind as a well-studied and constantly-monitored plasma source, we shall confirm the energy and angle resolution, the correct angular orientation and location of elements of the field of view (FOV), the energy and field-of-view scanning functionality, and the absolute detector response of the sensor. The efficiency of the anti-reflection surface treatments will be validated by measurement of the extent to which solar UV and particles are scattered into the sensor.

2.2.4 Data-Acquisition System—An onboard pulser will be used to create fixed-pattern artificial TOF spectra that can be acquired and compared with ground-based calibration. A second and more stringent validation will be achieved by processing the high-counting-rate random electron and TOF events caused by the solar wind and other naturally occurring plasmas. Solar-wind data from other space-borne instruments on the WIND and ACE spacecraft located near the Earth will be compared with the processed PEPE data to determine that all components of the PEPE data product are correct and free from artifacts.

2.2.5 High-Voltage System—The high-voltage system will be activated and brought up to full operating levels singly and in combinations required for spectrometer operation. Data from the high-voltage supply monitors and from the background intervals during the high-voltage scans will be used to measure and track detector-noise levels in order to ascertain long- and short-term operation criteria for drift stability and ripple. Automatic high-voltage (HV) turn-on sequences will be prepared and executed without operator intervention. The goal was to be able to turn on the HV system automatically within a period of 4 hours or less without intervention.

2.2.6 High-Density Packaging Architecture—If the optical and high-voltage systems' (sections 2.2.1, 2.2.2, 2.2.3, and 2.2.5) performances are nominal, the packaging architecture will be considered validated. The PEPE data acquisition technology (section 2.2.4) is largely unaffected by the architecture. The fact that PEPE's instrument density of 0.83 g/cm^3 is significantly higher than similar plasma spectrometers (values range from ~0.25 to ~0.5 g/cm^3) indicates that this design feature has been validated, provided PEPE functions correctly in flight.

2.3 Expected Performance Envelope

The scientific objectives for PEPE or any other plasma spectrometer require that it measure the N-dimensional particle-phase space consisting of 3 velocity coordinates and N-3 mass/charge coordinates in the frame of reference of the spacecraft. The time coordinate and 3 spatial and 3 attitude coordinates are required to put the plasma data in the proper context. These fiducial data are obtained from the spacecraft and, although they could affect PEPE's ability to deliver valid measurements, by convention the spacecraft team is responsible for that aspect of performance. The specific elements of performance of plasma instruments such as PEPE concern: a) the range of parameter space coverage, b) resolution within that range, and c) sensitivity for detecting charged particles within that range. The parameters that have to be measured are those that determine the details of the particle-distribution functions: namely, energy/ charge, mass/charge, and angle of the direction of particle arrival. Because the plasma environment is highly dynamic, it is also important that the entire range of measurement be covered in as short a time interval as possible.

The performance envelope is dictated not only by the measurement objectives mentioned above, but by the capabilities of the measurement technology. PEPE consists of an electrostatic ion-optical system (magnetic systems are impractical under the circumstances) and its supporting electronics. The optics in turn depend on the correct shape and location of the optical electrodes and the application of the correct voltages to correctly bias the optical elements at a given instant in time. Electrode shape and position were maintained through the usual design and manufacturing processes to an estimated ±0.005 inches. The magnitude and number of distinct voltages required is determined by the optical design. In the case of PEPE, eight HV supplies are required with voltages ranging from ±3.6 kV for the two micro-channel plate (MCP) detectors to ±15 kV for the main TOF voltages. The latter are the highest voltages in PEPE and, in part, determine the mass-resolution performance.

In order to cover a range of particle angles of arrival and their energies, two sets of coupled power supplies drive the deflection and energy-analysis optics (Figure 3). One set of supplies produces two fast-slewing (3×10^6 V/s) bi-polar supplies that deliver ±5.0 kV to deflect particles ±45 ° in elevation. The deflection supplies float with respect to two "bulk" supplies (Figure 3) as do the ESA supplies. The nominal dwell time at a single elevation step is 0.032 s, giving a rate of 0.512 s for a single, full-elevation scan of 90°. Similarly, the HV set driving the energy analyzer section is also swept, but at a lower rate of one step for each elevation scan. In this way, an entire scan of the PEPE range of energies and angles (TOF- mass measurements occur at every sample) takes place in 65.54 s. These times are sufficient for monitoring the solar wind (usual temporal resolution is 1 to 5 minutes). Higher time resolution needed for rapid flybys of asteroids and comets can be obtained by using shorter dwell times, restricted scan ranges that can be covered more rapidly. Power-supply scan patterns and dwell times are programmable (as explained in section 2.4.4).

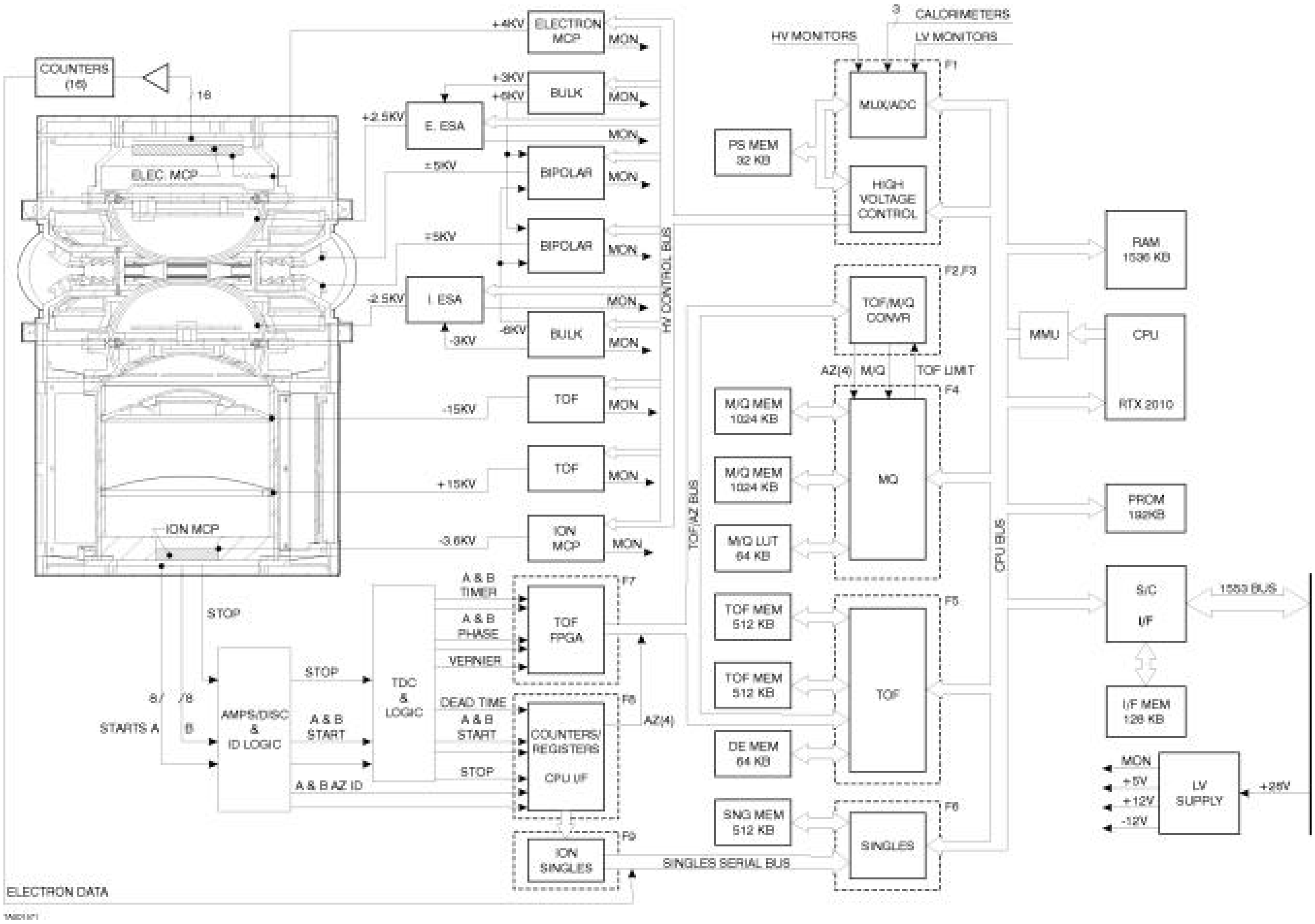

Figure 3. Schematic Block Diagram of the PEPE Electronic Subsystems and Their Relationship to Sensor Elements

