Spacelab 2 Plasma Diagnostics Package

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The Plasma Diagnostics Package is a small, deployable satellite designed to study the interaction of the Space Shuttle Orbiter with the ionospheric environment as well as to be used in joint experiments with the plasma depletion and the vehicle charging and potential investigations during the Spacelab 2 mission. This paper provides a brief description of the small spacecraft, its instrumentation and operation, and the scientific objectives of the investigations. A brief summary of the scientific results obtained thus far is also presented.

Introduction

THE Plasma Diagnostics Package (PDP) was one of 13 investigations that were a part of the Spacelab 2 mission that occurred during July 29–August 6, 1985. As its name implies, the PDP is equipped with a coordinated set of sensors and instruments designed to measure a wide range of parameters characterizing the ionospheric environment surrounding the Orbiter. The objectives of the investigation are to study the interaction of the Orbiter with the ionosphere, the interaction of an electron beam with the ionospheric plasma, and various naturally occurring ionospheric phenomena.

During the Spacelab 2 mission, the PDP was operated in its launch configuration in the payload bay, at various vantage points around the Orbiter while being maneuvered by the Remote Manipulator System (RMS), and at distances of up to about 400 m from the Orbiter while operating as a free-flying subsatellite of the Orbiter. In each of these operational configurations the PDP obtained measurements supporting the various scientific objectives. During much of the mission, the PDP was operated jointly with the plasma depletion and the vehicle charging and potential (VCAP) experiments for correlative studies.

The PDP had been flown previously on STS-3 as part of the first Office of Space Science (OSS-1) payload in March 1982.[1] The instrument complement was similar to the Spacelab 2 PDP, although not identical, and observations were obtained only from the payload bay and the RMS. There was no provision for the PDP to operate as a free flyer on STS-3.

Some of the primary conclusions obtained during the Spacelab 2 PDP flight are as follows:

1) The influence of the Shuttle Orbiter on the ionosphere extends beyond the 0.4-km region sampled by the PDP.

2) The Orbiter is surrounded by a water cloud that extends to distances as great as 8 km.

3) Ions formed by the "pickup" of contaminant water molecules are likely to be the source of intense, broadband electrostatic waves observed in the vicinity of the Shuttle Orbiter.

4) The Orbiter forms a well-developed wake in the ionosphere with a length of at least 250 m.

5) The injection of a 1-keV electron beam produces whistler mode waves analogous to very low frequency (VLF) hiss found naturally in conjunction with auroral electron beams.

6) The injection of the electron beam forms a narrow sheet of energetic electrons in the wake of the Orbiter that is accompanied by broadband electrostatic waves.

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In this paper, we outline the general scientific objectives of the PDP for the Spacelab 2 mission, describe the PDP and its complement of instruments, provide an overview of the operations of the PDP during the mission, and summarize the results gained to date from the PDP.

Scientific Objectives

One of the major scientific objectives of the PDP investigation on Spacelab 2 was to characterize and understand the interaction of the Orbiter with the ionospheric environment through which it flies. The Orbiter is a large object; in fact, it is large with respect to virtually all of the important plasma scale lengths at its approximately 325-km altitude orbit, including the thermal ion gyroradius. Furthermore, the Orbiter moves with great speed through the ionospheric plasma, typically about 8 km/s. This situation provides the opportunity to study the formation of wakes and turbulence generated by a large body moving through the plasma. All previous satellite measurements were of much smaller bodies and often in plasma regimes with much larger scale sizes.[2,3]

On Spacelab 2, the PDP carries out a coordinated set of wake observations at distances ranging from very close (i.e., a few meters) to nearly 400 m. In addition, the Orbiter provides its own set of active experiment opportunities in the form of chemical contamination experiments. The most obvious examples of these are the joint experiments with the Spacelab 2 plasma depletion experiment for which the PDP provides supporting in situ data for the ground-based observation of the effects of firing the Orbital Maneuvering System (OMS) engines in the plasma.[4,5] The Orbiter, however, is almost continuously depositing large quantities of contaminants into the ionosphere through outgassing leaks from pressurized vessels, the operation of the Reaction Control System (RCS) jets required to jet and maintain various attitudes, and the deliberate discharging of both liquid and gaseous water as normal maintenance operations.[6,7]

Another primary objective of the PDP on Spacelab 2 was to operate jointly with the Fast Pulse Electron Generator portion of the VCAP experiment provided by Stanford University and Utah State University.[8] The primary purpose of VCAP was to investigate the interaction of an energetic (1 keV) beam of electrons with the ionospheric environment. This experiment has importance for the study of naturally occurring auroral phenomena observed elsewhere in the ionosphere but takes advantage of the active control of the electron beam to isolate various aspects of the beam-plasma interaction. The electron beam studies were also undertaken during STS-3, but Spacelab 2 offered experiments that benefited from the STS-3 RMS experience and the important opportunity to observe at distances a factor of 10 or more larger in the free-flight configuration.

