Langmuir Probe Spacecraft Potential End Item Specification Document
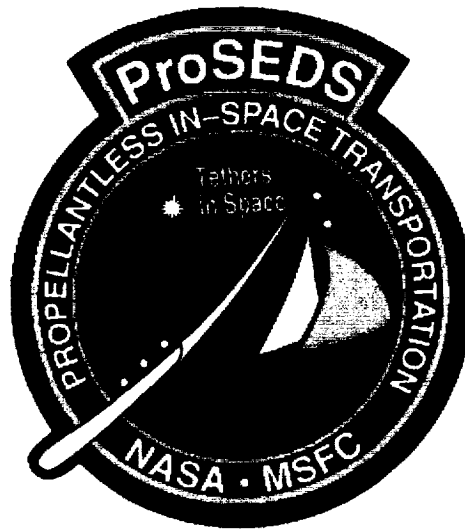

Space Physics Research Laboratory
The University of Michigan

List of Figures

List of Tables

1. Introduction

This document describes the Langmuir Probe Spacecraft Potential (LPSP) investigation of the plasma environment in the vicinity of the ProSEDS Delta II spacecraft. This investigation will employ a group of three (3) Langmuir Probe Assemblies, LPAs, mounted on the Delta II second stage to measure the electron density and temperature (n_e and T_e), the ion density (n_i), and the spacecraft potential (V_s) relative to the surrounding ionospheric plasma.

This document is also intended to define the technical requirements and flight-vehicle installation interfaces for the design, development, assembly, testing, qualification, and operation of the LPSP subsystem for the Propulsive Small Expendable Deployer System (ProSEDS) and its associated Ground Support Equipment (GSE). This document also defines the interfaces between the LPSP instrument and the ProSEDS Delta II spacecraft, as well as the design, fabrication, operation, and other requirements established to meet the mission objectives.

The LPSP is the primary measurement instrument designed to characterize the background plasma environment and is a supporting instrument for measuring spacecraft potential of the Delta II vehicle used for the ProSEDS mission. Specifically, the LPSP will use the three LPAs equally spaced around the Delta II body to make measurements of the ambient ionospheric plasma during passive operations to aid in validating existing models of electrodynamic-tether propulsion.

These same probes will also be used to measure Delta II spacecraft potential when active operations occur. When the electron emitting plasma contactor is on, dense neutral plasma is emitted. Effective operation of the plasma contactor (PC) will mean a low potential difference between the Delta II second stage and the surrounding plasma and represents one of the voltage parameters needed to fully characterize the electrodynamic-tether closed circuit. Given that the LP already needs to be well away from any near-field disturbances around the Delta II, it is possible to use the same probe with a simple reconfiguration of the electronics to measure potential with respect to the ambient plasma.

The LP measurement techniques are outlined in the following text and discussed in detail in the Appendix. The scientific goals of the investigation, the physical and electrical characteristics of the instrument, and the on-orbit measurement requirements are also discussed in this document.

1.1 Mission Objectives and Approach

ProSEDS Objectives

The overall objective of the ProSEDS flight experiment is to demonstrate and validate the aspects of electrodynamic tether technology required for applications in electrodynamic propulsion. Previous electrodynamic-tether flights have used fully insulated tethers with spherical collectors as subsatellites (the end point), but collection by a thin, uninsulated wire promises to be more efficient than that by a large spherical endmass. Theoretically, the long, uninsulated wire could represent a factor-of-forty increase in electron collection. To properly assess the ProSEDS tether's electrodynamic performance, sufficient knowledge of individual element responses is needed. With the HCPC on, the tether circuit is completed with the

ionospheric plasma—the situation to be explored. To properly assess ProSEDS tether electrodynamic performance, sufficient knowledge of individual tether circuit element responses is needed. In order to validate this technology and compare it to theory, knowledge of the local plasma parameters is necessary. The LPSP is responsible for several of these measurements, specifically the ionospheric plasma density and electron temperature (n_e and T_e), the ion density (n_i) and the spacecraft potential (V_s). The first three measurements (n_e, T_e and n_i) are intended to be made in the undisturbed ambient plasma. In order for the ambient plasma to be undisturbed, it is assumed that the HCPC is off and thus not masking the local plasma. The last measurement (V_s) is made when ever the other three are not being made, regardless of the status of the PC. The spacecraft-potential is measured between the spacecraft electrical ground and the surrounding ambient plasma.

Details of the ProSEDS Mission Objectives are found in other documentation, but in general, the following objectives support this overall goal.

Primary Objectives. The primary objectives of the ProSEDS experiment are: (1) to demonstrate significant, measurable electrodynamic tether thrust in space, and (2) to measure the current-collection performance of a "bare electrodynamic tether" under varied ionospheric conditions and determine its scalability for future applications.

Secondary Objective. The secondary objectives of the ProSEDS experiment include: (1) demonstrating the regulation, storage, and use of tether generated electrical power; (2) determining system performance during the extended mission phase (begins after orbit 16); (3) assessing tether survivability in AO, meteoroid, and orbital debris environment; (4) assessing tethered system dynamics during electrodynamic operation.

Approach

The LPSP directly supports the primary and secondary objectives of the ProSEDS mission by obtaining repeated measurements of the ambient electron density and temperature (n_e and T_e), the ion density (n_i), and the spacecraft potential (V_s). In order to validate this technology and compare it to theory, the local plasma parameters are necessary inputs to computer models. A description of the methods used for this process is given in the Appendix of this document.

1.2 Instrument Overview

The LPSP uses three Langmuir probes (LPs) spaced approximately 120° apart around the outside of the Delta II second stage as illustrated in Figure 1.2-1. These probes are attached via approximately-one-meter-long masts that are commanded to deploy when safely in orbit and ready to operate. The LP, mast, and clamping mechanism are collectively known as the Langmuir Probe Assembly (LPA). The LPs are connected to the LPSP electronics assembly by a single multi-conductor cable from each LPA. The electronics assembly shall be designed to bias and collect data from the sensors and to digitize the sensor signal data. The three LPs time-share a single electronics unit. Spacecraft power for the LPSP shall be conditioned by the electronics assembly to provide all required regulated operating and biasing voltages for the LPSP.

The LPAs consist of a segmented "mast" which has one cylindrical LP mounted at the mast end and 2 additional cylindrical probes positioned uniformly along the mast. The end probe

is used for ambient plasma measurements and V_s measurements during excited conditions. The LPAs are long enough to require that the sensors be held down during the launch and deployed on orbit (see Figure 1.2-2).

1.2.1 Subsystem Description

The LPSP consists of three assemblies of LPs and deployable masts (the LPAs), an electronics assembly, and interconnecting cabling. Each assembly will be described as though it is an independent physical assembly.

1.2.1.1 Langmuir Probe Assembly (LP/Mast) Assembly, LPA

The LP is located at the tip of the mast and is collinear with the main axis of the mast. The assembly includes a shaped memory activated (SMA) "pin-puller" deployment mechanism that releases the probe from its stowed position. SMA activation is provided by an interface to the LPSP electronics via connectors MJ45A, MJ49B, and MJ53C. In addition, to the LP probe, two small conducting cylinder areas (segment probes) will be present along the mast at its 1/3 and 2/3 distance points. These conductors, along with the LP probe itself will form a floating probe triplet to measure spacecraft potential. The LP sensor signals/bias connection to the electronics assembly is made by means of a multi-conductor tri-axial cable assembly from each of the three LPs. The cable is permanently attached to the LP Mast assembly.

1.2.1.2 LPSP Cable Assembly

The LPSP cable assembly contains the necessary interconnecting wires and tri-axial cables to interface the sensors with the electronics assembly. The cable assembly will travel around the outside of the Delta II second stage. The cable is permanently attached to the LP Mast assembly with a single connector for each mast that attaches to the LPSP electronics. The SMA release mechanism is controlled by the LPSP electronics with a single twisted pair cable connecting the release mechanism to the LPSP electronics. The cable is permanently attached to the release mechanism with a single connector for each release mechanism that attaches to the LPSP electronics. All cable assemblies have a copper overbraid over all wires to provide protection from the third stage rocket motor blast.

1.2.1.3 LPSP Electronics

The LPSP electronics assembly conditions the sensor outputs, converts the detected currents and voltages to digital signals, and presents the data to the ProSEDS data system. Power is received from the spacecraft and converted to those potentials needed to bias the sensors and operate the signal conditioning and conversion electronics. The electronics assembly mounts on the instrument pannel and is located between two of the LPs on the Delta II second stage, opposite the ProSEDS tether deployment equipment.

1.2.2 Instrument Pictorial Views

The LPSP electronics mounted to the ProSEDS spacecraft is shown in Figure 1.2-1.

LPSP Electronics
Attached to ProSEDS
Instrument Panel

LP Mast (1 of 3)
shown in deployed
position.
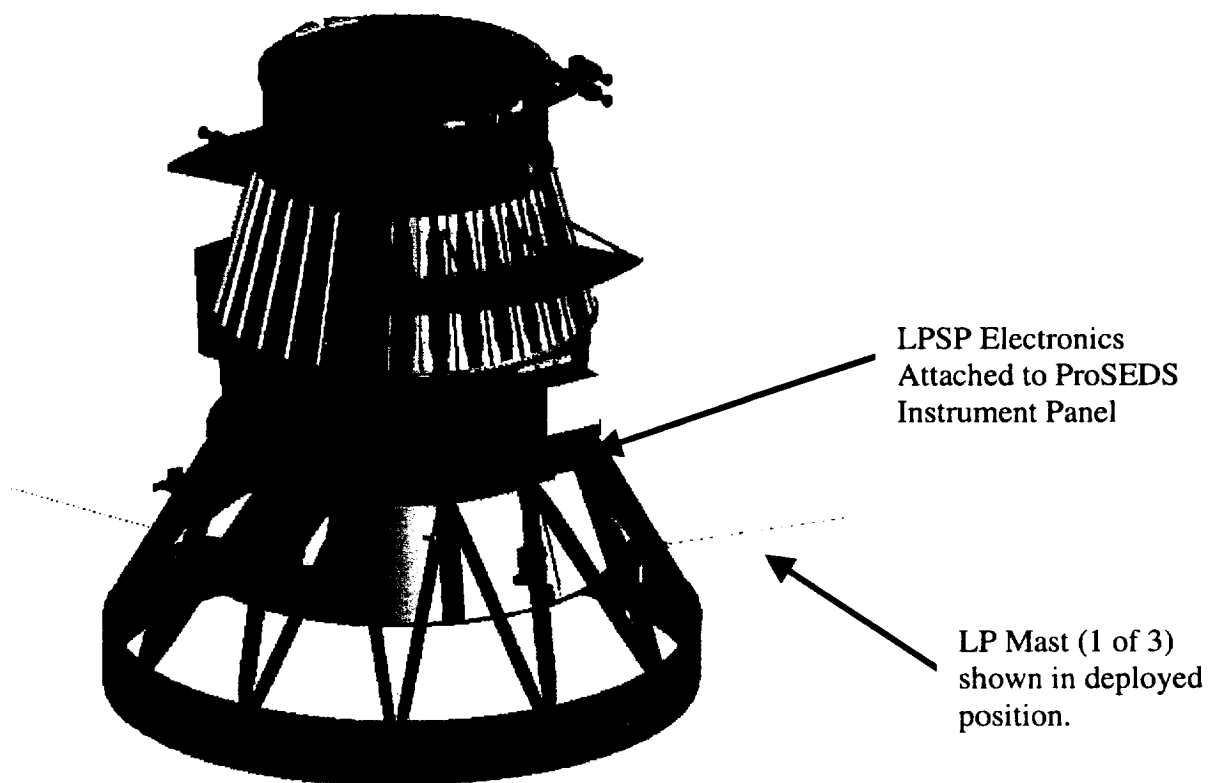
Figure 1.2-1 View of LP and LPSP electronics assembly attached to the Delta II spacecraft.