Instrument sensitivity is determined by: 1) The instrument aperture (related in turn to the available volume and mass allocated to the instrument) and 2) the energy/charge andangular-resolution requirements. The latter set the size of the gaps between the field elements and determine the high voltages needed to establish the electrical forces across them (since electrical force ~ voltage/optical-element separation). Sensitivity is usually given in units of $[\text{cm}^2 \text{ sr}] \times$ [detector counts/incident target particle] (see the PEPE Fact Sheet). Thus, sensitivity and resolution are directly related to the mass and electrical power allocated to the instrument. The design of PEPE was meant to optimize sensitivity for a given set of resources; however, it is difficult to normalize the PEPE performance per unit resources relative to that of other instruments. The ultimate validation is the fact that PEPE obtains excellent solar-wind measurements at relatively high resolution with a fraction of the resources of existing instruments. The comparable plasma analyzers on the WIND spacecraft [8], for example, have about the same range of energy and angular acceptance as PEPE, but do not have either mass/charge analysis capability or a swept FOV (WIND is a spinner).

The WIND instruments are combined with several others in a package so that only very rough estimates can be made of their weight and power; however, it appears that they are comparable to those of PEPE. Since PEPE includes the added features of TOF mass spectrometry and a swept field-of-view (WIND is a spinning spacecraft and does not require a swept FOV), we conclude that PEPE has perhaps a factor of 2 advantage in performance for the same mass. One other figure of merit is the mass density of the packages: PEPE's ratio of mass to volume is 0.75 g/cm^3, whereas that of the WIND instrument is ~0.25 g/cm^3, similar to that of CAPS. An informal survey of plasma spectrometers shows that instrument density is typically 0.25 to 0.5 g/cm^3, indicating that PEPE's goal of producing relatively high-packaging density has been achieved.

2.4 Detailed Description

2.4.1 Miniaturized 3-dimensional Linear Electric Field (LEF3D) Time-of-flight (TOF) Optics—Figure 4 shows a cross-section of PEPE's LEF3D cylinder together with characteristic particle trajectories and major features of the instrument. CAPS' Ion Mass Spectrometer (IMS) contains an LEF3D spectrometer similar to PEPE but larger in volume by a factor of ~8. The IMS is made up of 30 discrete field-rings joined by a series of resistors. This arrangement produces the electric field configuration needed to make high-resolution TOF measurements. The approach taken with PEPE was to eliminate the rings altogether, replacing them with a monolithic ceramic cylinder coated with a layer of high-resistance, vapor-deposited chromium oxide. The volume of the cylinder materials was reduced by a factor of ~5. The cylinder itself was made smaller by a factor of ~2 and its aspect ratio (height to width) reduced to produce a design that is volumetrically smaller by a factor of ~8. The key performance factor—namely, the resolution of ion-flight-path timing—was reduced by a factor of 2 owing primarily to shorter flight paths, but was still acceptable for PEPE's science objectives.

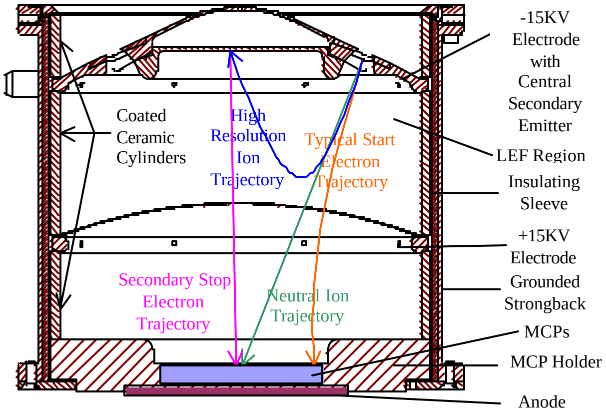

Figure 4. Cross-sectional Detail of the PEPE TOF Cylinder

When ions exit the curved analyzer plates (section 2.4.3), a large negative potential accelerates them into thin ($1\mu\text{g/cm}^2$ or ~50Å thickness) carbon foils. The foils form the entrance to the time-of-flight mass/charge analyzer. Electrons that are released by the passage of the ion through the foil are accelerated onto the outer annulus of the MCP stack at the bottom of the TOF section. They all take a uniform time of about 2ns to get to the MCP. There they start a clock that will be used to determine the time-of flight for the ion that released them. Ions are generally neutralized by their passage through the foils. In this case, they continue down the TOF section until they (with high probability) strike the center section—or "stop" section—of the MCP. This stops the clock and standard time-of-flight mass spectroscopy. The knowledge of the ion's initial energy to determine its velocity is used to determine the ion's mass. Mass resolution $M/\Delta M$ is only about 5 for this process. If the ion remains charged and it's energy is not too large to be turned around by the high voltage on the curved grid (heavy-curved line in Figure 4), it will "bounce" in the linearly-increasing electric field just as a mass on a spring would. The time for one-half oscillation of this bounce is independent of energy or angle of flight of the ion; therefore, the TOF is proportional to the square root of only the mass/charge and, thus, the mass resolution for TOF of this type is much higher than in simple field-free TOF systems. Ions that do bounce hit a secondary emitter at the top of the TOF section and the resulting electrons are drawn to the center "stop" portion of the MCP. The mass resolution in the case is calculated at ~20.

All three regions (acceleration, LEF3D, and deceleration) of the TOF section use ceramic cylinders with resistive coatings to produce in them a uniform-electric field; however, only the center section requires the coating to have varying thickness to produce the linearly-increasing electric field.

2.4.2 High-Speed TOF Electronics—The CAPS instrument relied on TOF electronics capable of 750 ps (10^{-12} s) resolution and pulse-pair resolution of 40 ns. The timing electronics required high-speed amplifier discriminator chains and logic (referred to as front-end electronics [FEE]) and a time-to-digital converter (TDC) that required a significant amount of power and component-board space. With reference to the functional block diagram shown in Figure 3, the PEPE design maintains the CAPS functionality and, in addition, doubles the number of angular-position channels encoded in order to capture finer details of the solar-wind ion distribution. Because PEPE's TOF optics operate in substantially the same way as those of the CAPS instrument, they required similar performance but with reduced resources. The FEE and TDC circuits were redesigned using chip-on-board technology. In addition, a direct digital-encoding scheme was incorporated to register the increased number of angular channels. The PEPE timing circuits required about 50% less power than the IMS unit and occupied about 40% less board space.