Finally, it was planned to investigate naturally occurring ionospheric phenomena with the PDP while in free flight, but one of the most important discoveries of the Spacelab 2 PDP is that one must move much further away from the Orbiter than the 400-m distances achieved during Spacelab 2 to fully escape the influence of the Orbiter.[6,7,9] Hence, the ambient ionospheric studies have been overshadowed by the Orbiter and electron beam interaction studies. It should be noted that some natural phenomena were observed, such as VLF whistlers, therefore, some such studies are still possible.

Instrumentation

Spacecraft Description

The PDP was designed and fabricated by the University of Iowa and is a unique Spacelab experiment in that it is designed to make observations while 1) attached to the Spacelab pallet in the payload bay, 2) being maneuvered about the Orbiter by the RMS, and 3) operating as an independent satellite in orbit near the Orbiter. To accomplish the third goal, the PDP had to be designed primarily as a free-flying satellite, but with provisions to be carried aloft within the payload bay and to be grappled and articulated by the RMS. Modifications late in the development of the PDP further allowed its recapture, preserving the possibility of reusing all or part of the spacecraft in future programs.

The PDP, shown in free flight during the Spacelab 2 mission in Fig. 1 and in schematic form in Fig. 2, is cylindrically shaped with a diameter of about 42 in. (1.07 m) and a weight of about 625 lb (284 kg). Various sensors are mounted on the four deployable booms, and numerous instruments have apertures through the spacecraft skin. The appendage at the top of the spacecraft is an electrical grapple fixture that allows the PDP to be manipulated by the RMS as well as operated electrically through cables in the RMS that are connected to a special switch panel on the aft flight deck of the Orbiter.

The small cylinder just below the grapple fixture contains a momentum wheel loaned by the Smithsonian Institution from the ATS-G satellite. The wheel is used to store angular momentum in the PDP prior to release for free flight. The stored angular momentum was subsequently used to spin the PDP up to about 4.6 rpm during the free-flight phase by allowing the momentum wheel to spin down with respect to the PDP structure. Prior to recovery, the wheel was spun up again to transfer the angular momentum back out of the structure, thereby despinning the spacecraft to allow recapture by the RMS.

Instrument Summary

The PDP contains an integrated set of instruments to provide a broad range of measurements of plasmas, dc and oscillatory electric and magnetic fields, and neutral pressure. Because of funding limitations, many of the scientific instruments are flight spare units from such projects as IMP, Helios, and ISEE. Table 1 provides an overview of the various scientific instruments flown on the Spacelab 2 PDP, the investigators providing the instrumentation, and a brief summary of the measured parameters. The sensor locations are shown in Fig. 2.

PDP Operations

The PDP operations performed during the Spacelab 2 mission can be organized best by separating them into operations performed while 1) on the Spacelab pallet, 2) being manipulated by the RMS, and 3) functioning as a free-flying satellite in orbit with the Orbiter. In the following subsections, we will describe briefly the operations in each of these phases. Table 2 summarizes the major PDP in-flight operations.