The LPA Mast is depicted in Figure 1.2-2 and is shown in its stowed, pre-launch configuration. The probe release assembly pictured contains the SMA pin puller. When released, the probe and mast will rotate 110° around the pivot housing.
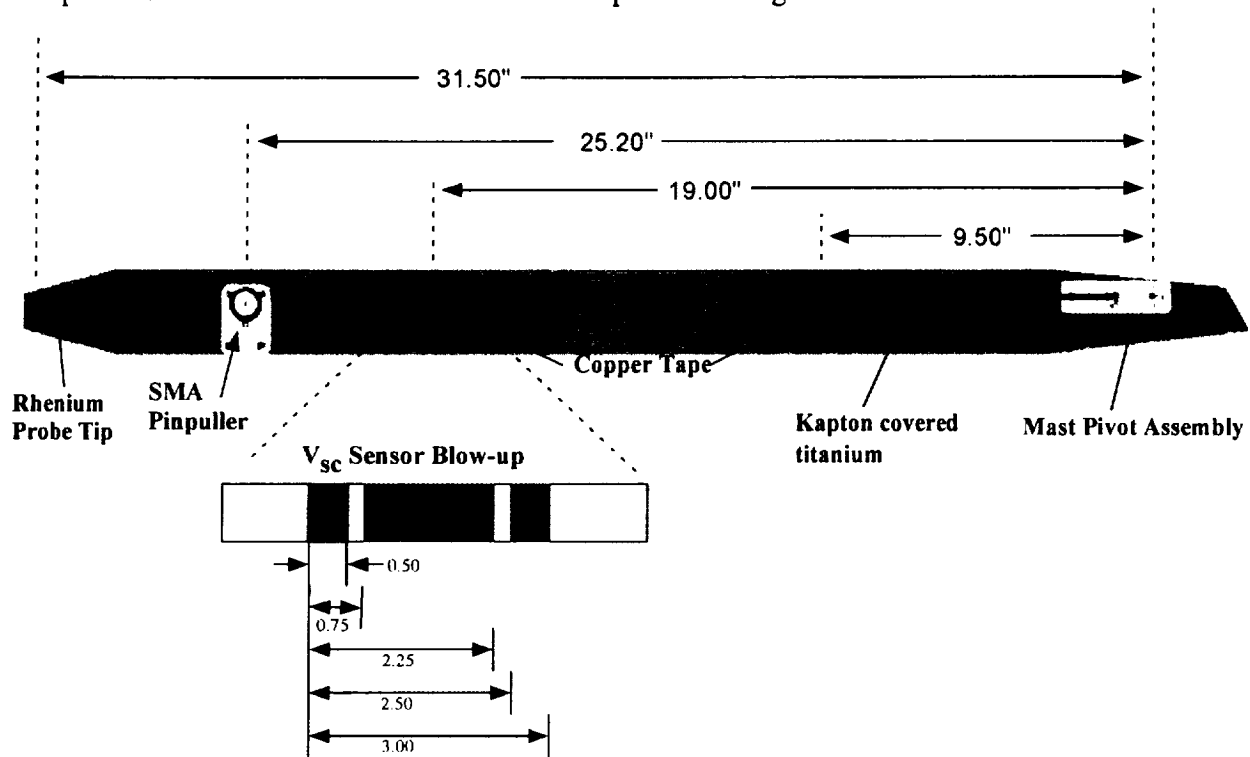
Figure 1.2-2 Deployment assembly of the LP on the mast.

1.3 Definitions

The following definitions shall apply to the equipment types referred to within the body of this document:

1.3.1 Flight Unit

Refers to the unique assemblage of hardware, firmware, and software designed for, and installed on, the Delta II to satisfy the mission requirements.

1.3.2 Ground Support Equipment

Refers to the non-flight support equipment that is required for servicing, simulating, testing, loading software programs, maintaining, and verifying operation of the flight configuration of the experiment. Additionally, ground support equipment (GSE) may also refer to equipment for storing and transporting the flight-unit elements.

1.3.3 Acronyms and Abbreviations

The following acronyms and abbreviations are defined as references for use within the body of this specification:

C&DH	Command and Data Handling
EEE	Electronic, Electrical and Electromechanical
EIS	End Item Specification
EMI	Electromagnetic Interference
EMC	Electromagnetic Compatibility
GSE	Ground Support Equipment
HCPC	Hollow Cathode Plasma Contactor
ICD	Interface Control Document
LP	Langmuir Probe
LPA	Langmuir Probe Assembly
LPSP	Langmuir Probe and Spacecraft Potential
PC	Personal Computer
QA	Quality Assurance
RAM	Random Access Memory
TBD	To Be Determined

1.4 Applicable Documents

1.4.1 Specifications

The following documents form part of this technical specification to the extent specified herein:

MSFC-RQMT-2901	ProSEDS Requirement Verification and Compliance Database (ProSEDS RVC)
MSFC-RQMT-2965	LPSP Interface Requirements Document (LPSP IRD)
MIL-STD-461C	Electromagnetic Interference Characteristics for Equipment
MIL-STD-462	Measurement of Electromagnetic Interference Characteristics of Equipment
MIL-B-5087	Bonding, Electrical, and Lightning Protection for Aerospace Equipment

1.4.2 Design Guidelines

The following documents shall be utilized as design guidelines as required by the ProSEDS sponsor:

GSFC Ref. Pub. 1124, Revision 2, Outgassing Data for Selecting Spacecraft Materials.

MIL-HDBK-5F   Metallic Materials and Elements of Aerospace Vehicle Structures

MIL-C-5541D   Chemical Conversion Coatings on Aluminum and Aluminum Alloys

1.4.3 Supporting Documents

075-1004	LPSP Mast Assembly
075-1050	LPSP Electronics Assembly
075-1055	LPSP Release Mechanism Assembly
075-1201	LPSP Detector Deck Electrical Schematic
075-1241	LPSP Control Deck Electrical Schematic
075-1038	LPSP Electronics Box Interface
075-1040	LPSP Mast and Release Interface
075-3052	Estimated Delta II Plasma-Sheath Distances for ProSEDS
075-3201	LPSP & HVCM Thermal Vacuum Procedure
075-3217	LPSP Functional Test Procedure
075-3219	LPSP High Voltage Test Procedure
075-3218	LPSP Voltage Sense Calibration Procedure
075-3225	LPSP Mast Thermal Cycling Procedure

2. The LPSP

2.1 Requirements

The range of plasma conditions the instrument must cover include:

- plasma density (N_e, N_i) 10^3 to 10^7 cm^{-3}
- electron temperature (T_e):   500 to 5000 K
- Satellite Potential   0 to -500 V

2.2 Measurement Techniques and Issues

A detailed description of the LP method is given in the Appendix of this document. Here, we simply note that the measurements are made by exposing the LP sensors to the plasma and applying suitable voltages to alternately attract and retard the ambient ions and electrons. This method generates current-voltage (I-V) waveforms that are measured, stored, and telemetered to Earth for computer curve fitting to yield the related geophysical parameters. The I-V characteristic of the LP sweep yields n_e, T_e, and n_i. Because of the four orders of magnitude in plasma density the measurement of the ionospheric density is achieved by measurement of electrons, n_e, at the lowest densities and n_i, at the highest densities. A switch will also permit the measurement of spacecraft potential, V_s, with respect to the plasma. Section 2.3 discusses the

voltages that will be put through the LPs for these purposes. For background ionosphere n_e and T_e measurements, the probe axis should be within $\pm 45°$ of perpendicular to the plasma ram flow. The use of the three LPAs is intended to assure that this condition is met independent of rotation about the tether line-of-action.

The tether current and open circuit emf are straightforward measurements with a history based on TSS-1 and TSS-1R. The voltage between the negative end-body (the Delta II) and the ionosphere is more difficult to determine. Unlike the measurements of the ambient ionospheric plasma characteristics, the Delta II spacecraft potential must be measured during active current-flow operations. If the hollow cathode plasma contactor (HCPC) works as intended and without problems, we expect that the spacecraft potential will be limited to the order of -30 to -60 V. By itself, this would represent an error on the order of 5 percent in a Kirchhoff Voltage Law-like loop equation. However, if the HCPC does not work as expected, or if it suffers a failure or degradation, the spacecraft potential could reach many hundreds of volts negative. Since this translates directly to an error in the calculated performance of the electrodynamic tether, these are clearly not acceptable levels of error. The spacecraft potential should be measured accurately and reliably.

The LPSP supports this need by measuring the spacecraft potential with resect to one of three floating probes along the LPA axis. The primary measurement will be made with respect to the end probe (LP probe) and the other two will help assess if the end probe is outside of the sheath.

2.2.1 Delta-II Sheath Distance as Function of Spacecraft Potential

To ensure that the ProSEDS Langmuir Probe Spacecraft Potential (LPSP) experiment is able to make accurate measurements of plasma parameters and spacecraft potential, an estimate is needed of the expected plasma-sheath distance as a function of spacecraft charging voltage. Proper LPSP operation requires that the Langmuir probes (LPs) are situated in "undisturbed" plasma, which requires that they be outside of the plasma sheath that develops around the ProSEDS Delta-II second stage. For the LP measurements this situation is assured by making them when the ProSEDS system is in a passive state and there is no charging (In such a situation, the floating potential of the spacecraft would generate a sheath less than about a centimeter for typical ionospheric densities). Of greater concer, the spacecraft potential (SP) measurement requires that at least one sensor is located outside of the sheath in undisturbed plasma. This section provides an estimate of the Delta-II sheath size for a range of plasma densities and charging levels and provides design guidelines to ensure that the LPSP operates properly.

2.2.1.1 Assumptions

The following assumptions are made in this analysis (a complete description of this analysis is available in SPRL Doc. No. 075-3052). First, the Delta-II second stage is approximated as a cylinder of radius $r_a = 1.2$ m. Second, the ion species is assumed to be atomic oxygen ($m_i = 2.66 \times 10^{-26}$ kg) with an ion temperature $T_i = 0.1$ eV $= 1160$ K. Third, since the spacecraft velocity of $v_s \sim 7.5$ km/s (with respect to the surrounding plasma which corotates with the Earth) is much faster than the ion thermal velocity, the ions are approximated as having a directed flow velocity equal to the spacecraft velocity. Fourth, the sheath is assumed to approximate a "thin" sheath, i.e., the sheath size is smaller than the radius of the spacecraft and is approximately planar.