2.4.3 Integrated Ion/Electron Optics—At the time that CAPS was designed, two entirely separate instruments were needed to measure electrons and ions. This required two sets of housings, separate-entrance collimators and fore-optics, separate high-voltage supplies to drive the two electrostatic analyzers, and separate mounting locations to obtain clear fields-of-view. The duplication of functions required a fairly high investment in resources. In addition, because Cassini, like DS1, is a 3-axis stabilized spacecraft, CAPS required some way to articulate its field-of-view in order to sample the wide range of viewing space occupied by target plasma distributions. On Cassini, the solution was to use a motor/actuator that rotated the entire CAPS instrument (weighing 20 kg) over a range of ±104°. PEPE was designed so that electron and ion optics share a common entrance aperture that eliminates duplication of this optical element (Figure 2). After crossing the collimator, electrons and ions enter an electric field region created by the inner electrodes of two electrostatic-energy analyzers (ESA) (Figure 1). In a manner similar to the CAPS design, the energy analyzers are cylindrically symmetric, an arrangement that allows the instrument to view over a range of 360° in the plane perpendicular to Figure 2. Unlike CAPS, however, a set of toroidal electrodes was placed just outside the PEPE entrance aperture to deflect incoming ions and electrons in such a way that the instrument FOV can be scanned over a range of ± 45° in the plane of Figure 2. The result is that PEPE covers a larger range of observation space with dramatically reduced resources allocated to the optical system. The toroidal-deflection electrodes create an electric field that is terminated at the surface of the PEPE instrument by a toroidal-shaped wire-mesh grid. In order to ensure grid shape and stability, the wire-mesh material was formed in a vacuum-driven jig that shaped the grid and held it in place while the edges of the grid material were epoxied to the grid frame. The resulting toroid mesh was then plated with a thin Ni coating to bond the wires into place and further guarantee the shape. The electron optics made use of a dynode structure that converts the incoming electron flux into low-energy secondary electrons that can be easily concentrated onto a small MCP detector. This device reduces the size and complexity of the MCP that would otherwise be required to cover the exit aperture of the electron-energy analyzer. After the PEPE optical electrodes were machined and metal plated with nickel and copper, they were treated with the Ebanol-C process that develops a thin layer of anti-scattering microscopic crystals that are both rough and black.

2.4.4 Data-Acquisition System—The primary data product of CAPS' IMS TOF system is two 2048-channel TOF spectra generated every 62.5 ms. CAPS' maximum data rate is 16 kbits/s. In contrast, the maximum PEPE downlink rate is only 1024 bits/s for a similar amount of raw data from the TDC. This requires a very high degree of onboard capability for restructuring the angle/energy sweep program and the compression of the resulting data products. In order to provide this kind of a flexible program for optimum data return under all conditions likely to be encountered during the mission, PEPE was equipped with programmable control-of-sample dwell time (factor of 8), a voltage-scan program, and data-acquisition and processing capability. The PEPE system is functionally comparable to that of the CAPS instrument but uses about one third of the resources. However, PEPE relies more heavily on FPGA's (ACTEL 1280) than did CAPS and less on its low-resource processor (RTX2010).

Spectral scanning is carried out by setting the deflection and ESA supplies to their highest commanded levels and then stepping the supplies down. The deflection supply completes a scan and then the ESA is stepped. The nominal method of scanning is the "survey" mode (see Figure 5, Figure 6, and Figure 7) that covers the full 16-step elevation × 128-step energy scan (8 of the energy scan steps are used for background measurement). If the target-plasma population is restricted in velocity space (e.g., the solar-wind or cometary ionospheres) or the DS1-mission strategy requires that PEPE restrict its data rate, then PEPE can be programmed in several ways that provide more optimal data return. The simplest way to lower the data rate is to integrate the spectra over longer intervals (up to 20 minutes, equivalent to 50 bits/s). More efficient scans can be made by targeting a restricted volume of phase space and creating a smaller region-of-interest (ROI) angle/energy scan that can be scanned at a higher rate than nominal. A second way of producing a ROI is simply to select a subset of the current spectrum (whether full or ROI) and send back only those products.

Data products (electrons, ion singles and TOF, housekeeping) from a completed energy × angle × angle × TOF spectrum are acquired into separate memory arrays (Figure 3). After acquisition of the current spectrum, the

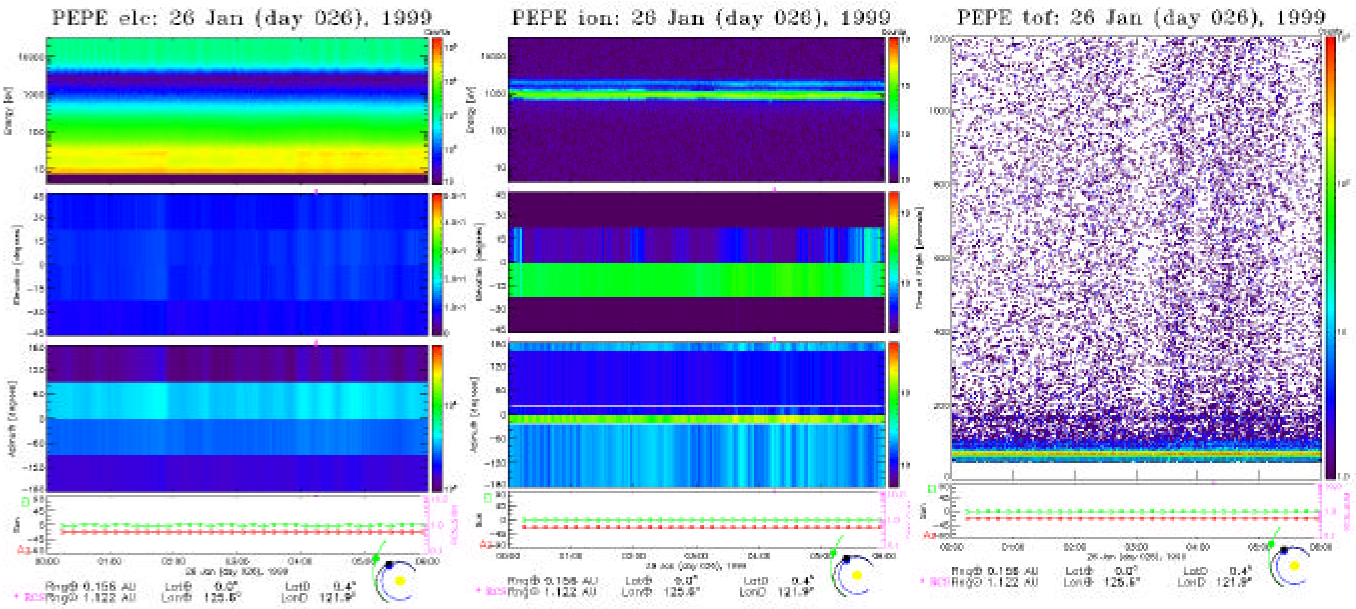

Figure 5. Data from 26 Jan. 1998 0000-0600 UT Illustrating PEPE's Response to Quiescent Solar-Wind Plasma (Note the lack of interference from solar photons that would appear at all energies near elevation zero in both the ion and electron spectra.)

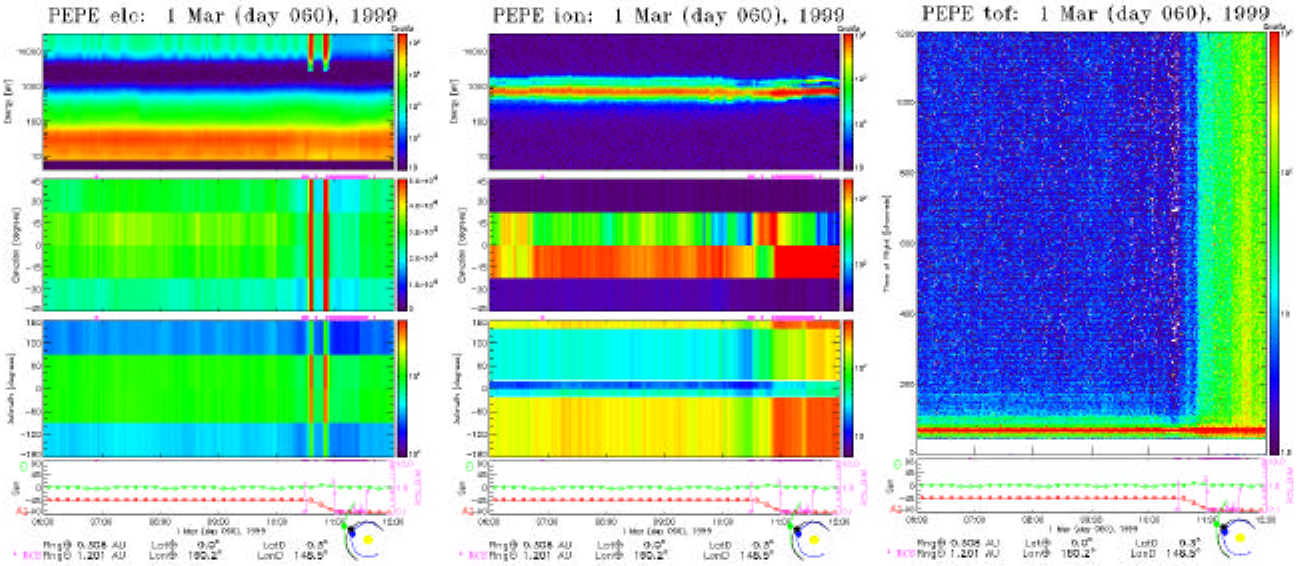

Figure 6. Data from 1 March 1998 0600-1200 UT Illustrating PEPE's Response to Disturbed Solar-Wind Conditions (Note the bright vertical bars in the electron data that are caused by attitude-control-thruster firings and the related change in DS1 orientation. The thrusters cause a large cloud of photoelectrons to be created from gas molecules released during the firing.)