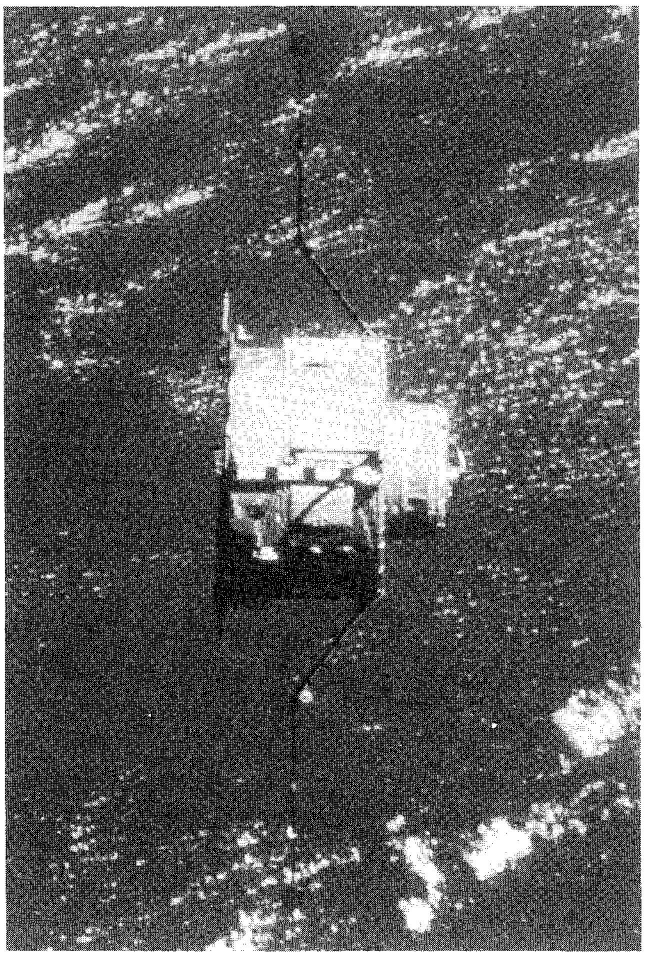

Fig. 1 Photograph of the PDP deployed in its free-flight configuration during the Spacelab 2 mission.

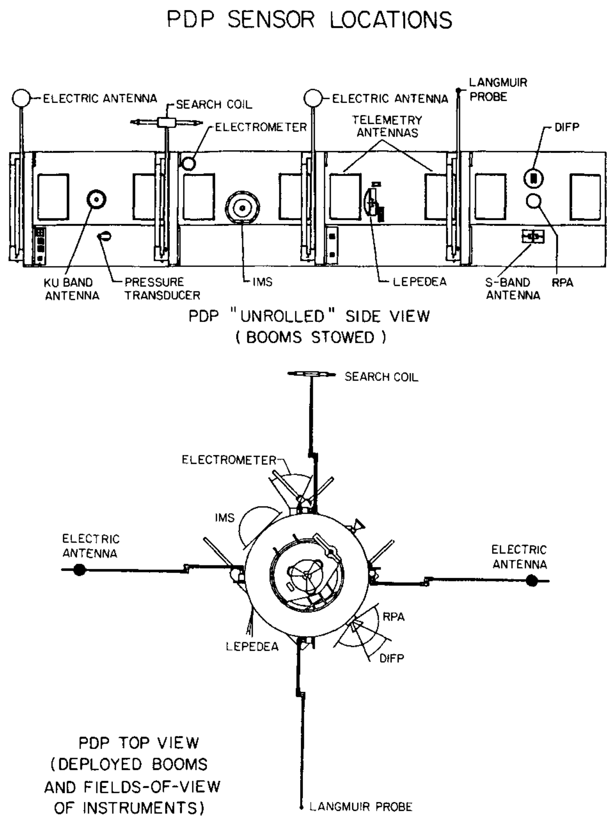

Fig. 2 Top panel shows locations of the various instrument viewports and sensors (see Table 1) in a schematic of the PDP shown with the sidewall of the spacecraft "unrolled." The bottom panel is a view of the PDP from the top showing the locations of the booms and the boom-mounted sensors in the fully extended configuration. The fields of view of the plasma analyzers are also indicated.