2.2.1.2 Sheath Distance Calculations

The Child–Langmuir (CL) law describes the relationship between voltage, sheath distance, and current for a sharp-sheath-edge model. The values of estimated (worst-case) sheath radius for the Delta-II second stage is given in Figure 2.2-1 as a function of spacecraft potential. This analysis indicates that for nominal F-peak densities ($> 10^{11}$ m^{-3}) the outer LPA probe should be outside of the sheath for up to several hundred volts of charging. At lower densities, nominal charging is still measurable, but beyond +100 V the sheath dimension can exceed the probe length. This technique of spacecraft potential measurement will be capable of supporting primary data periods when near the F-peak (300-400 km altitude). At lower altitudes and densities, (nighttime) high charging will only be partially measurable.
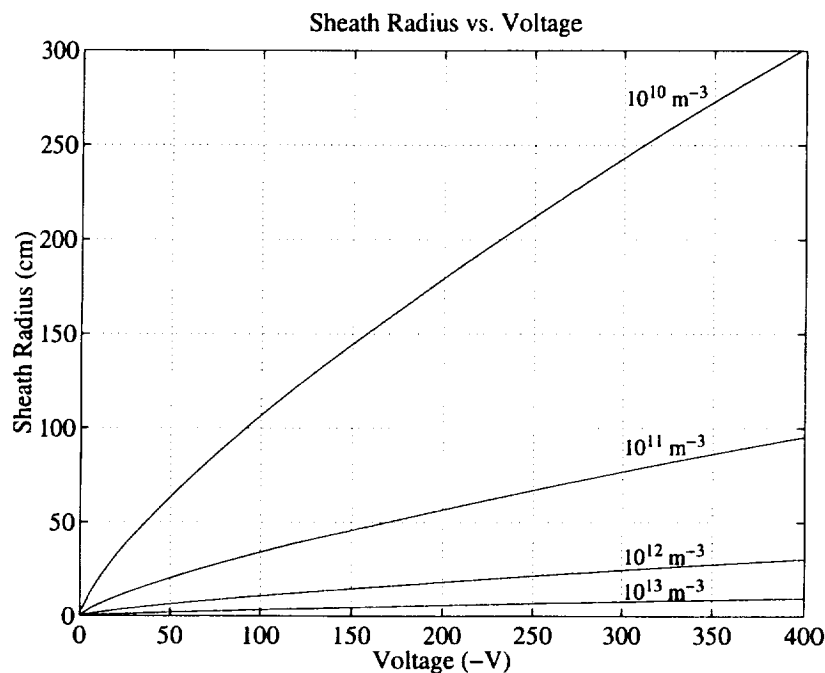
Figure 2.2-1 Estimated (worst-case) sheath distance plotted against spacecraft voltage for various plasma densities using the modified Child-Langmuir model.

2.3 Langmuir Probe Operation and Modes

2.3.1 Background

A technique was developed in the early 1970's to optimize data collection from Langmuir probe (LP) instruments used for plasma density and temperature measurements [Brace et al., 1973; Krehbiel et al., 1981; Brace, 1997]. The technique is called adaptive scanning and is depicted in Figure 2.3-1. The term "framing" is used to describe the adjustment of the current-amplifier gain and the sweep-voltage amplitude to correspond to the existing plasma temperature and density. The main purpose of curve framing is to focus the limited telemetry samples on the

portion of the current–voltage (I–V) curve that contains electron temperature, T_e, while still providing adequate measure of ion and electron density, n_i, and n_e, respectively. Thus, samples are not wasted on the far saturation regions. The technique also has the advantage of providing an adaptive method under highly variable plasma conditions providing rapid enough feedback is provided to reframe the curve. For the ProSEDS application, the same basic flight-proven technique will be utilized for accurate T_e measurements. Full I-V sweeps of sufficient accuracy and repetition rate will be also utilized to address unknown conditions that can not be anticipated and will induce complex, time variant responses to the plasma around the Delta-II.

There are three basic operational modes and one cleaning mode: acquisition sweep (can be thought of as a full-sweep assuming adequate settling time is provide between samples to obtain accurate measurements), adaptive sweep, and adaptive scan mode (the adaptive scan is not presently planned for ProSEDS). The acquisition sweep is used to quickly locate the approximate plasma temperature and voltage across the full bias sweep range and provides an initial "coarse" framing (the level of coarseness depends on the number of samples). The adaptive sweep performs a high-resolution sweep and refines the frame to a high level of precision. The adaptive scan uses critical points to permit high time resolution.

2.3.1.1 Acquisition Sweep

The curve-framing process is started with an acquisition sweep. A large enough negative voltage is applied to the probe to assure operation somewhere in the ion-saturation region, typically -10 V. The current gain range is then changed sequentially until the ion current, $I_1 = -I_i$ produces an output sufficient to assure that only the ion-saturation region and electron-retardation regions will remain on-scale when a full I–V curve is taken. (Note that the ion current is conventionally plotted downward as illustrated in the Figure 2.3-1.) The probe sweep voltage is then quickly stepped toward +10 V (typical) while observing the current. The voltage at which the total current is $I_2 = -I_1$, which corresponds to an electron current of $\sim 2I_i$ is stored as V_2. An additional voltage point, denoted V_3, is stored when the total current reaches $I_3 = -4.436I_1$ and $I_e \sim 5.436I_i$. Note that $5.436/2 = 2.718 = e$ and corresponds to $V_3 - V_2 = kT_e$.

2.3.1.2 Adaptive Sweep

Using V_1, V_2, and V_3, The I–V curve is now ready to be "framed". The sweep voltage is started at $9kT_e$ less than V_2. The probe voltage is then stepped in increments of $kT_e/4$ (or smaller) to ensure adequate resolution. Again, the voltages at I_2 and I_3 are stored. In addition, the sweep is extended to $V_3 + 2kT_e$ with a current gain down range typically required, obtaining the inflection point, thus identifying the plasma potential, V_p. An overscan of 2 V is added to get an I_e reading well into the electron saturation region. Subsequent sweeps continuously re-adjust the offset and range based on the previous sweep. In the event that no current thresholds are detected, the system returns to the acquisition sweep mode.

2.3.1.3 Adaptive Scan

In order to provide higher temporal resolution at a low data rate, an adaptive scan can also be performed during which currents are measured at V_1, V_2, V_3, and V_5. These voltages are updated frequently to ensure that they are optimized for a changing plasma environment. This operation is will not be used for LPSP on the ProSEDS mission.
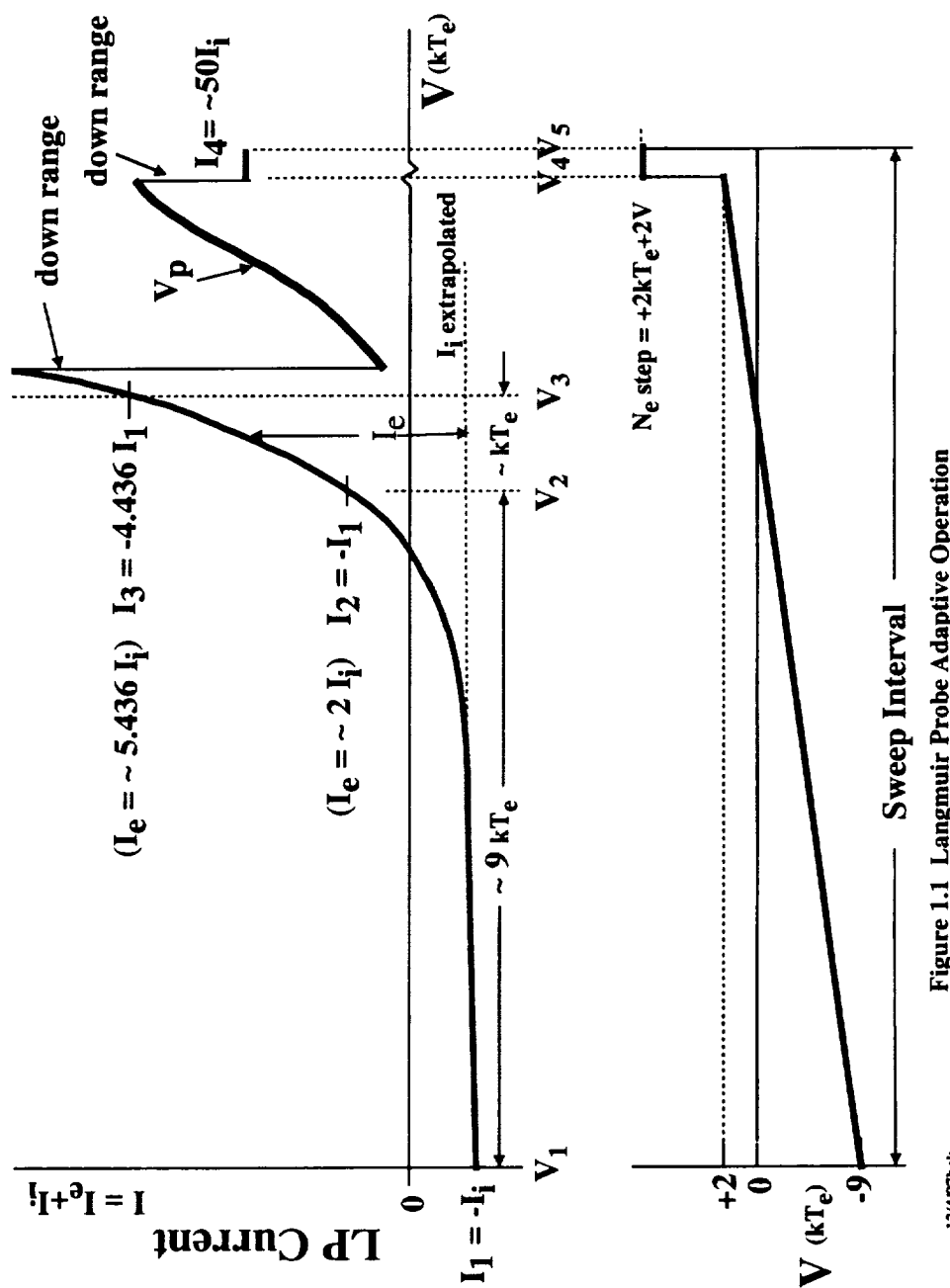
Figure 2.3-1 Langmuir probe adaptive operation

2.3.2 Operational Parameters

The operation of the LPSP is based on and limited by certain parameters, which are listed in Table 2.3-1. As Table 2.3-1 shows, the LPSP can sweep the probe voltage through 4096 steps (12 bits). Over the range of 20 V (-10 V to 10 V), this means that each voltage step would be 4.88 mV apart. This represents the smallest available step size, *i.e.*, voltage-step resolution. The actual step size sufficient to give meaningful results is determined by the temperature jump associated with each step. A certain maximum temperature change between steps will allow enough detail to characterize the plasma. In the acquisition sweep and adaptive sweep, the voltage width of each step can be calculated from this maximum temperature change, and the number of steps can then be found.

Table 2.3-1 LPSP sweep parameters

Sweep Parameters	Specifications
Number of sweep voltage steps	4096 steps (12 bits)
Voltage range	20 V (-10 V to +10 V)
ΔV/bit	4.88 mV/bit
ΔT/bit	56.61 K
Current amplifier settle time	2 ms max.
Data Transmission Rate	9600 bits per second
Maximum temperature	5000 K
Minimum temperature	500 K
Maximum average data rate	1800 bps

Additionally, Table 2.3-1 shows the maximum data rate for the LPSP, which is an average of 1800 bits per second. Table 2.3-1 also shows a minimum current amplifier settle time of 2 ms maximum. The current amplifier allows the minimum sample time of 2ms, the data transmission rate of 9600 bps requires 2.083ms to transmit the 2 bytes of data obtained with each sample. The minimum sample time of 2.083ms is limited by both the data transmission rate and the amplifier settling time. The amplifier settling time applies to range changes and small steps (<200 mV) of the sweep voltage. Relay switching and large steps in sweep voltage require longer settling times, the LPSP allows longer settling times where necessary.