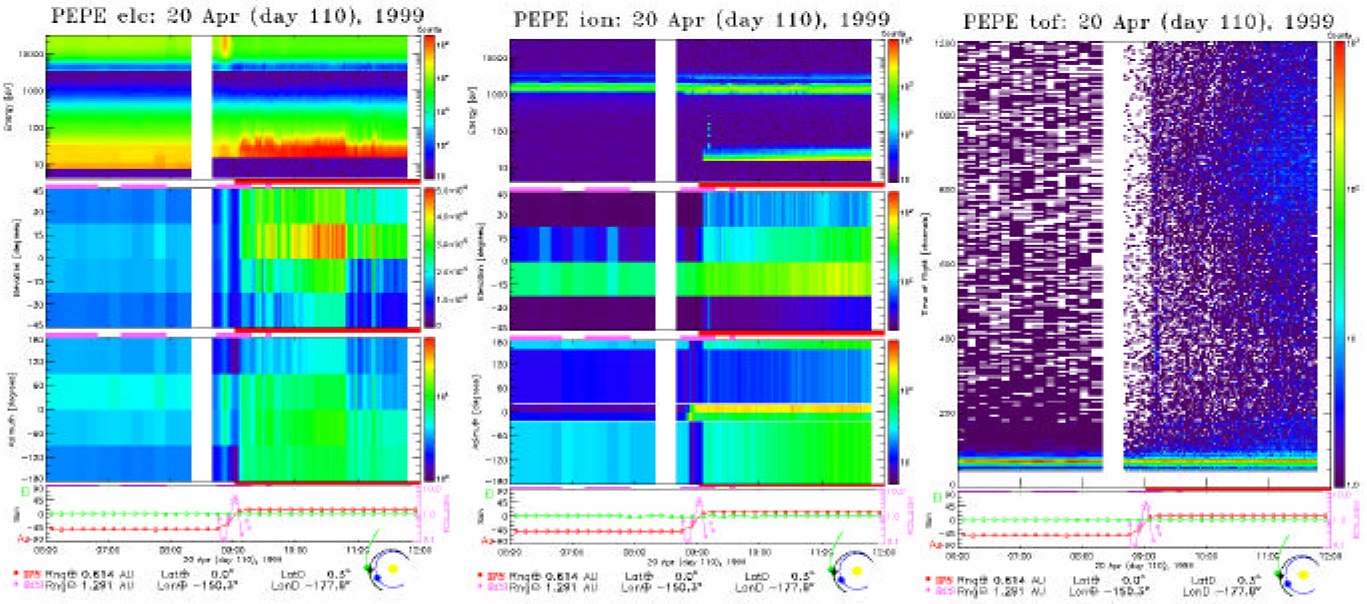

Figure 7. Data from 20 April 1998 0600-1200 UT Showing the Startup (~0905 UT) and Operation of the IPS Xe+ Thruster (The data gap is caused by data-mode changes on DS1. Electron fluxes mask the solar-wind and spacecraft electrons while the Xe+ ions are clearly seen at energies just above the PEPE cutoff of 16 eV.)

data memory is read out while a second spectrum is acquired into a second, identical memory. The two memories (consisting of 1.25 Mbytes each) are operated in ping-pong fashion to ensure the continuous availability of data for compression operations prior to transmission. In addition to forming raw TOF spectra, the system also histograms the TOF data, selects certain pre-programmed, regions of the spectra, and assigns counts within that region to M/Q channels. When operational, the M/Q histogrammer compresses the TOF data efficiently and reduces the amount of data needed to transmit composition information to the ground. Output-data rates can be varied from 1024 bits/s to 25 bits/s. The makeup of this data stream (e.g., the emphasis placed on electron vs. ion data, or TOF vs. singles data) can be changed on command

Over the course of the DS1 mission it has been necessary to reprogram parts of the data-acquisition and processing system to meet the needs, for example, of observations during the flyby of the small asteroid Braille at a velocity of 15 km/s. In that case, a new data sample period four times faster than the designed speed was implemented that could meet the requirements for faster sampling of a reduced region of interest in energy and angular space. Onboard programs used to bring up the PEPE high-voltage system have also been modified several times, as have the data products associated with particular scanning programs.

2.4.5 High-Voltage System—The PEPE electron and ion optics are driven by a system of 8 high-voltage supplies (Figure 3) ranging from programmable but relatively static voltages of ±3.6 kV and ±15 kV to fast-settling 12-bit controlled supplies of ± 2.5 kV and ±5.0 kV. There are two sets of ±5.0 kV bi-polar supplies that bias the toroidal deflection electrodes. Performance requirements for the supplies represented compromises in which some characteristics, such as drift and ripple, were allowed to increase slightly in order to simplify circuit design and parts counts. The compromise requirements were based on an assessment of the minimal relaxation that would produce acceptable performance. For example, the deflection and energy-analyzer optics have finite transmission passbands that can be relaxed somewhat in favor of reduced requirements on power-supply stability.

2.4.6 High-Density Packaging Architecture—PEPE contains eight high-voltage power supplies that deliver voltages throughout the instrument (see Figure 2). In order to save the weight and volume associated with bulky high-voltage connectors and cabling, the high-voltage supplies were co-located with the optical elements requiring biasing. Several of the supplies, including the ±15 kV supplies, were designed as single units that could easily be installed during final instrument buildup. However, other supplies were located deep within the optical system. These were generally hardwired to the optical elements and made use of optical or structural elements for both housing and mounting the supplies. In the CAPS design and the design of many conventional-plasma sensors, the optical elements and electronic components are usually separated into different compartments (if not entirely separate boxes). As is apparent from Figure 2, the PEPE-optical components are tightly packaged with PEPE-electronic components, particularly in the area of high-voltage supplies and detector electronics. In some cases, the optical paths pass through electronics boards and electronics circuits are placed inside the optical elements, such as the domes of the two electrostatic energy analyzers. This folded-up configuration saved a considerable amount of volume and, therefore, mass, compared to conventional packaging. The particular technologies used to produce compact design include: new methods for fabrication and surface treatment of high-voltage optical electrodes, incorporation of high-voltage signal de-coupling capacitors within detector-anode structures, monolithic microchannel-plate (MCP) holders with integral resistor/capacitor dividers, vapor deposition of thin high-ohmic resistive materials that replace discrete resistor chains, fabrication of suspended sections of multilayer printed-wiring assemblies that allow high-areal throughput of the optical beam through a PWA, high-voltage power supply housings manufactured from metal-coated plastics, and the extensive use of parylene coatings on high-voltage multipliers, which allowed the use of unpotted components. As mentioned above, the packaging density of PEPE is 0.83 g/cm^3, which is the highest value for plasma spectrometers of which the authors are aware.