Table 1 Spacelab 2 PDP scientific instruments

Instrument	Provider	Measurement
Ion mass spectrometer (IMS)	J. M. Grebowsky Goddard Space Flight Center	Thermal ions; 1–64 amu; 20–2×10^{6} cm^{-3}
Retarding potential analyzer (RPA)	D. L. Reasoner Marshall Space Flight Center	Ions; 0–15 eV; 20–10^{7} cm^{-3}
Differential ion flux probe (DIFP)	N. H. Stone Marshall Space Flight Center	Ions; 0–15 eV; 6×10^{-2}–3×10^{5} cm^{-3}; 3-deg angular resolution in range of ±45 deg from PDP equator
Lepedea	L. A. Frank Univ. of Iowa	Ions and electrons; three-dimensional velocity distributions; 2 eV–36 keV; plus electrometer with range 10^{9}–10^{14} electrons/cm^{-2} s^{-1}
Langmuir probe	N. D'Angelo Univ. of Iowa	Thermal electrons; 10^{3}–10^{7} cm^{-3}; $500<T_e<4000$ K; $\Delta N/N$ spectrum up to 178 kHz
Neutral pressure gage	J. S. Pickett Univ. of Iowa	$10^{-7}<P<10^{-3}$ Torr
Triaxial fluxgate magnetometer	S. D. Shawhan NASA Headquarters	±1.5 G with 0.012 G resolution; 3 axes; 10-Hz sample rate per axis
dc electric field detector	D. A. Gurnett Univ. of Iowa	±2-V/m single axis; 0.5-mV/m resolution (booms extended); 20-Hz rate; plasma potential ±8 V; 20 – mV resolution
Plasma wave receivers	D. A. Gurnett Univ. of Iowa	Electric: 30 Hz–17.8 MHz in 24 channels; magnetic: 35 Hz–~10 kHz in 11 channels; wideband analog: 5 Hz–30 kHz electric and magnetic
S- and K_u-band monitors	G. B. Murphy Jet Propulsion Lab.	S-band: 1.4–3.0 GHz; K_u-band: 13.5–14.5 GHz

Table 2 Spacelab 2 PDP significant events timeline

Event	Date 1985	GMT
Launch	7/29	2100
PDP activation in bay	7/30	0039
PDP grappled by RMS	7/30	2326
RMS-mounted observations begin	7/30	2338
PDP parked over port wing	7/31	0835
RMS-mounted observations resume	7/31	1840
PDP parked over port wing	7/31	1928
RMS-mounted observations resume	7/31	2023
PDP parked over port wing	7/31	2114
PDP released for free-flight	8/1	0010
PDP captured, end of free flight	8/1	0620
PDP parked over port wing	8/1	0644
Additional RMS-mounted observations[a]	8/2	1824
PDP latched in bay[b]	8/2	2241
PDP deactivation	8/6	0528
Landing	8/6	2000

[a] PDP was used as a target for infrared glow observations.
[b] Power to the PDP was occasionally cycled off for thermal considerations.

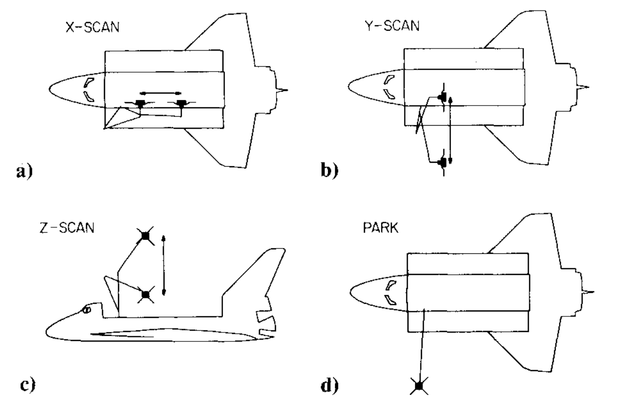

Fig. 3 Most of the RMS manipulations of the PDP during Spacelab 2 were the series of motions parallel to the principal axes of the Orbiter shown here. A few other special sequences were also used that are not shown here.

Pallet Operations

The PDP was carried into orbit while latched onto the Spacelab pallet and was returned to Earth in the same configuration. The initial activation and checkout were performed just a few hours after launch as soon as the payload bay doors were opened and the Spacelab support systems were activated. During the on-pallet operations early in the mission, the PDP was able to monitor the activation of other instruments from an electromagnetic interference point of view as well as observe the initial outgassing of the Orbiter and its payload.[10] All PDP instruments were activated soon after the PDP was powered up with the exception of the Lepedea, which uses a high-voltage power supply and is susceptible to coronal discharge prior to complete outgassing.

The PDP also spent the final four days of the mission positioned on the pallet while intensive solar and dark sky observations were being performed by other Spacelab investigations. During this time, the PDP passively monitored the payload bay environment and supported the VCAP electron beam experiments. The solar observations required a bay-toward-sun attitude for many orbits in succession, which led to overheating of a few of the PDP subsystems. In response to the overheating, the PDP was deactivated occasionally to allow temperatures to return to acceptable values. No thermal damage was experienced despite the elevated temperatures.