2.3.3 Operational Modes

ProSEDS operates in four modes: Open circuit mode, Shunt mode, Resistor Mode, and Battery Charge Mode. The LPSP operates in four modes as well: Full Acquisition Sweep, Moderate Acquisition Sweep + 2 Adaptive Sweeps, V_s measurements, and Probe Cleaning. The operating modes are explained below. The comparison of the time-scales for the ProSEDS and LPSP modes is shown in Figure 2.3-2; the modes are identified in Table 2.3-2.

Figure 2.3-2 Operational mode timelines for ProSEDS and LPSP.

Table 2.3-2 ProSEDS and LPSP Operational Modes

ProSEDS and LPSP Operational Modes			
ProSEDS		**LPSP**	
Mode	Description	Mode	Description
Mode 1a	Open Circuit, HCPC off	Mode A	Vs Measurements
Mode 1b	Open Circuit, HCPC on	Mode B	Ni + Moderate Acquisition Sweep + Adaptive Sweeps
Mode 2	Shunt	Mode C	Ni + Full Acquisition Sweep
Mode 3	Resistor	Mode D	Probe Cleaining (Intermittent)
Mode 4	Battery Charge		

Each cycle is either 80 or 60 seconds in duration. ProSEDS modes 1a and 1b, both being parts of Open Circuit Mode, last 35 seconds, combined, and contain all of the LPSP electron density and temperature measurements (i.e., acquisition sweeps and adaptive sweeps).

The LPSP operates in one of the three modes, described below, in each second of the scan sequence. All measurements for any of the modes are completed in less than 1 second. The LPSP measures spacecraft potential, V_s during active ProSEDS operations. V_s is the only measurement made during LPSP Mode A, a V_s measurement is made on all 9 segments (3 on each mast) during each Mode A operation. LPSP Mode A also occurs early in ProSEDS 1a since spacecraft potential could be changing dramatically.

2.3.3.1 LPSP Mode A - V_s Measurements

Figure 2.3-3 shows a timing diagram of a Mode measurement sequence. This sequence is repeated each second that the LPSP is performing Mode A operations. This figure shows the approximate time scales for the measurement sequence. The 9 LP segment traces (LPn seg m) show which segment is connected to the measurement unit. The Relay trace shows when the relays are energized to select the next probe or probe segment. The Range trace indicates when a measurement is made to select the range to be used. The Vs trace indicates when the spacecraft potential measurement that is inserted in the telemetry is made.

During Mode A, the sequence shown in Figure 2.3-3 is all that is happening. In Mode A, only the measurements of V_s are made. Every second of Mode A will follow an identical sequence as shown in Figure 2.3-3 with the rest of the second empty.

The V_s measurement is actually the compilation of nine measurements, one on each segment of each probe (three segments per probe). The measurements taken on the inner segments of each probe (those closer to the spacecraft, seg 2 & 3 with 3 being the closest) are for validating the outer probe measurements (seg 1) in the presence of the plasma sheath around the vehicle. The Relay, Range, and Vs times are not to scale in Figure 2.3-3, the time that each segment is selected is shown to scale. The relays are energized for 6ms, the range select reading occurs 2ms after the relays are denergized, and finally the Vs reading is made 4ms after the range select reading. Segments 2 and 3 of each probe require longer settling time to recover from disturbances caused by the relays switching.

The original LPSP design called for the n_i measurments to be made in Mode A after the V_s measurments were complete. The n_i measurement requires the probe to be driven to -10V relative to the spacecraft to measure the ion current. When the probe is allowed to float to make V_s measurements the ion current must charge the mast capacitance. The high effective plasma resistance (it varies with ion density) can give time constants several seconds long. Discharging the probe to make n_i measurements would seriously degrade the accuracy of the V_s measurements. Thus it was necessary to eliminate the n_i measurement from the Mode A sequence.
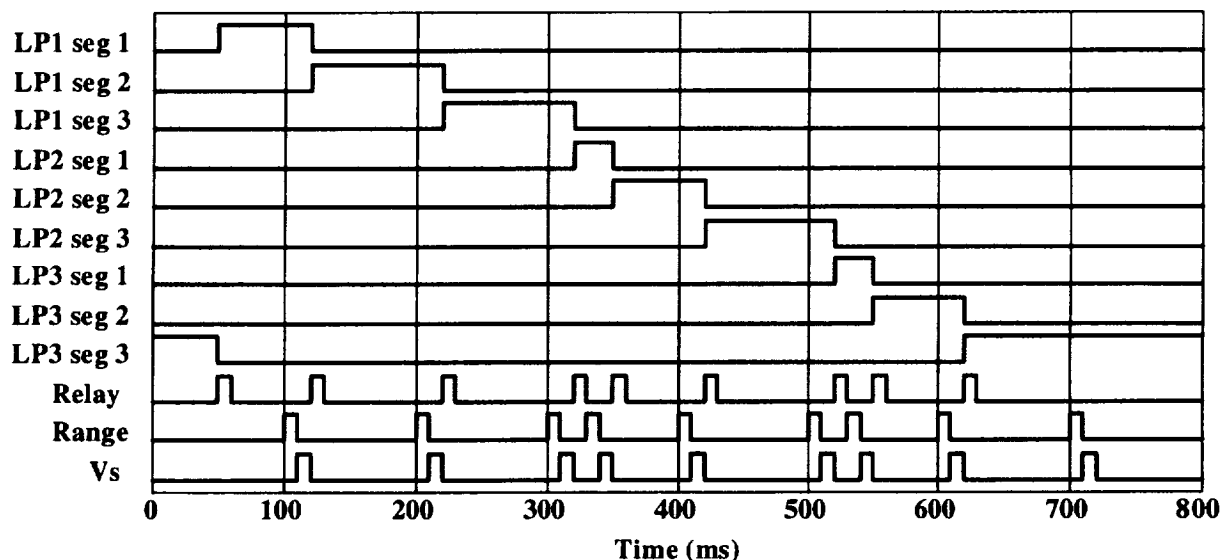
Figure 2.3-3 Timing diagram of the LPSP Mode A measurement sequence.

2.3.3.2 LPSP Mode B – Moderate Acquisition + Adaptive Sweeps

The LPSP starts this mode by performing a 128 step acquisition sweep from -10V with a step size of 156.25 mV (sweep range of -10V to 9.844V) on one Langmuir probe. The probe current at -10V is stored as I1 and inserted into telemetry (this data point is a n_i measurement). During the sweep, the voltage where I $\geq$-3I1 is stored as the spacecraft potential V_{sc}.

A 64 step adaptive sweep is then performed from V_{sc}-1.5V with a step size of 39.0625 mV (sweep range of V_{sc}-1.5V to Vsc+0.9609V). Prior to the start of the sweep the current is measured at −10V, stored as I1 and inserted into telemetry. During the sweep the sweep voltages, V2 where $I \geq -I1$, and V_{sc} where $I \geq -3I1$ are stored. The LPSP calculates Vt = V_{sc}-V2 with V_t min = 39.0625 mV. This produces a sweep that is a fixed step size adapted to the spacecraft potential.

A second 64 step adaptive sweep is performed starting at V_{sc}-10Vt with a step size of Vt/4 (sweep range of V_{sc}-10Vt to V_{sc}+5.57Vt with step size from 9.76mV to 156.25mV in 9.76 mV increments). This sweep is adapted to both spacecraft potential and electron temperature and is similar to the adaptive sweep described in 2.3.1.2 except that the LPSP uses only integer math to calculate the current thresholds.

The n_i data, along with all the probe current from the 128 step and 2-64 step sweeps are inserted in the telemetry in this mode. The first time this mode is executed in a scan sequence the three sweeps are performed on probe 1. Each subsequent time the mode is executed the three sweeps are performed on the next probe in the sequence 1, 2, 3, 1.... Note that a n_i measurement is made before each of the LP sweeps, so there will be at least 4 n_i measurements made in each Mode B sequence (3 sweeps + the 128 step sweep starts and −10V).

2.3.3.3 LPSP Mode C – Full Acquisition Sweep

The LPSP performs a 256 step acquisition sweep from −10V with a step size of 78.125 mV (sweep range of −10V to 9.922V) on one Langmuir probe. The initial n_i reading, along with all 256 steps of probe current are inserted in the telemetry in this mode. The first time this mode is executed in a scan sequence the sweep is performed on probe 1. Each subsequent time the mode is executed the sweep is performed on the next probe in the sequence 1, 2, 3, 1.... The data from the Mode C sweep contains two n_i measurements, the initial I1 current and the 1st point of the 256 step sweep.

2.3.3.4 LPSP Mode Sequence

Figure 2.3-4 shows the 60 second timeline from Figure 2.3-2 expanded to show the timing diagram for the first 35 seconds of a cycle, or ProSEDS Mode 1a and 1b. This expansion shows the approximate time spent making measurements in each of the modes, a new measurement cycle is started at 1 second intervals.

The first 15 seconds shown in Figure 2.3-4 are still in Mode A from the previous cycle. In this time, the ambient plasma is allowed to return to normal conditions after the plasma contactor is turned off. Following this is Mode B, for 6 seconds providing 2 measurements on each probe. Mode C starts 21 seconds into the cycle and lasts 3 seconds providing 1 measurement on each probe. Mode B operates for the last 6 seconds of ProSEDS Mode 1a and then for all 5 seconds of ProSEDS Mode 1b. The LPSP performs Mode A measurements each second for the rest of the 60 or 80 second sequence. The LPSP electronics starts an 80 second sequence when a Sync command is received from the ProSEDS data system. The receipt of another Sync command will abort any mode currently in progress and start another 80 second sequence. A 60 second sequence is produced by sending a Sync command every 60 seconds. If no Sync command is received for 85 seconds after power up, the LPSP will automatically start an 80 second sequence. If a Sync command is not received within 5 seconds after an 80 second sequence is complete, the LPSP will start another 80 second sequence automatically.
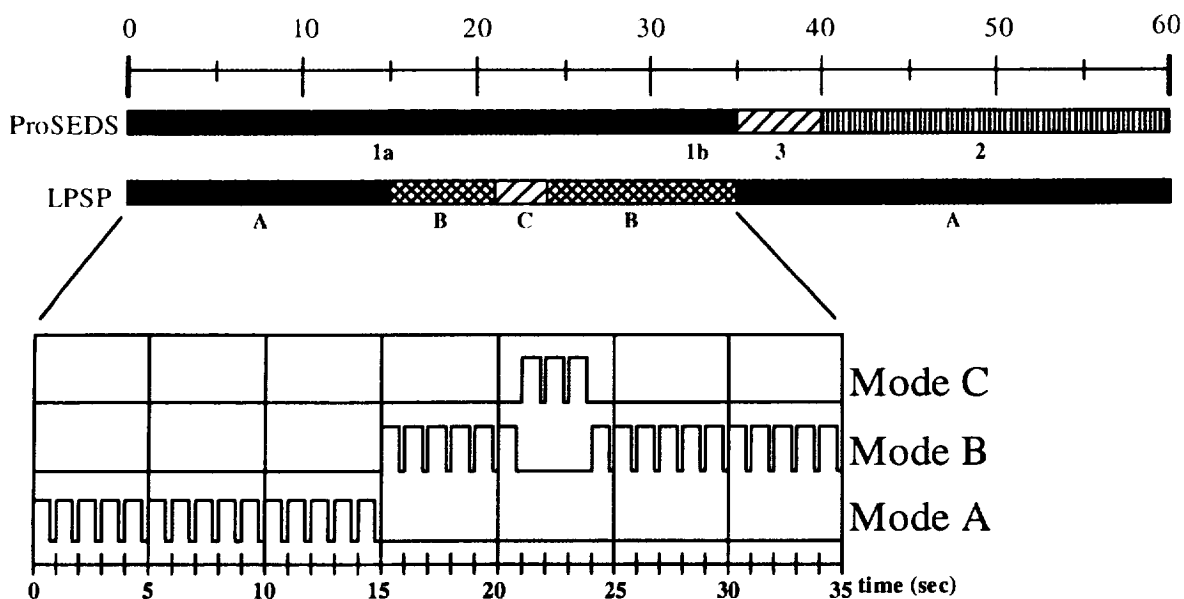
Figure 2.3-4 Expanded timing diagram of the first 35 seconds of the LPSP cycle, corresponding to ProSEDS Modes 1a and 1b.