2.5 Technology Interdependencies

2.5.1 PEPE Plasma Spectrometer Technology—Because PEPE is a highly capable plasma spectrometer, we have been able to demonstrate the effects that the DS1 ion propulsion system (IPS) and the DS1 spacecraft itself have on local plasma populations and on observations of solar-wind electrons and ions incident on the DS1 spacecraft. PEPE data taken during attitude maneuvers clearly show that there is a strong and irregular photoelectron sheath around the spacecraft. The sheath seems to be effected by the presence of large (~±50 V) differential potentials on the SCARLETT solar arrays and intermittently by the use of the attitude-control thrusters. Data also shows the very noticeable effect that the IPS has on the local-plasma population: low-energy, charge-exchanged xenon ions ejected by the interaction of the primary 1 keV beam with neutral xenon are observed by PEPE at energies up to ~40 eV (see Figure 7 and Reference [9]). Thermal electrons associated with the Xe$^+$ beam are accelerated up to ~100 eV and completely dominate the solar-wind electron flux. Nonetheless, the PEPE observations during IPS thrusting show that observations can still be made of solar-wind ions, though not of electrons.

2.5.2 Data-Acquisition and High-Voltage Systems—The flexibility of the PEPE data-acquisition and operating system technologies has allowed a number of unplanned new modes to be introduced in response to unexpected spacecraft-operational situations or measurement opportunities. A new ROI mode made unexpected use of the PEPE high-voltage supply technology when it was found that the supplies could be programmed to operate at four times their normal speed. The clock rate of the instrument was increased by a factor of four to allow fast scanning to take place. This new fast mode enabled higher time-resolution-measurements to be made during the asteroid flyby (lack of signal was due to the very weak or non-existent outgassing rate of the object) and will be used again during the planned cometary encounter.

2.6 Test Program

This section summarizes test objectives and success criteria that were used to meet the requirements for instrument validation set forth in Section 2.2. It should be emphasized, however, that the restricted schedule and budget under which PEPE was produced and tested often prevented detailed procedures from being drawn up. Moreover, there was little formal documentation of many test results for the same reason. This section will, therefore, address the test program in a quantitative way wherever possible but will resort to qualitative discussion if necessary.

2.6.1 Ground Test—

2.6.1.1 Miniaturized 3-dimensional Linear Electric Field (LEF3D) Time-of-flight (TOF) Optics—The TOF resistive-cylinder technology was tested by measuring the amount of current drawn with high voltage applied. The resistances of the 3 sections of the cylinder were consistently above 10 Gohm, the value required to meet high-voltage supply-load requirements. The high-voltage stand-off capability of the resistive cylinder was tested repeatedly. Several cylinder combinations were tested at 20% overvoltage (±18 kV) with varying results. The ultimate performance of the cylinder on the ground was very much effected by the amount of test time in which the system could be pumped to sufficiently high vacuum (~10^{-8} Torr) for periods of several weeks. In the end we were not able to achieve a stable-applied cylinder voltage above ~±8 kV, which was set as the initial on-orbit operating value. (Ironically, just a few weeks after PEPE was delivered, we were able to demonstrate a technology for potting the ceramic cylinders in a way that permitted ±18 kV to be achieved rather easily.) We planned to operate at the ±8 kV level initially and then boost the voltage after extensive outgassing was obtained on orbit.

The LEF3D optics and associated high-speed TOF electronics were tested in the LANL ion beam prior to integration with the rest of the PEPE instrument. The tests produced TOF spectra that were difficult to interpret because the beam was not collimated to reduce scattering and neutrals before it entered the TOF section. Ray-tracing simulations of the TOF optics indicated that the goal of $M/\Delta M \sim 20$ could be reached at ±15 kV.

2.6.1.2 High-Speed TOF Electronics—The TOF electronics were integrated with the optics prior to final testing before delivery. Detailed examination of the TOF spectra indicated that the TOF resolution per channel was 0.75 ns as required. The pulse-pair resolution of 40 ns was also achieved. Logical functions associated with the rejection of non-coincident events and correlations of coincident events were demonstrated. The performance of the built-in-test (BIT) pulser functions was consistent with results taken in the ion beam. Because of the compactness of the final delivery schedule, functional tests associated with measuring circuit dead times under the conditions of randomly-arriving events presented by the ion beam were not carried out.

2.6.1.3 Integrated Ion/Electron Optics—Because of schedule concerns, it was not possible to carry out tests of ion- and electron-optical components at the subsystem level (except for the TOF cylinder discussed above), which is the usual procedure before integration of an instrument. Therefore, the entire optical system was integrated and tested/calibrated at one time in the ion/electron-calibration system at SwRI. The pumpdown period prior to PEPE calibration also served as a single-cycle thermal vacuum test during which the instrument was first cycled hot to +60° C for 48 hours. This satisfied the hot-cycle requirement and also provided a high-vacuum (~10^{-6} Torr) bake-out period as well. A hot start and functional test were performed with the instrument in equilibrium at +45° C. The temperature was then lowered to –35° C and 3 cold starts were performed successfully. Cooling the instrument for these tests had the added advantage of reducing the chamber pressure to 4×10^{-8} Torr, thereby permitting internal-instrument surfaces to outgas more rapidly. The reduced-chamber pressure was an absolute must in order to allow the instrument interior to reach an estimated internal pressure in the 10^{-7} Torr range, where it would be safe to operate high voltage.

Ion beams of several energies were fired at the instrument and successfully recorded as singles events. The ion data indicated that the PEPE energy and angle passbands were in the correct locations and that the PEPE energy-analyzer constant (relating applied voltages to the incident ion energy) was correct. The energy-analyzer constant of 13.07 was close to that determined by ray-tracing (12.8). The angular-deflection constant (see Fact Sheet) could not be verified in the ion beam, although the functionality of the deflector system was verified. Tests of the ability of the multiple-anode system showed that it was operational. An interface problem between the data-acquisition system and the TDC prevented us from obtaining ion TOF-data during an end-to-end test of the optics and electronics. The test was deferred to flight.

A broad energy/angle-electron source was used to stimulate the electron side of the PEPE optics simultaneously with the ion side and this qualitative test was successful. The swept-FOV function was demonstrated for both species, as was the ability to produce scanned-energy spectra. The ion/electron-beam tests also demonstrated qualitatively that both MCP detectors were operational and operating at roughly nominal efficiencies.

2.6.1.4 Data-Acquisition System—During bench testing, the system successfully acquired all of the data types generated by the internal-pulser system. During vacuum testing, the system successfully acquired and formatted electron- and ion-singles data. The interface problem referred to above was corrected on the bench, but tests of the repaired system were deferred to flight operations.

2.6.1.5 High-Voltage System—The eight power supplies making up the PEPE high-voltage system were first tested on the bench and shown to operate as specified. In particular, the individual voltage levels, voltage waveforms, and transition slew rates were all shown to be within specifications. Once the supplies were integrated with the sensor, it became impossible to test them directly at the output because the electrodes would not tolerate operation at full voltage in air (this is a standard complication). After system assembly, the supplies are monitored on the primary side in PEPE housekeeping data; however, the only way to validate supply operation is through data produced by plasma populations in flight.

Vacuum testing of the high-voltage system was monitored by the ion and electron detectors and by voltage monitors located on the primary side of the supply transformers. Because of problems encountered earlier during testing of the TOF cylinder, tests of the integrated TOF-HV system in vacuum were limited to ±8 kV. Even at this level, it was noted that the positive TOF-HV monitor tended to sag to slightly lower values. There was no further opportunity to re-test this problem and no fix was attempted on the bench. Because of the relatively high-vacuum pressures during ground testing, the testing of automated-HV turn-on sequences was deferred to flight.

2.6.1.6 High-Density Packaging Architecture—The final ground assembly of the unit proved that the high-density packaging concept worked to the extent that all the parts were inside. Successful high-voltage tests in vacuum (except for the positive TOF-HV sag noted above) proved that the optical and high-voltage systems were packaged correctly. Voltage breakdown during the test would have been indicated by high background rates in the electron and ion MCP detectors; this was not observed. The PEPE instrument density of 0.83 g/cm^3 was determined by dividing the instrument mass by a calculated volume.