RMS Operations

The PDP was grappled by the RMS at 1 day, 2 h, and 26 min into the mission (or mission elapsed time), corresponding to 2326 Greenwich Mean Time (GMT) on July 30, 1985. During the next 3 days, the PDP was manipulated actively by the RMS in studies of the Orbiter-ionosphere interaction and electron beam interactions, for a total data-gathering period of about 11 h. During the remaining portion of those 3 days, the PDP was either stowed in a noninterfering position over the port wing at a park point (Fig. 3d) or was in free flight.

During the active portion of the RMS operations, the PDP was moved about the Orbiter in a number of preprogrammed maneuvers in support of the various scientific objectives. Several of these maneuvers are depicted in Figs. 3a–c. The primary maneuvers moved the PDP longitudinally parallel to the roll axis of the Orbiter (X scans), or parallel to the pitch axis of the Orbiter (Y scans), or vertically up and down over a fixed location in the bay (Z scans). The maximum extension of the RMS is about 15 m. However, the PDP was never more than about 13 m from the Orbiter while attached to the RMS. At various times during the scans, the PDP could be rotated about its spin axis by the wrist actuator of the RMS so that instruments with directed fields of view could be swept through different look angles or pointed in various special directions, such as the velocity vector of the Orbiter.

The RMS programs were specialized to the PDP scientific objectives. For example, the X and Y scans were used to execute beam searches, i.e., to move the PDP through the electron beam to sample the region of direct beam-plasma interaction as well as the surrounding environment. One particularly useful maneuver coupled the rotation of the PDP about the RMS wrist axis in one direction with the roll of the Orbiter in the opposite direction at identical rates such that the PDP was swept alternately through ram and wake orientations while holding a specific instrument's look direction parallel to the velocity vector of the Orbiter. This particular maneuver was designed to allow detailed studies of the near wake of the Orbiter.

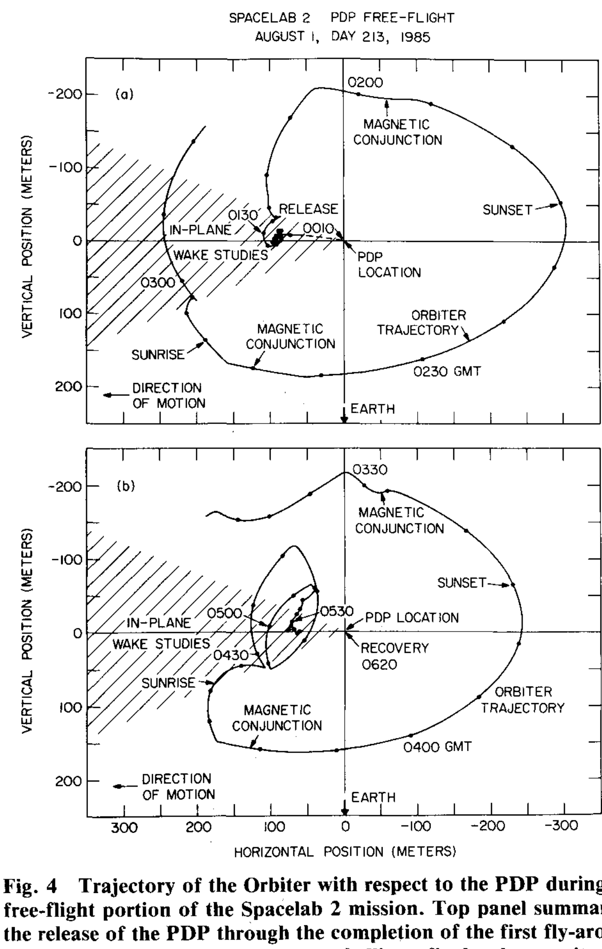

Fig. 4 Trajectory of the Orbiter with respect to the PDP during the free-flight portion of the Spacelab 2 mission. Top panel summarizes the release of the PDP through the completion of the first fly-around ellipse. Lower panel shows the second ellipse, final wake transits, and the approach for recovery.

Free Flight

The free-flight portion of the PDP operations was the most innovative part of the Spacelab 2 PDP investigation. This activity was not undertaken during the previous STS-3 mission, and we believe that the PDP free-flight experiments were the first of their type in space plasma physics. Several rocket experiments have included detached payloads for the diagnosis of beam interactions, but none have included both the active control of relative position and attitude for the purposes of studying vehicle-plasma interactions as well as the beam-plasma interactions, especially in conjunction with a large body such as the Orbiter.