2.3.3.5 Cleaning Mode D

The Cleaning Mode is used to remove any potential contaminates by bombarding the probes with 150 V electrons. This function is activated by the ProSEDS data system by applying a Clean command. Each time this mode is initiated a sixty second cleaning cycle is activated, during the 60 seconds each probe is cleaned for 20 seconds in the order 1,2,3. Activating the cleaning signal will terminate any of the other LPSP modes (including Mode D), and start a cleaning cycle. The probes will be cleaned for 2 minutes each at initial turn-on for a total of 6 minutes. No Data is transmitted from the LPSP during the cleaning cycle. Once the cleaning cycle is complete the 150V cleaning voltage is turned off and the LPSP remains idle. If a Sync or Clean command is not received within 25 second after the cleaning cycle ends the LPSP will automatically start an 80 second data collection sequence.

2.3.4 Data Summary

Table 2.3-3 contains a summary of the measurements made, and the science data obtained from each of the LPSP operational modes described above.

Table 2.3-3 LPSP Operational Mode Data Summary		
Function	Description	Data Obtained
A	Measure Vs on all 3 masts (9 segments)	Vs
B	Measure Ni and performs a 128 step acquisition sweep –10V to 10V 64 step fixed range, Vsat adapted sweep 64 step Vsat and Vkt adapted sweep	Ni, Ne, and Te (1 probe)
C	Measure Ni and performs 256 step high resolution sweep –10V to 10V	Ni, Ne, and Te (1 probe)
D	Probe Cleaning	None

2.4 Electrical Interfaces

2.4.1 The Electronics

A single electronics unit will operate the Langmuir Probes. Its functional block diagram is shown in. Figure 2.4-1 Documents 075-1201 and 075-1241 contain detailed electrical schematics of the two decks that make up the LPSP electronics unit. The measurement system consists of an electrometer (current amplifier) and a voltage generator, and can operate any one of the probe sensors. The electrometer is a current to voltage amplifier. The electrometer inputs can be cycled quickly through all sensors to provide nearly simultaneous measurements from all three probes. This method of switching is performed by a system of relays. An Actel 1280, Field Programmable Gate Array (FPGA), controls sequence timing.
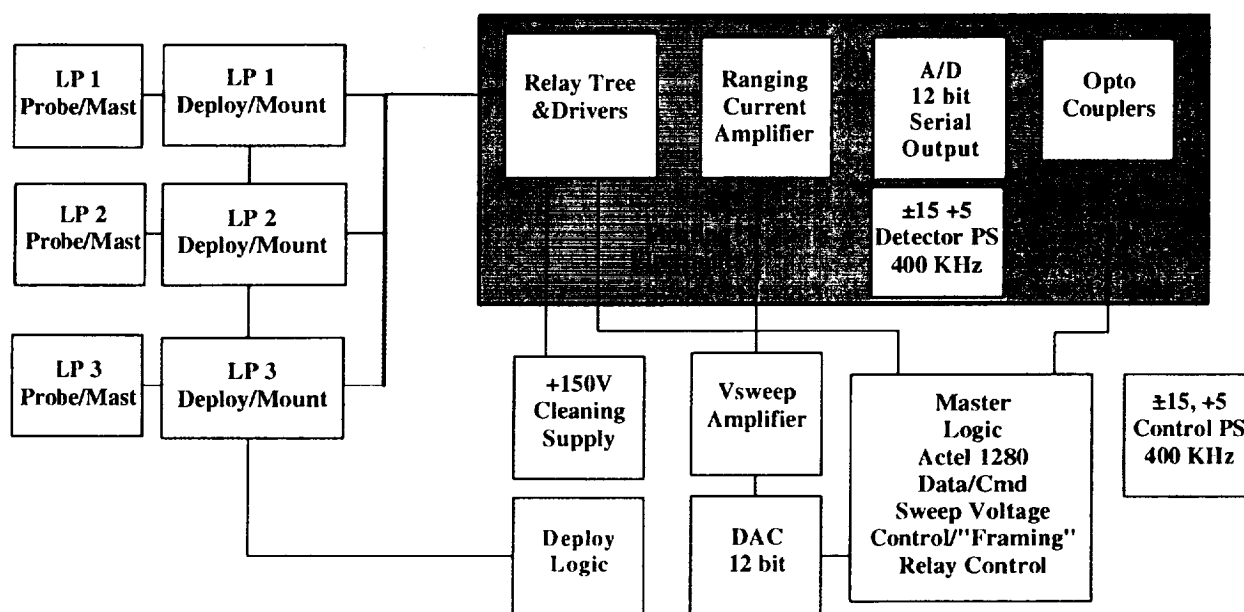
Figure 2.4-1 LPSP Functional Block Diagram

2.4.2 Power

2.4.2.1 Power Distribution

The LPSP receives +28 ± 6 V_{DC} from the ProSEDS power supply. The LPSP electronics box contains 2 separate power supplies. The main supply produces ±15V_{DC} and +5V_{DC} to operate the control logic, relays and the sweep voltage generator. The secondary of these voltages are referenced to chassis of the LPSP box. It also produces ±15V_{DC} and +5V_{DC} to power the floating electronics (current amplifier and ADC). These supplies are referenced to the sweep voltage generator output. The second supply produces the +150V_{DC} used for probe

cleaning. This supply is switched off by the FPGA control logic when the probes are not being cleaned.

The LPSP also requires a second +28 ± 6 V_{DC} power input to deploy the probes. This input can be switched on / off independent of the other +28 V input. Power must be applied to this input to allow the Release command to deploy the Langmuir Probe masts

2.4.2.2 Power Requirements

2.4.2.2.1 Data Collection Average Power

The maximum input power that the LPSP electronics will draw during the 60 and 80 second data collection cycles is shown in Table 2.4-1 under nominal operating conditions and at the extreme operating conditions for input voltage and temperature.

Table 2.4-1 LPSP Maximium Average Input Power in Data Collection Mode

LPSP Maximum Average Input Power			
Temperature	Vpri = 22.0V	Vpri = 28.0V	Vpri = 34.0V
20 °C	0.9W	0.9W	0.9W
60 °C	0.9W	0.9W	0.9W
-40 °C	0.9W	0.95W	1.10W

2.4.2.2.2 Data Collection Peak Power

During the 60 and 80 second sequence the LPSP switches measurement channels using latching relays. The relays are energized for 6ms each time a measurement channel is switched, the peak input power required by the LPSP during the relay switching is:

Peak Data Collection Input Power: 3.6 Watts

2.4.2.2.3 Cleaning Mode Input Power (Mode D)

The maximum input power required by the LPSP during cleaning mode varies considerably with plasma density. Two mathematical models were used to determine what current would be drawn to the Langmuir probe when 150 V_{DC} was applied. Based upon that analysis, a very conservative maximum value of 10mA is assumed. (The actual current draw will probably be smaller.) The maximum cleaning power that can occur under normal operation is listed below. To prevent excessive input power during unexpected operating conditions the cleaning supply is short circuit protected. The maximum input power the LPSP electronics will draw with the cleaning supply shorted is also listed below.

Maximum Cleaning Input Power: 3.2 Watts
Maximum Short Circuit Input Power: 5.0 Watts

2.4.2.2.4 LP Deploy Input Power

The power required to deploy the LP probes is independent of the primary input power to the rest of the LPSP electronics. The probes can be deployed with the LPSP primary input power on or off. The SMA's that deploy the masts have a resistance of 6Ω, the LPSP electronics adds 33.9Ω in series with this for a total of 39.9Ω. All 3 actuators are activated simultaneously so the effective load on the deploy power buss will be 13.3Ω. The deploy power can be calculated using the following equation.

$$Power = V_{deploy}^2 / 13.3$$

where V_{deploy} is the voltage applied to the deploy power input.

The release mechanisms activate in 100 ms or less, when they release they open circuit the load connection and reduce the deploy power to zero. The deploy input current and power is listed below for several input voltages.

V_{deploy}	I_{depoy}	Power
22.0V	1.65A	36.4W
28.0V	2.11A	58.9W
34.0V	2.56A	86.9W

2.4.3 Command Requirements

2.4.3.1 Deploy Commands

Deployment of the LPSP masts will be accomplished using three Shape Memory Actuated pin-pullers (SMA's) manufactured by TiNi Aerospace Inc. The SMA's use a nitinol shape-memory trigger to release a spring-activated pin, which holds the mast in its non-deployed position. When sufficient current is run through the SMA for a given length of time, the nitinol wire shrinks and pulls the detent trigger, which allows the pin to retract and releases the mast for deployment. The activation current will be set to 0.70 A, which gives adequate contingency above the 0.5 A minimum current specification, as well as drawing a total of 2.1 A, which should be safely within the capabilities of the ProSEDS deployer's power supply. This activation current requires a minimum pulse time of 200 msec to fully retract the pin. The pulse time for the DEPLOY TTL-level signal from the Data System has thus been specified at 1 sec to ensure deployment.

To achieve an activation current of 0.70 A from the 28-V power supply, each SMA must be put in series with a 34-Ω resistor capable of dissipating 18 W of power for 1 second.