2.6.2 Flight Test—Once on-orbit, the PEPE instrument was activated successfully over two DS1 passes on December 8 and 9, 1998. The initial data returned during this period confirmed that end-to-end performance of the PEPE system was nominal (although no detailed-quantitative results could be obtained immediately). On December 10, the IPS was turned on with PEPE operating. It was immediately clear that the fluxes of Xe+ ions and electrons in the lower part of the PEPE energy range were too intense for the PEPE MCP detectors. Subsequent to this, a patch to the PEPE software blocked PEPE energy scans from operating below 16 eV in order to reduce the intensity of the IPS fluxes to tolerable levels on the detectors.

2.6.2.1 Miniaturized 3-dimensional Linear Electric Field (LEF3D) Time-of-flight (TOF) Optics—Once on orbit, the LEF3D optics were used to determine the TOF and M/Q spectra of solar-wind ions. The E/Q ion spectra obtained from the ion singles events also reflect the composition of the solar wind during periods when the solar-wind Mach number is high (>8). These spectra were compared with TOF spectra to demonstrate that the latter were in quantitative agreement. It was also possible to observe xenon and molybdenum ions in the TOF spectra as would be expected during periods of IPS thrusting. Final confirmation of the operation of the TOF system awaits observations of cometary molecules that break up to produce more complex TOF spectra. Resolution of the solar-wind TOF spectra (Figure 8) is consistent with anticipated low-resolution values of M/ΔM ~5. High-resolution features have been identified in the spectra corresponding to M/ΔM ~17 to 21. The resolution of the H^+ peak at a TOF of 70 channels (1 channel = 0.75 ns) is somewhat lower; however, that is expected because of the larger fraction of error that is introduced by the TOF electronics at these short times. Preflight calibration indicated that these were the approximate resolutions; however, because calibration of the TOF section was performed without the collimation provided by the energy-analysis section, it was not possible to determine the exact mass resolution. Figure 8 shows the direct events data (fully resolved and uncompressed) from approximately 3 hours of accumulated time on 2 different days in the solar wind. In Figure 8, the data from both days was summed over energy so that TOF peaks could be more easily picked out. Each peak was analyzed using the energy information also provided in the data. The notation used in the peak labels refers to the ion-charge state before entering PEPE and after the arrow the state that exited the foil is shown. The branching ratios for each ion is known and the peaks, as labeled, are consistent with known charge-state branching ratios in thin-carbon foils and the attendant efficiencies. It is somewhat difficult to determine the ultimate-mass resolution for the TOF section because the high-charge states in the solar wind rarely emerge unchanged or more positive from the foils; unless this is the case, ions will not "bounce" and be measured at high resolution.

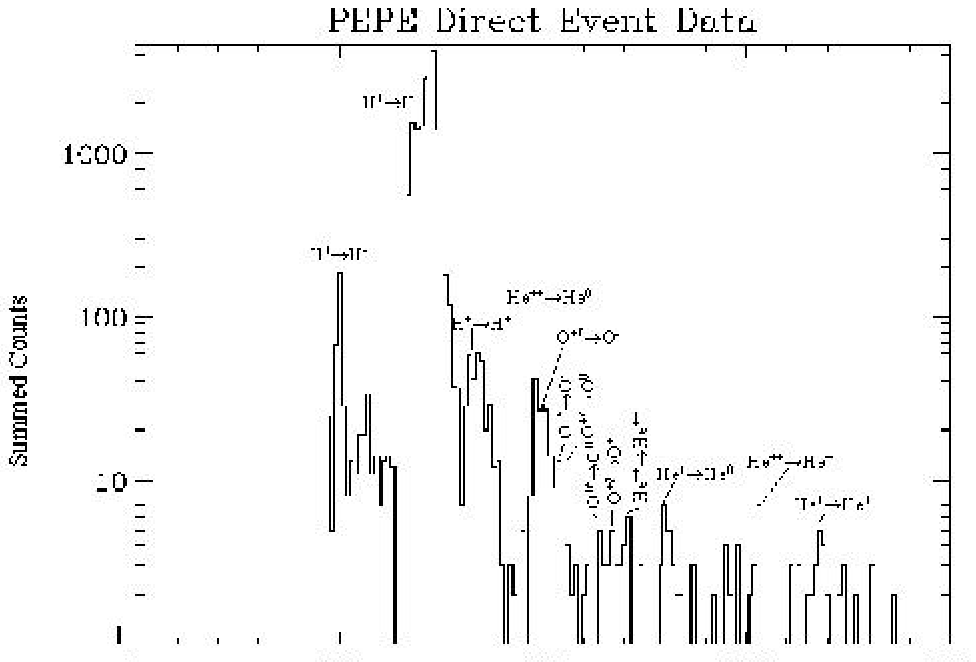

Figure 8. TOF Spectrum Based on Direct Event TOF Data (This shows solar wind ions at the highest available TOF resolution. Note that the peaks that originated as He^+ are believed to have derived from the pressurization system of the spacecraft thruster system and not the solar wind.)

2.6.2.2 High-Speed TOF Electronics—The TOF electronics appear to deliver performance consistent with ground measurements. The presence of high-resolution TOF peaks in the spectra confirms the proper functioning of the TOF electronics. The operation of the BIT function has been confirmed in-flight.

2.6.2.3 Integrated Ion/Electron Optics—PEPE data obtained from observations of the solar wind were compared with WIND/SWE instrument data (Figure 9) to obtain calibration factors relating flux intensity and energy/angle response of PEPE to engineering values of density, temperature, and flow velocity. PEPE's values appear consistent within ~10% of measurements made by the WIND instrument. This estimate is based on what appear to be valid correlations between observations made at PEPE and those made at WIND, which is ~10^6 km distant. The comparison was established by time-shifting the two solar-wind ion spectra until maximum correlation of the density, bulk, and thermal velocities were found. The result is fairly good, as is apparent from Figure 9.

Several other features of the optics have been confirmed as well. PEPE optics and anti-reflective surface treatments were designed to allow the aperture to face directly into the Sun without creating a large flux of internal photoelectrons and resulting background. As seen in Figure 5, a spectrum of the quiet solar wind shows that the PEPE optics are solar blind to the extent that there is no perceptible background above that caused by the spacecraft itself. The cause of the electron background signal at energies >4 keV is not understood. This background is variable, at times disappearing, and does not seem to be related to spacecraft attitude. As is apparent from Figure 5, the background does not interfere with measurements of electrons from either the solar wind or the spacecraft sheath. The data at the bottom of Figure 5 indicate that the spacecraft attitude during which the data were obtained was such that the PEPE aperture was directly viewing the sun at the time. The ability of the deflection optics to keep the solar-wind beam in the instrument FOV despite turns made by the spacecraft is also demonstrated in Figure 6, where the solar wind is quite active but is still tracked by the PEPE deflection system. This shows that the deflection system operates correctly (at least up to solar-wind energies of several keV).

Another important test of the instrument is demonstrated by the data shown in Figure 7**,** which are taken from a period when the IPS engine was turned on and operated. The ion data clearly show the start-up of the thruster at 0910 UT. The slight disturbance in the electron spectrum at 0850 UT seems to be related to attitude-control thruster firings prior to the main-engine firing at 0910. The electron fluxes intensify just before that time, probably in response to the plasma neutralizer that emits large numbers of electrons. It is also clear the electron fluxes are highly variable; however, the reason is not understood.

Figure 10 shows the average TOF spectra summed over energy and angle for each of three full days. On the day of year (DOY) 009 of 1999, the IPS was not running. On DOY 083 and DOY 216 of 1999, the IPS ran continuously throughout the day and there was very little, if any, thruster activity. The line spectra clearly show a molybdenum (Mo) peak that appears only on the later day when the IPS had accumulated many hours of firing. The peak at ~450 TOF bins is possibly argon; however, possible sources of argon are unknown. This could be a molecular peak with nearly the same total mass. Further investigation is required; however, it is clear that PEPE is capable of providing a very detailed analysis of processes around the spacecraft.