The constraints on the free-flight activities were severe, especially from the point of view of time allotted against the requirements of other Spacelab 2 investigations and RCS propellant usage. The latter constraint was much more severe than planned due to the loss of about 2000 kg of OMS propellant during the abort-to-orbit procedure executed as a result of the premature shutdown of the center main engine on ascent.

The free-flight phase of the mission can be broken down into deployment and back-away, fly-around "ellipses," wake transits, and approach and recovery. The total time for the free flight was about 6 h. Figure 4 shows the relative trajectory of the Orbiter with respect to the PDP. The first panel shows the back-away and first fly-around ellipse. The second panel shows the second fly-around ellipse, wake transits, and approach. Three hours were utilized during the two orbits of fly-arounds depicted in Fig. 4. During the fly-around ellipses, the Orbiter was flown out of the orbit plane and to positions along the magnetic field line threading the PDP to look for Alfvén waves generated by the Orbiter and to do electron beam experiments. During the portion of the orbit when the Orbiter preceded the PDP in flight, the Orbiter was brought back into the PDP orbit plane to study the Orbiter's wake at distances between 50 and 250 m. When the Orbiter was in the cone on the left side of the panels in Fig. 4, it was in the plane of orbit of the PDP so that the Orbiter's wake would pass over the PDP at varying distances. In the remainder of the ellipses, the Orbiter was flown out of the PDP's orbit plane to intercept the magnetic field line threading the PDP.

The back-way and approach maneuvers were completed with the Orbiter upstream from the PDP, i.e., with the PDP in or near the wake of the Orbiter. This configuration allowed additional observations of he Orbiter's wake to be made at distances intermediate to those achieved while on the RMS and in the free-flight fly-around maneuvers. It was anticipated that, during the intervals when the PDP preceded the Orbiter at distances of over 300 m, the PDP might be able to sample the unperturbed ionospheric medium. However, the PDP was never far enough upstream to avoid the neutral gas cloud and its associated effects so that a truly ambient ionospheric observation could be made.

Summary of Results

Studies of the Shuttle Environment

Perhaps the most profound discovery of the PDP flight aboard Spacelab 2 is that the Orbiter is accompanied in the ionosphere by an extensive gas cloud of contaminants consisting primarily of water.[6,7,10,11] This conclusion is consistent with observations made by the ion mass spectrometer,[6,11] pressure gage,[10] and Lepedea[7] on the PDP. The Orbiter releases contaminants through the operation of the RCS thrusters, normal operation of the Orbiter fuel cells and cooling systems, leakage from pressurized vessels, and outgassing.

The neutral water is subject to ionization by a number of processes in low Earth orbit with charge exchange with the ambient O^+ ions being the primary reaction. As ions are created, they are "picked up" immediately by the magnetic field sweeping through the cloud at the orbital velocity of the Orbiter, about 8 km/s, and, hence, form a highly anisotropic distribution of ions known as a "ring distribution." The Lepedea has measured these ring distributions from free-flight vantage points at several locations around the Orbiter.[7] The measurements indicate a neutral water production rate of about 2.5×10^{22} s^{-1} from the Orbiter.[7] The pickup ions form a long ion trail behind the Orbiter. At certain times, the contaminant water ions can actually be the dominant species in the region within a few meters of the Orbiter.[6] A model of the neutral water cloud suggests that it has a density of 6×10^9 molecules cm^{-3} at 50 m from the Orbiter and extends to ~ 8 km with densities of ≥ 1 cm^{-3}.[7]

Since ring distributions are typically unstable to the generation of plasma waves, it is possible that these distributions are responsible for the broadband electrostatic waves observed in the vicinity of the Orbiter by the plasma wave receiver.[9,12] This noise typically has a broad spectrum from a few hertz to 20-30 kHz. The broadband electric field strength of the turbulence is about 1-5 mV/m. The waves are generally most intense in the region downstream of the Orbiter, although high intensities are also observed near magnetic conjunctions. The wave intensity is correlated with RCS thruster activity, although some noise is still present when no thrusters are being fired.

The S- and K_u- band receivers were used to survey the electric fields associated with the operation of the Orbiter communication links at various locations around the payload bay.[13] For those systems that avoid the main beam of the radar, the maximum field strength is less than 2 V/m. For those payload elements subjected to the main beam, a design guideline of 300 V/m provides an adequate safety margin at K_u band. The S-band fields measured were several decibels below the worst-case predictions. An instrument in the payload bay can expect to be subjected to S-band fields of magnitude <2 V/m.