The SMA's are activated by Teledyne 412D Relays with the coil driven by IRLR120 power MOSFET's. This is logic level MOSFET so the probe release circuitry will be activated as long as the Release input pin is held in a logic high state ($V_{IH} > 2.0V$). The Release Input has a 100KΩ input impedance and can be driven by 5V TTL or CMOS logic levels . A simplified circuit schematic is shown below in Figure 2.4-2.
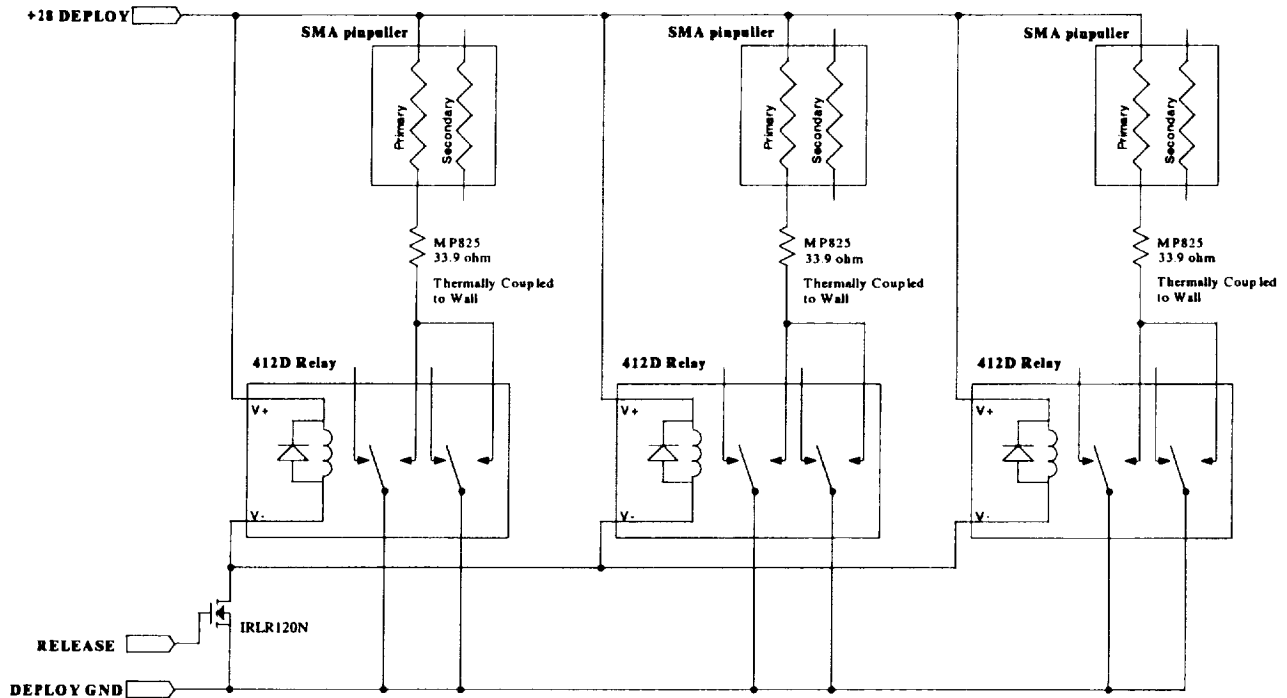
Figure 2.4-2 Langmuir Probe Deployment Circuitry

2.4.3.2 LPSP Operational Controls

The operation of the LPSP electronics is controlled by two input signals, SYNC, and CLEAN. Both of these inputs are 5V CMOS logic level inputs. A rising edge on these signals triggers the start their respective functions. The minimum high level pulse width required for these inputs is 10 μs. The internal timing of the LPSP data collections sequence starts within 50μs of the rising edge of SYNC, the LPSP has a 100ms delay after SYNC occurs until the 1st measurements of Mode A are made. The LPSP finishes the measurement sequence for any mode by 750ms of the 1 second interval. This dead time of 250ms at the end and 100ms after the beginning of each second gives the controlling system a time interval for SYNC pulses to occur without interrupting any measurement sequence in progress. For a 60 second sequence, no measurement sequence will be cut short or extra data received if the time between SYNC pulses is between 59.75 sec and 60.1 seconds.

The CLEAN pulse starts a Mode D cleaning cycle. This mode cleans each probe for 20 seconds, for a total of 60 seconds and then switches the cleaning supply off and discharges the probe voltage to chassis. If consecutive cleaning cycles are to be run, the preferred timing is to allow at least 61 seconds between cleaning pulses. If a data collection sequence is to be started after a clean cycle, the preferred timing is to wait 1 second after the clean cycle completes before applying a SYNC pulse.

Violating the above timing requirements will not damage the LPSP electronics, but it may result in partial data packets or unusual instrument readings for several seconds after a SYNC command. A SYNC or CLEAN command will immediately abort any operating mode in progress and start a new sequence corresponding to the command received. Once a SYNC or

CLEAN command is received the LPSP electronics will ignore subsequent commands for 200ms after the first command is received. If SYNC or CLEAN occur within 50ms of each other the CLEAN command will be executed and the SYNC ignored.

2.4.4 Telemetry / Data Requirements

2.4.4.1 Science Data

The LPSP electronics deck transmits RS422 serial data at 9600 bps in the following format:

8 bits of data with 1 start, 1 stop bit and no parity.

2.4.4.1.1 LPSP Operation Mode Data Packets

The LPSP operates in one of 4 modes at all times. One of the modes A-C is performed each second in both the 60 and 80 second operating cycles; each mode produces a telemetry packet. Mode D (probe cleaning) produces no telemetry data. The size of the science data sent in telemetry and the measurement time for each of the modes is listed in Table 2.4-2.

Table 2.4-2 LPSP Data Summary		
Mode	Data (bits)	Execution Time (ms)
A	144	608
B	4216	577
C	4136	548
D	NA	NA

Modes A – C produce a fixed length data packet each time the mode is executed. Only one mode will be executed each second. The format of data packet for the modes is given in Table 2.4-3 to Table 2.4-5

Table 2.4-3 Mode A Telemetry Packet				
Data Field	# Bytes	Repetitions	Byte No	Description
Segment Voltage	2	1	1-2	Probe 1 Segment 1 voltage
Segment Voltage	2	1	3-4	Probe 1 Segment 2 voltage
Segment Voltage	2	1	5-6	Probe 1 Segment 3 voltage
Segment Voltage	2	1	7-8	Probe 2 Segment 1 voltage
Segment Voltage	2	1	9-10	Probe 2 Segment 2 voltage
Segment Voltage	2	1	11-12	Probe 2 Segment 3 voltage
Segment Voltage	2	1	13-14	Probe 3 Segment 1 voltage
Segment Voltage	2	1	15-16	Probe 3 Segment 2 voltage
Segment Voltage	2	1	17-18	Probe 3 Segment 3 voltage

Table 2.4-4 Mode B Telemetry Packet

Data Field	# Bytes	Repetitions	Byte No	Description
Start Voltage	2	1	1-2	Initial sweep voltage, always 0 (-10V)
Voltage Step	1	1	3	D/A sweep step size, always 32
Probe Current	2	1	4-5	LP current at –10V (n_i)
Probe Current	2	128	6-261	LP current and range sweep data
Start Voltage	2	1	262-263	1st adaptive sweep start voltage
Voltage Step	1	1	264	1st adaptive sweep step size, always 8
Probe Current	2	1	265-266	LP current at –10V (n_i)
Probe Current	2	64	267-394	LP current and range
Start Voltage	2	1	395-396	2nd adaptive sweep start voltage
Voltage Step	1	1	397	2nd adaptive sweep step size (2,4,6...32)
Probe Current	2	1	398-399	LP current at –10V (n_i)
Probe Current	2	64	400-527	LP current and range

Table 2.4-5 Mode C Telemetry Packet

Data Field	# Bytes	Repetitions	Byte No	Description
Start Voltage	2	1	1-2	Initial sweep voltage, always 0 (-10V)
Voltage Step	1	1	3	D/A sweep step size, always 16
Probe Current	2	1	4-5	LP current at –10V (n_i)
Probe Current	2	256	6-517	LP current and range

Each of the data fields is defined as follows:

- Start Voltage: The initial bias voltage in a Langmuir probe sweep. It is a 12 bit unsigned integer in a 2 byte field with the 8 lsb in the 1st byte and the 4 msb in the 2nd byte. The 4 msb of the 2nd byte will be 0. The voltage represented is determined by: Vbias = 10*(n/2048 – 1) where n is the 12 bit number (0 to 4095).

- Voltage Step: The size of the bias voltage step in a Langmuir probe sweep. It is an 8 bit unsigned integer that represents the counts added to the sweep voltage D/A for each step in a sweep. A sweep starts at "Start Voltage" and is incremented by "Voltage Step" for each step in the sweep.

- Segment Voltage: The voltage measured on each segment of a probe. It is a 12 bit signed integer in 2's complement notation. It is stored in a 2 byte field with the 8 lsb in the 1st byte and the 4 msb in the second byte. The 4 msb of the 2nd byte contain probe and range data (see Table 2.4-6 for format).
  The voltage represented is given by: Vsc = Vfs*(n + 0.5)/2048 where –2048 ≤ n ≤ 2047, n is the value of the segment voltage field in telemetry. The value of Vfs is specified in Table 2.4-6. This formula gives the voltage of the spacecraft relative to the voltage sense segment with the segment used as the ground reference.

- Probe Current: The current flowing in the Langmuir probe. This is a 2 byte field that contains 12 bits of current measurement and 4 bits for probe / range information. The current measurement is a 12 bit signed integer in 2's complement notation. The 1st byte contains the 8 lsb of the 12 bit current. Bits 0 to 3 of the 2nd byte contain the 4 msb of the 12 bit current. The 4 msb of the 2nd byte contain probe and range data (see Table 2.4-6 for format). The probe current is given by:
  Iprobe = Ifs*(n + 0.5)/2048 where n ≤ –2048 and n ≤ 2047, n is the 12 bit current value. Ifs is the full scale current value which will be 1 of 4 values as indicated by the 2 bit range field (see Table 2.4-6). Using this formula ion currents will be reported as negative current and electron current will be positive.

- Probe / Range Field: The Segment Voltage and Probe Current data fields contain probe and range information encoded into the 4 msb of 2nd byte of the field. The probe field indicates which mast the data applies to. The range field specifies which current or voltage range was used for the measurement. The format for these fields is shown in Table 2.4-6.

Table 2.4-6 – Probe / Range Data Field Description						
Probe Field Bit		Probe	Range Field Bit		Current Range	Voltage Range
7	6	Selected	5	4	Ifs	Vfs
0	0	1	0	0	100 μA	NA
0	1	2	0	1	10 μA	NA
1	0	3	1	0	1 μA	5000 V
1	1	NA	1	1	100 nA	500 V

Bit 7 represents the most significant bit (msb), bit 0 the least significant bit (lsb) of a byte
NA: indicates this field value is not used and will not appear in telemetry data.

2.4.4.1.2 LPSP Data Packet Sequence

The LPSP electronics transmits a 2 byte sync code before the 1st data packet in each 60 or 80 second sequence. The sync code is the 1st 2 bytes transmitted after a SYNC pulse is received by the LPSP electronics. The sync code is also transmitted before the start of any 80 second data sequence that is automatically initiated by the LPSP.

The LPSP sync code is: EB D0 hex, transmitted in the order shown. This sync code was chosen because this two byte sequence will never occur in measurement data produced by the LPSP. The 2 msb of each of these bytes are logic 1, two consecutive bytes with a logic 1 in the 2 msb will never occur in the LPSP data.

The sequence of data packets received in telemetry is determined by which operating cycle (60 or 80 second) that ProSEDs is performing. The first 60 seconds of the 80 second cycle are identical to the 60 second cycle. The sequence of telemetry packets for both cycles is given in Table 2.4-7.

Table 2.4-7 LPSP Data Packet Sequence			
LPSP Mode	Repetitions	Cumulative Time (sec)	LPSP Data (bits)
Sync Code	1	0	16
A	15	15	2160
B	6	21	25296
C	3	24	12408
B	11	35	46376
A	25	60	3600
60 sec Cycle Total		**60**	**89856**
60 sec Cycle Average Data Rate: 1497.6 bits/sec			
A	20	80	2880
80 sec Cycle Total		**80**	**92736**
80 sec Cycle Average Data Rate: 1159.2 bits/sec			

2.4.4.2 Time Distribution Requirements

A synchronization pulse shall be provided at the start of each sequence. The sync pulses will occur at either 60 or 80 second intervals. The LPSP will start a sequence on the rising edge of this signal.