2.6.2.4 Data-Acquisition System—The data system has successfully acquired, compressed, and transmitted more than 75,000 full spectra in the course of operations so far. All of these spectra have been plotted in a summary format shown, for example, in Figures 5, 6, and 7. Examination of the different spectra indicate that the data system acquires and formats the data correctly. High-counting-rate random electron and ion TOF events have been observed throughout this period and have been processed correctly. As noted above, a comparison of PEPE's solar-wind data with that from WIND/SWE indicates that acquisition and processing of PEPE data are being carried out correctly and are free of artifacts that might be introduced by this process. The mass/charge (M/Q) function has not been fully tested because emphasis has been put on the analysis of other data formats.

2.6.2.5 High-Voltage System—The high-voltage system appears to operate correctly. However, a recent anomaly with the operation of the TOF system may be related to sagging of the +HV monitor noted during vacuum testing of the system on the ground. This problem is under investigation. Both ion- and electron-detector backgrounds are very low (<1 count/cm^2 s [see the spectra in Figures 5 and 6]) and are consistent with the thermionic and cosmic ray backgrounds expected in space. This indicates that very little, if any, noise or ripple is being introduced by the supplies. PEPE's automatic HV turn-on sequence now in use is executed automatically and brings PEPE to full operation within 2 hours (vs. the 4 hours that were originally planned).

2.6.2.6 High-Density Packaging Architecture—The optical and high-voltage systems have performed correctly in flight. This demonstrates that the high-density packaging architecture of PEPE (0.83 g/cm^3) is successful.

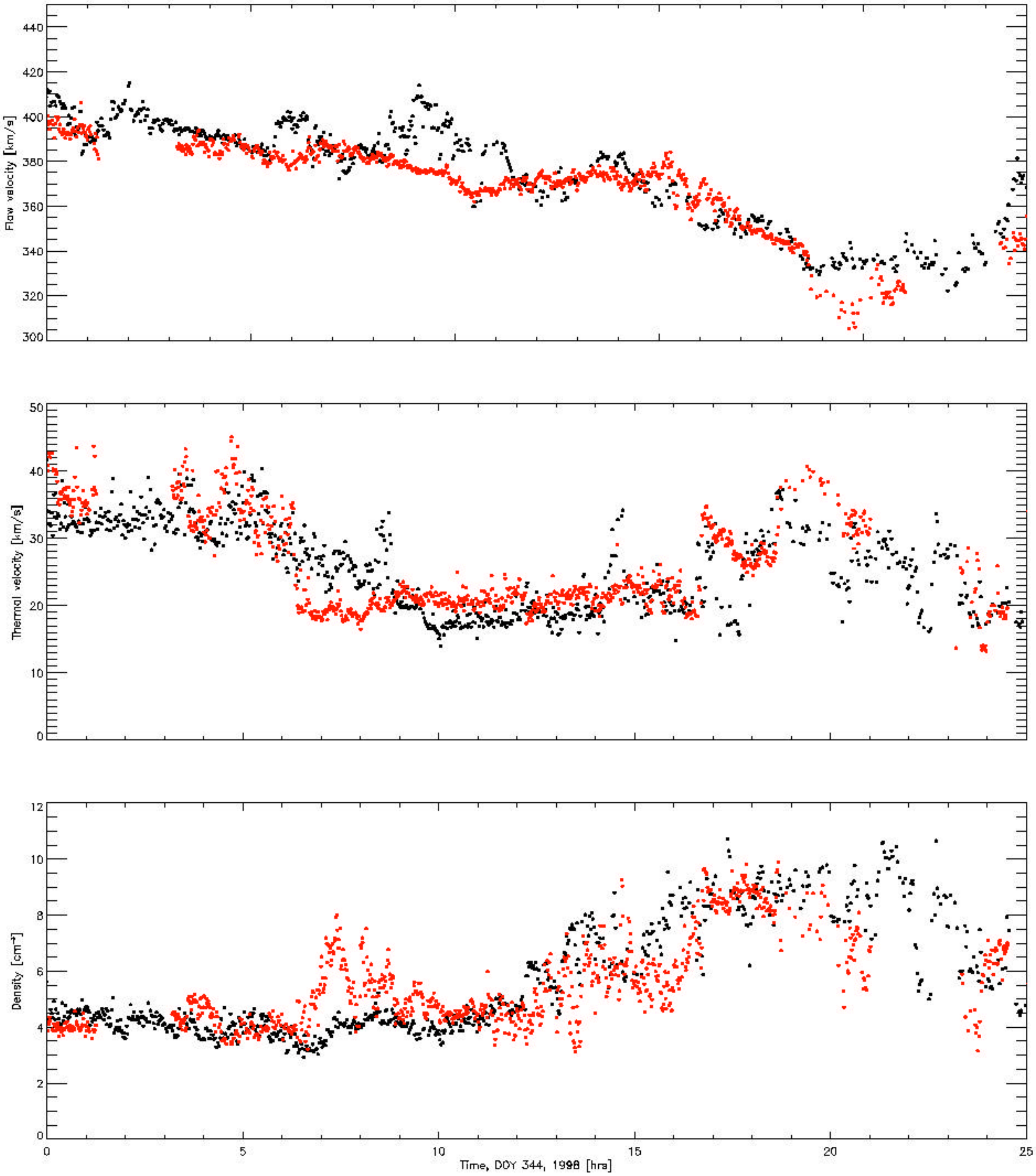

Figure 9. Spectra Comparing Solar-Wind Data From PEPE and the WIND/SWE Instrument (PEPE dataare in red. The two time series have been shifted to obtain the best-time series correlation. Figure courtesy Frank Crary.)

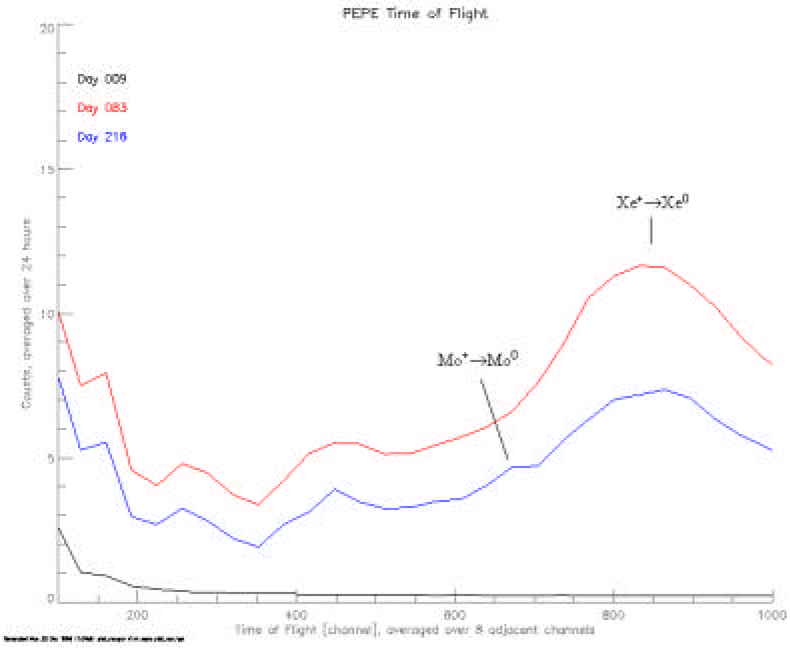

Figure 10. Daily Average TOF Counts for a Day Without IPS Firing (Day 009, 1999), a Day With Continuous IPS Firing Early in the Mission (Day 083, 1999), and a Day Much Later in the Mission With Continuous IPS Firing (Day 216, 1999) (Note the appearance of a molybdenum peak on the last day.)

2.7 Comparison Between Ground and Flight Test

Most of this comparison has been carried out during the discussion of ground and flight tests mentioned above. PEPE has generally proven itself to be a very capable and flexible plasma spectrometer. It is impossible to create any of the space-plasma environmental conditions encountered in space by PEPE on the ground. Ground calibration is restricted to unidirectional, mono-energetic beams of particles that are a poor approximation of the plasmas encountered in space. The single problem that has been encountered in flight (TOF-high-voltage operation) was known from ground testing, but could not be addressed because of the impacted-development schedule. The fact that a successful method was found to address this problem for future applications of the technology by potting the TOF cylinder indicates that the miniaturized-TOF system can be made to work successfully on a future mission.