Wake Studies

The motion of the Orbiter through the ionosphere leads to the formation of a well-developed wake in the downstream region.[14,15] The PDP was operated both on the RMS and in a free-flight path specifically designed to provide information on the characteristics of the wake both in the near vicinity of the Orbiter (within a body radius of the obstacle of about 10 m) and in the distant wake, out to about 250 m. From RMS and back-away observations, the density in the near wake can be two or more orders of magnitude less than the ambient density, whereas the electron temperature on the boundary of the wake region can be observed to increase by more than a factor of 2. At greater distances, the magnitude of the density depletion is less, sometimes only about 10%. One striking result, however, is that even at distances of 250 m, the wake is still well defined and of simple structure. There is no evidence of large-scale turbulence in the distant wake. It should be mentioned, however, that small-scale wavelike turbulence often characterizes the boundary of the wake region[15]; it is possible that this turbulence is similar in character to the broadband electrostatic noise discussed earlier.

Some work on comparisons of the Spacelab 2 PDP wake observations with wake models has been completed.[16] The model used in these comparisons is the Polar code,[17] which neglects the magnetic field and uses a self-similar solution to the expansion of a plasma into a vacuum as its foundation. The observed electron and ion densities measured by the PDP during passages through the Orbiter's wake at distances out to a few hundred meters are compared with predictions of the model. In the distance range less than 30 m, the model underestimates the density by as much as an order of magnitude; the presumption is that outgassing from the Orbiter can be a substantial contributor to the wake density within a few body scale sizes. Beyond 30 m, the agreement is very good (within about 10%) between the model and observations, provided one allows for variations in the ambient density with position as predicted by the International Reference Ionosphere model.[18] The observations show a lack of fine structure in the density of the wake and are, therefore, consistent with the behavior of wakes in regimes where the ion and electron temperatures are similar. Comparisons of the wake observations and the collisionless plasma expansion model[19] suggest that the plasma wake of the Orbiter closes much faster than predicted by simple thermal expansion, implying that the ions filling the wake have been accelerated. Furthermore, some minor inconsistencies in the depth of the wake as a function of distance from the Orbiter observed by the PDP are evidence for crossing ion streams[15] such as those observed in laboratory plasmas.[20]

Beam-Plasma Interactions

The PDP and VCAP jointly designed numerous experiments for the Spacelab 2 mission for the purpose of understanding various aspects of the interaction of an energetic (1 keV) electron beam with the ionospheric plasma. One of the primary characteristics of the interaction is the generation of waves. Early studies have concentrated on whistler mode waves, called "VLF hiss"[21] which are thought to be generated via a coherent Cerenkov process associated with bunching of electrons in the continuously firing beam.[22,23] The VLF hiss was detected easily because of a funnel-shaped frequency-time signature observed in the plasma wave data set. The funnel-shaped spectrum is a result of well-understood propagation characteristics of the whistler mode waves and leads to an understanding of the beam emissivity as a function of distance along the beam. Further studies[8,24,25] involve wave generation by a pulsed beam, where the pulsing frequency of the beam is in the VLF range. The resultant waves are found at harmonics of the pulsing frequency.

Other studies concerning the interaction of the electron beam with the ionosphere include the dc electric fields set up in the vicinity of the beam in response to the current systems driven by the beam.[26] Analysis of the PDP Lepedea measurements of electrons associated with the beam-plasma interaction demonstrates that there is a narrow sheet of energetic electrons in the wake of the Orbiter.[27] This sheet of electrons is threaded by magnetic field lines from the upstream injection of the primary electron beam. Numerical simulations of the beam-plasma interaction show the generation of low-frequency, broadband electrostatic waves similar to those observed by the plasma wave receiver.

Conclusions

The Plasma Diagnostics Package investigation on the Spacelab 2 mission was extremely successful. Virtually 95% of the objectives of the investigation were achieved, and the results referred to in the previous section attest to the scope of the science results obtained during the flight. Those 5% of the objectives that were not met owing to the shortage of Reaction Control System (RCS) propellant were primarily experiments that involved the firing of RCS thrusters in a predetermined way to measure their effects and those experiments that were to have been performed during a planned, third orbit of fly-around. The thruster-associated objectives were partially achieved via coincidental firings of RCS thrusters during the execution of various maneuvers. The loss of the third orbit of fly-arounds resulted primarily in the loss of repetitions of experiments achieved during the first two orbits.

Acknowledgments

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