2.4.4.3 Housekeeping

The LPSP telemetry data stream doesn't contain any housekeeping data. The ProSEDS data system will monitor a temperature sensor mounted inside the LPSP electronics box to provide a measurement for the overall spacecraft thermal balance. The temperature sensor is a 3000Ω thermistor that is connected through the LPSP/Spacecraft connector (MJ17). The LPSP doesn't provide any signal conditioning electronics for this sensor.

2.4.5 Interface Connectors and Pin Assignments

The LPSP electronics box interfaces with the ProSEDS spacecraft electronics through a 15 pin D connector (MJ17) attached to the control deck (lower). The Langmuir probes communicate with the electronics box through 3 connectors (MJ47A, MJ51B, and MJ55C for probes 1,2,3 or A,B,C respectively) attached to the detector deck (upper). The release mechanism connects to control deck (lower) through 3 connectors (MJ45A, MJ49B, and MJ53C for probes 1,2,3 respectively).

The pin out for the spacecraft connector is shown in Figure 2.4-3, the pin out for one of the release and Langmuir probe interface connectors are shown in Figures 2.4-4 and 2.4-5 (the other two mast connectors have identical pin functions). The spacecraft connector (MJ17) pin functions are listed below.

| Pin	Description
1	LPSP Electronics Primary Power Input, 28Vdc
2	Deploy Power Input, 28Vdc
3,11	LPSP Temperature Sense, 3KΩ thermistor connected between pins
5	Test, 5V logic input, leave open for normal operation
6	Sync, 5V logic input, rising edge starts new LPSP data cycle
7	Clean, 5V logic input, rising edge starts a 60 second probe cleaning cycle.
8	Release, 5V logic input, High level energizes mast release mechanism
9,10	+28V return, LPSP electronics and release mechanism input power return.
13	LPSP electronic Chassis connection.
14	Serial Data Output High – RS422 data output high
15	Serial Data Output Low – RS422 data output low
4,12	No Internal connection

LPSP / Spacecraft Connector
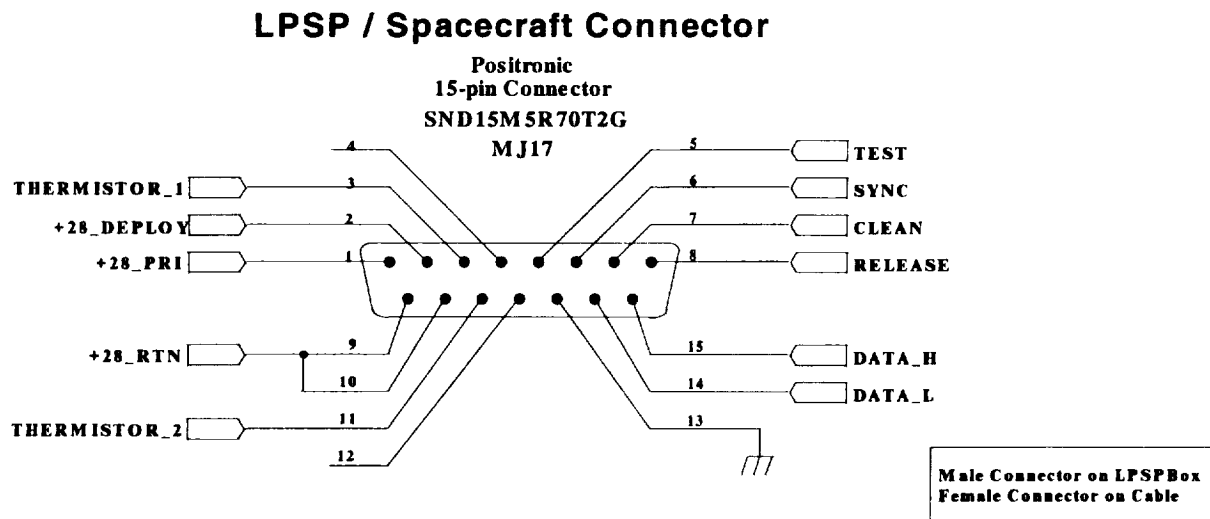
Figure 2.4-3 LPSP Spacecraft Interface Connector
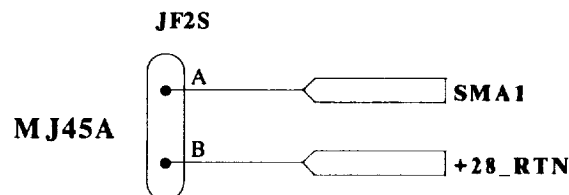
SMA Deployer Connectors

Figure 2.4-4 LPSP Release Mechanism Interface Connector
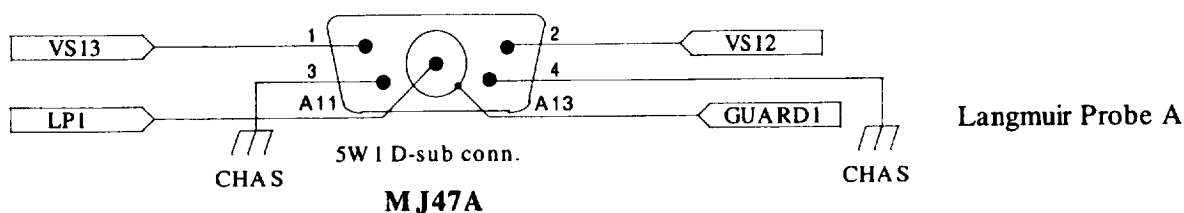
LP Mast Connectors

Positronic

Figure 2.4-5 LPSP Langmuir Probe Interface Connector

2.5 Mechanical

The LPSP consists of three sensor assemblies, three release mechanism assemblies, and one electronics assembly.

2.5.1 Configuration

The mechanical interface dimensions for the LPSP electronics and sensor assemblies are given in the following interface drawings

075-1038	LPSP Electronics Box Interface
075-1040	LPSP Mast and Release Interface

2.5.1.1 Mounting Baseplate Criteria

The mounting baseplate for the LPSP electronics box shall have the following interface:

Surface Flatness: 0.005 inches/foot
Surface Finish: not greater than 125 micro-inches rms

2.5.2 Mass Properties

The total mass of the LPSP, including the electronics box, Langmuir probe assemblies, release mechanisms, and all interconnect harness is 2.17 kg or 4.79 lbs. The mass of each item is listed below:

Assembly	Part No	Mass (grams)	Mass (lbs)
LPSP Elecronics	075-1050	558	1.23
Mast A	075-1004-1	347	0.76
Mast B	075-1004-2	320	0.70
Mast C	075-1004-3	540	1.19
Release A	075-1055-1	117	0.26
Release B	075-1055-2	99	0.22
Release C	075-1055-3	194	0.43

Total Mass   2175   4.79

2.5.3 Alignment

Figure 2.5-2 shows the alignment of the probes. They are mounted on three 31.5" (0.80 m) masts perpendicular to the Delta II second stage axis. A longer length (~1.5 m) was originally desired to give better assurance to be out of the spacecraft sheath at the highest possible potentials, but physical constraints on the Delta II limited the length. The probes are spaced approximately 120° apart with an accuracy of ±5°. After deployment, each mast will be nearly perpendicular to the Delta-II radial axis surface, within ±10°. The LPSP electronics box has no Field of View (FOV) requirements, and is securely placed onto the ProSEDS electronics box.

Figure 2.5-2   Langmuir Probe Spacing

2.5.4 Mounting Footprint

The LPSP shall meet the interface requirements specified in the LPSP IRD (MSFC-RQMT-2965) and the following University of Michigan Interface Drawings:

075-1038 LPSP Electronics Interface
075-1040 LPSP Mast Interface

2.5.5 Field of View

No obstructions other than the Delta second stage.

2.5.6 Handling Operations and Lift Points

No special requirements. Precaution must be taken to ensure proper care during transit operations.

2.6 The Sensors

The LPs will be mounted on masts and deployed after orbit injection as has been done for many previous orbital spaceflight missions. A Shaped Memory Alloy, SMA, activated pin puller will be used for this purpose.

Figure 2.6-1 illustrates the design of the LP sensors. The probes use a triaxial mast which is 31.5 inches long. The rod consists of a solid central element, an inner cylindrical tube, and an outer cylindrical tube, all insulated from each other by teflon or PEEK sleeving. All three elements of the rod are made of titanium for high strength and low mass. Second and third voltage sensors are mounted at the 1/3 and 2/3 points along the mast length and are simple 2" conducting copper cylinders.

Probe with Triax Extension Mast

075-1001   Langmuir Probe Tip Design

Figure 2.6-1 The LP sensor and Mast end

3. LPSP Technical Specifications

3.1 Functional Configuration

3.1.1 General Description

The LPSP shall be designed to measure, process and transmit data collected from 3 Langmuir probe mast assemblies, each mast assembly will have one langmuir probe and 2 voltage sensing segments.

The input section of the experiment shall consist of the LP sensors, along with their associated mounting and deployment mechanisms. Three 31.5 inch Langmuir Probe Assemblies, LPAs, shall be located at approximately 120° intervals around the Delta II. The LPAs each have a deployment mechanism to permit the sensors to be folded out of the way for launch, and then deployed for use.

Each LPSP LPA assembly shall be connected to the LPSP electronics assembly by means of a single multiconductor cable assembly for each LPA. The LPSP electronics assembly shall be designed to bias and collect data from the sensors and to digitize the sensor signal data for transfer to the spacecraft Data system. Spacecraft power for the LPSP shall be conditioned by the LPSP electronics assembly to provide all required regulated operating voltages and biases for the experiment.

One temperature sensor is located within the LPSP electronics package. This sensor is conditioned and read by the spacecraft Data System for verification of the spacecraft thermal design.

3.1.2 System Performance Specifications

3.1.2.1 Langmuir Probe & Deployment Mechanisms

The LP mast deployment mechanisms consist of a spring loaded, hinged, pivot housing and a shape-memory activated release mechanism. All three masts are deployed simultaneously by applying 28 ± 6 Vdc to the deploy power pin (MJ17 pin 2) and applying a +5V logic (>2.5V) signal to the Release input (MJ17 pin 8) for 1 second. When the release input is held high the release mechanisms provide a 13.3Ω ± 5% load on the deploy power input. The release mechanisms go to an open circuit when the pin puller releases the mast. The maximum release time is 100 ms. The deploy power is applied to the release mechanisms as long as the RELEASE input is held high, if resistive loads are used to simulate the release mechanisms during testing, the RELEASE pin should be held high for a maximum of 1 second with a maximum duty cycle of 10%. Exceeding this specification could result in damage to the current limiting resistors in the LPSP electronics box.

3.1.2.1.1 LP Mast Construction

The LPA mast is a solid triaxial tube common to all three LPAs. The lengths of the triaxial masts will be 31.5 inches. The LP masts are all deployable and have a common end design for their attachment to the pivot housing. The probe end of each LPA will support a [0.183 inch

diameter × 2 inches long] Rhenium wire probe. These probes are electrically connected to the center conductor and mechanically held by threading onto the mast center conductor. The triaxial LPA mast shall have the inner "shield" tube exposed to the plasma at the end of the LPA mast for 1 inch and shall be driven electrically at the same potential as the collector to act as an electrical guard element. The conductive outer "shield" tube in addition to providing the mechanical support for the collector must be at the same potential as the rest of the spacecraft to provide electrical shielding. The outer surface is covered with Kapton tape to assure that the conductive surface of the mast is not exposed to the plasma around the spacecraft. This is necessary to assure the mast doesn't effect the voltage sense measurements.