3.0 TECHNOLOGY VALIDATION SUMMARY

PEPE and its related technologies have been demonstrated to work very well during the flight phase of the mission. All of the six technologies incorporated into PEPE have been validated during the flight phase of the mission with the exception of the operation of the high-voltage system at maximum voltage. However, later tests of an improvement made to the technology on the ground show that the miniaturized TOF system and associated high-voltage subsystem work very well and will be available for future missions. The PEPE data are of very high quality and are finding their way out to the wider scientific community for further analysis. The ultimate test of PEPE performance must wait for the arrival of the DS1 spacecraft at one or both of the target comets during 2001. That opportunity will allow PEPE to demonstrate the full capability of the six-instrument technologies while contributing to our understanding of cometary physics.

4.0 TECHNOLOGY APPLICATION FOR FUTURE MISSIONS

The PEPE instrument is ideally suited for comprehensive studies of space plasmas on future planetary and magnetospheric missions. The ion/electron optics that perform an analysis of ion and electron directions of arrival and energies have already been incorporated into the Ion Electron Spectrometer instrument scheduled to be flown on the Rosetta Cometary mission in 2007. Individual PEPE technologies, such as the miniaturized high-voltage power supplies, have already served as the basis of improvements in this area. The group at SwRI responsible for the supplies have built a prototype of the MCP supply that weighs 60 grams (vs. the 100 grams for the equivalent PEPE supply). The data acquisition system is being further miniaturized by using more capable gate arrays. In addition, the possibility of custom ASICS designed for this purpose are being investigated for future planetary missions requiring much harder parts.

5.0 LIST OF REFERENCES

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Appendix A: PEPE's Telemetry Channels

W	HKID	New Name	Original Name	Chan ID	Type	Bit pos	Bit len	Calibration	State Title	Units
0	0		CCSDS_HEADER	n/a	n/a	0	96	n/a	n/a	n/a
6	0		mon_mcp_ion	G-0301	unsigned	96	16	u16 * -0.97568-12.3	n/a	volts
7	0	mon_mcp_elc (spelling)	mon_mpc_elc	G-0302	unsigned	112	16	u16 *1.067556-11.9	n/a	volts
8	0		mon_tof_p15k	G-0303	unsigned	128	16	u16 * 3.991378-54.6	n/a	volts
9	0		mon_tof_n15k	G-0304	unsigned	144	16	u16 * -3.98304+37.8	n/a	volts
10	0		mon_sys_p5	G-0305	unsigned	160	16	u16 * 0.001280	n/a	volts
11	0		mon_sys_n5	G-0306	unsigned	176	16	(-1) * u16 * 0.001280	n/a	volts
12	0		mon_sys_p12	G-0307	unsigned	192	16	u16 * 0.003290	n/a	volts
13	0		mon_calor_1	G-0308	unsigned	208	16	u16 * 0.001221	n/a	volts
14	0		mon_calor_2	G-0309	unsigned	224	16	u16 * 0.001221	n/a	volts
15	0		mon_calor_3	G-0310	unsigned	240	16	u16 * 0.001221	n/a	volts
16	0	(Note type change)	eha_generr	G-0311	digital	256	16	n/a	n/a	n/a
17	0	(Note type change)	eha_volterr	G-0312	digital	272	16	n/a	n/a	n/a
18	0	(Note type change)	mon_esa_elc	G-0313	digital	288	16	Note Children sheet	n/a	n/a
19	0	(Note type change)	mon_esa_ion	G-0314	digital	304	16	Note Children sheet	n/a	n/a
20	0		mon_def_pos	G-0315	unsigned	320	16	(u16-2048) * 2.4414	n/a	volts
21	0		mon_def_neg	G-0316	unsigned	336	16	(u16-2048) * 2.4414	n/a	volts
22	0		*spare*	G-0317	digital	352	1	n/a	n/a	n/a
22	0		ps_fix_stat	G-0318	status	353	1	n/a	OFF | ON	n/a
22	0		ps_swp_stat	G-0319	status	354	1	n/a	OFF | ON	n/a
22	0		ps_mcp_elc	G-0320	status	355	1	n/a	DISABLED | ENABLED	n/a
22	0		ps_mcp_ion	G-0321	status	356	1	n/a	DISABLED | ENABLED	n/a
22	0		ps_tof_p15k	G-0322	status	357	1	n/a	DISABLED | ENABLED	n/a
22	0		ps_tof_n15k	G-0323	status	358	1	n/a	DISABLED | ENABLED	n/a
22	0		ps_bulk_en	G-0324	status	359	1	n/a	DISABLED | ENABLED	n/a
22	0		ps_SafeArm_c	G-0325	status	360	4	n/a	SAFED | DIV16 | ARMED	n/a
22	0		ps_SafeArm_s	G-0326	status	364	4	n/a	SAFED | DIV16 | ARMED	n/a
23	0	ps1_ps4_regs	ps_status_0	G-0327	digital	368	16	n/a	n/a	n/a
24	0	ps7_abdv_reg	ps_status_1	G-0328	digital	384	16	n/a	n/a	n/a
25	0		if_rti_count	G-0329	unsigned	400	16	n/a	n/a	n/a
26	0		if_sa_error	G-0330	digital	416	16	n/a	n/a	n/a
27	0		if_time_cnt	G-0331	unsigned	432	16	n/a	n/a	n/a
28	0		if_heart_cnt	G-0332	unsigned	448	16	n/a	n/a	n/a
29	0	sc0_ctrl_reg	if_status_0	G-0333	digital	464	16	n/a	n/a	n/a
30	0	sc1_obst_reg	if_status_1	G-0334	digital	480	16	n/a	n/a	n/a
31	0	SPARE	*spare*	G-0335	digital	496	1	n/a	n/a	n/a
31	0	SPARE	imp_ram_err	G-0336	status	497	1	n/a	OK | ERROR	n/a
31	0	SPARE	imp_rom_err	G-0337	status	498	1	n/a	OK | ERROR	n/a
31	0	SPARE	imp_shrd_err	G-0338	status	499	1	n/a	OK | ERROR	n/a
31	0	SPARE	imp_watchdog	G-0339	status	500	2	n/a	DISABLED | ENABLED	n/a
31	0	SPARE	*spare*	G-0340	digital	502	2	n/a	n/a	n/a
31	0	SPARE	*spare*	G-0341	digital	504	8	n/a	n/a	n/a
0	1		CCSDS_HEADER	n/a	n/a	0	96	n/a	n/a	n/a
6	1	ps2_swpa_reg	imp_status_0	G-0342	digital	96	16	n/a	n/a	n/a
7	1	ps3_swpb_reg	imp_status_1	G-0343	digital	112	16	n/a	n/a	n/a
8	1	SPARE	*spare*	G-0344	digital	128	1	n/a	n/a	n/a
8	1	SPARE	dpu_ram_err	G-0345	status	129	1	n/a	OK | ERROR	n/a

Appendix B: Date of PEPE's Turn-on and Provisional Times-of-Data-Capture List

Note: PEPE operation times are approximate to nearest hour. Intervals lasting less than 24 hours without operations are not recorded.

Start Time (UT)	Date	Stop Time (UT)	Date	Comments
0140	08 Dec 98	0110	10 Dec 98	PEPE Checkout
1900	06 Jan 99	1700	17 Jan 99	
0600	21 Jan 99	0800	01 Feb 99	
2300	02 Feb 99	0300	10 Feb 99	
0000	13 Feb 99	0100	17 Feb 99	
0000	18 Feb 99	1900	23 Feb 99	
0100	25 Feb 99	0100	16 Mar 99	
1200	23 Mar 99	2000	03 May 99	
0300	26 May 99	1900	07 Jun 99	
2300	11 Jun 99	2400	11 Jul 99	
0000	13 Jul 99	1800	05 Aug 99	Turned off due to DS1 anomaly