3.1.2.2 LP Design Specifications

In order to minimize the LP measurement errors, the design shall employ a collector having acceptably low work function patchiness. This is typically controlled through manufacturing control of the grinding and polishing of the probe. The LPSP langmuir probe is manufactured from Oriented Rhenium, the manufacturer will provide spectrograph data and a micrograph showing crystal orientation, obtained from a sample of each probe to verify probe construction.

In order to avoid contamination of the LP probe, the electronics can be commanded to apply a cleaning potential of +150 ± 50 VDC to the collector with respect to the outer shield.

In addition, space craft potentials as high as -500 V are possible. In order to withstand this operating potential, the probe and the mast construction shall be able to withstand up to 750 Vdc. This will be tested using a HI-pot test under conditions of 1 atm and $<10^{-4}$ torr.

3.1.2.3 Langmuir Probe Current Measurments

The LPSP Electronics contains an electrometer and an applied voltage generator along with appropriate multiplexing to permit measurement of LP currents on 3 probes. The Langmuir probe technique requires that the collector, immersed in the plasma, be biased relative to the spacecraft potential, and that the current collected in the probe be accurately measured by an electrometer. To accommodate varying plasma densities the LPSP electrometer has 4 selectable gains and a 12 bit A/D converter to digitize the collected current for further processing. The probe bias voltage is controlled by a 12 bit D/A converter over a ±10V range.

3.2 Design Specifications

3.2.1 Electrical Design Specifications

The LPSP electronics performs two different measurment functions during a 60 or 80 second cycle: Langmuir Probe Voltage/Current sweeps to measure plasma parameters, and spacecraft potential measurements to determine the spacecraft bias relative to the plasma.

3.2.1.1 Langmuir Probe Measurement Specifications

The LPSP performs Langmuir Probe current measurements in operating Modes B and C during a 60 or 80 second sequence (see 0). Measurements are made on one probe during each Mode B or C operation, the other two probes are connected to spacecraft chassis or left floating.

3.2.1.2 Bias Voltage and Current Accuracy

During Langmuir Probe measurements of N_e, N_i, and T_e the langmuir probes bias voltage is swept over a –10V to 10V range and the current collected by the LP is measured by the electrometer in the LPSP electronics. The electrical specifications for the electrometer and the bias voltage generator are listed in Table 3.2-1.

Table 3.2-1 Electrometer and Bias Generator Specifications

Number of selectable gain ranges:	4 decade
Maximum electrometer sensitivity:	0.488 picoamps/bit
Nominal Gain Ranges:	±100.3 na, ±1.006μa, ± 9.928μa, ± 99.39 μa full scale, Tolerance ±2%
Combined span and offset error:	±1 % of Full Scale (Note 1)
System noise floor:	100 picoamps RMS
Maximum electrometer sample rate	480 samples/second
Probe Bias Generator Range	-10.0, +9.995 VDC ±40mV
Probe Bias Generator resolution:	12 bits = 4.88 mv/bit
Probe Bias Generator RMS error	15 mV RMS Max (Note 2)
Probe Bias Generator Max error	±25 mV Max (Note 2)

Note 1: Post Calibration Spec. A linear fit to test data from the min, max and room operating temperatures will be done for each gain range. This max error spec applies to deviations from the linear fit curve.

Note 2: Post Calibration Spec. A linear fit to test data from the min, max and room operating temperatures will be done for the Bias generator data. This max error spec applies to deviations from the linear fit curve.

3.2.1.2.1 Voltage Sweep Timing

The Langmuir probe voltage sweep timing for Mode B is shown in Figure 3.2-1. This mode consists of three voltage sweeps as described in 2.3.3.2. Each sweep starts with a range select sequence to determine which range is used at the start of a sweep. During this time the LPSP makes 4 current readings with the probe biased at –10V, starting with the ±100μa range. If the ADC current reading is ≤ ≈1/30 of full scale (ADC digital value of 61) on any of the current measurements, the electrometer is switched to the next higher gain range (ie ±10μa, ±1μa, ±100na). This is repeated 4 times to pick the most sensitive current range that gives a reading < 1/3 of full scale. This procedure assures that the threshold of –3(initial current) is on the same range as the initial current reading. After the range select is finished the LPSP performs the 128 or 64 step voltage sweep. Any current reading >90% full scale (ADC digital value of 1845) during the sweep caused the LPSP to switch to the next lower gain range for the

next current reading. This algorithm doesn't prevent saturated ADC readings so data analysis routines should remove any saturated readings from the analysis.

The basic step timing of the LP sweep is 2.083 ms (1/480 sec). This time interval is determined by the time required to transmit the 2 bytes (20 bits) of measurement data at 9600 bps. The LPSP can buffer only 1 data point, the current data point is transmitted during the setup time for the next. All of the timing delays in the sweep are an integer multiple of this basic time step. The extra delay times are added at points were large steps in the probe bias voltage may occur to allow the current amp more settling time. The Mode C LP sweep timing is the same as the 128 step sweep shown in Figure 3.2-1 except there are 256 steps instead of 128.
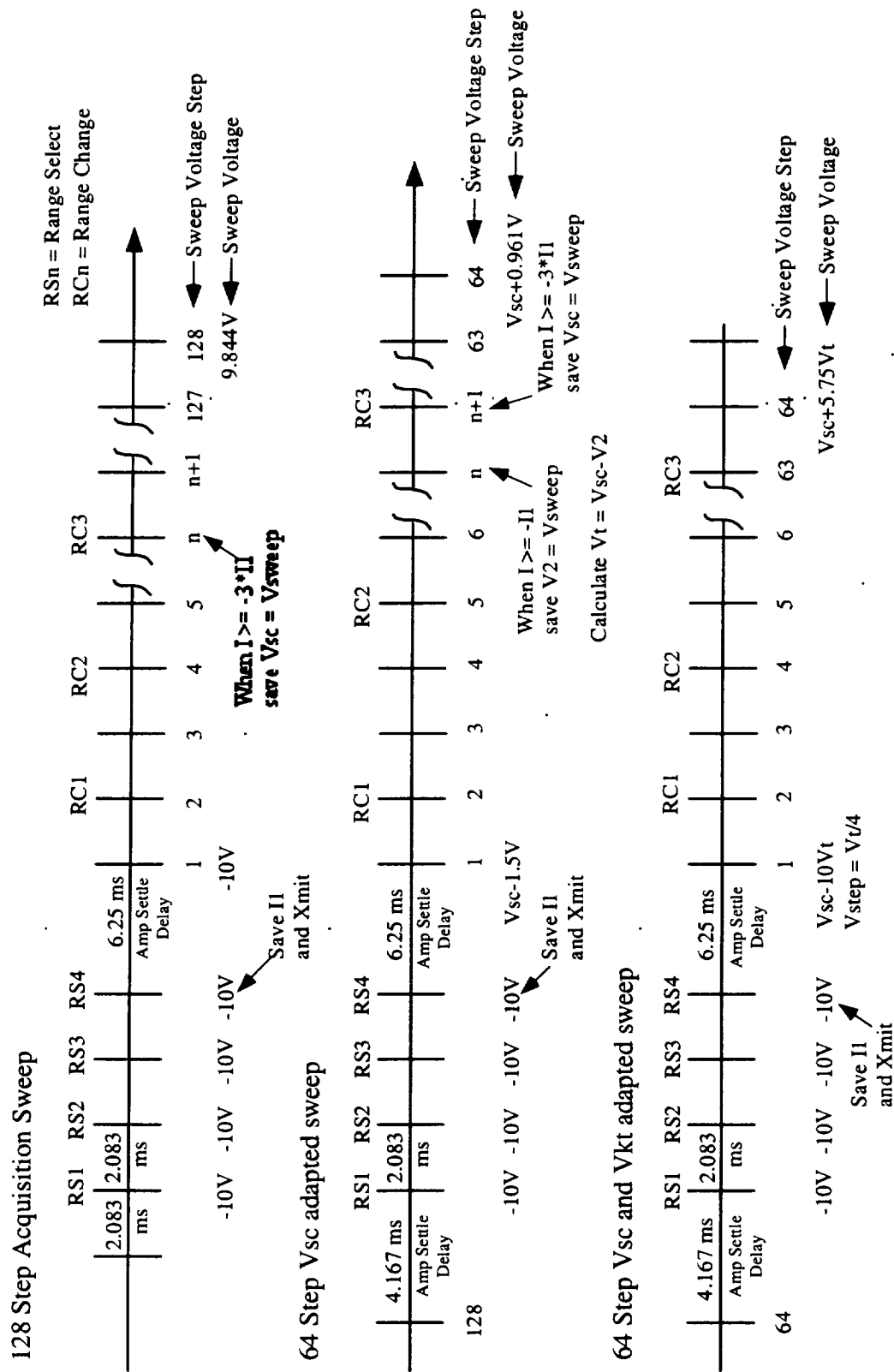
128 Step Acquisition Sweep

64 Step Vsc adapted sweep

64 Step Vsc and Vkt adapted sweep

RSn = Range Select
RCn = Range Change

Figure 3.2-1 LPSP Mode B Langmuir Probe Sweep Timing

3.2.1.3 Spacecraft Potential Measurement Specifications

The LPSP electronics performs spacecraft potential measurements when operating in Mode A. The potential measurements are made by switching a 5000 MΩ resistor in series with the Langmuir probe and measuring the current flowing through the resistor with the electrometer. Potential measurements are also made on two other copper sense pads on each mast, these segments have the 5000 MΩ resistors permanently in series with the electrometer input. Readings are made on the two most sensitive current ranges ±100na and ±1μa, this gives ±500V and ±5000V ranges for the spacecraft potential measurements. In this configuration the LPSP becomes a voltmeter with a 5000 MΩ input impedance. Only 1 of the 9 segments is connected to the electrometer at a time, the other segments are connected to spacecraft chassis by an impedance of 5100 MΩ. This high impedance is necessary to minimize the probes effect on the plasma environment around the spacecraft.

3.2.1.3.1 Spacecraft Potential Accuracy

The spacecraft potential measurement accuracy is effected by several factors, the primary ones are:

1. The plasma sheath distance around the spacecraft. (See 2.2.1)
2. The effective plasma impedance in series with LPSP input impedance.
3. The settling time constant caused by mast capacitance and input impedance.
4. The accuracy of the 5000 MΩ resistors and electrometer in the LPSP.

Items 1 - 3 are primarily related to plasma density and produce measurement errors that can't be compensated for unless plasma density is known. The plasma interface to the Langmuir probe looks approximately like a series resistance for potential differences between the probe and the plasma of > 20V (probe biased negative relative to the plasma). The value of the plasma resistance varies essentially linearly with ion density. Figure 3.2-2 shows the equivalent input circuit for the LPSP electronics in spacecraft potential measurement mode, resistor Rp represents the plasma effective resistance. The model only applies to large potential differences (>20 V) between the probe and plasma. Ideally the probe needs to be at the same potential as the plasma to record the spacecraft potential; however, due to the loading effect the probe will not reach the plasma potential at low plasma densities.
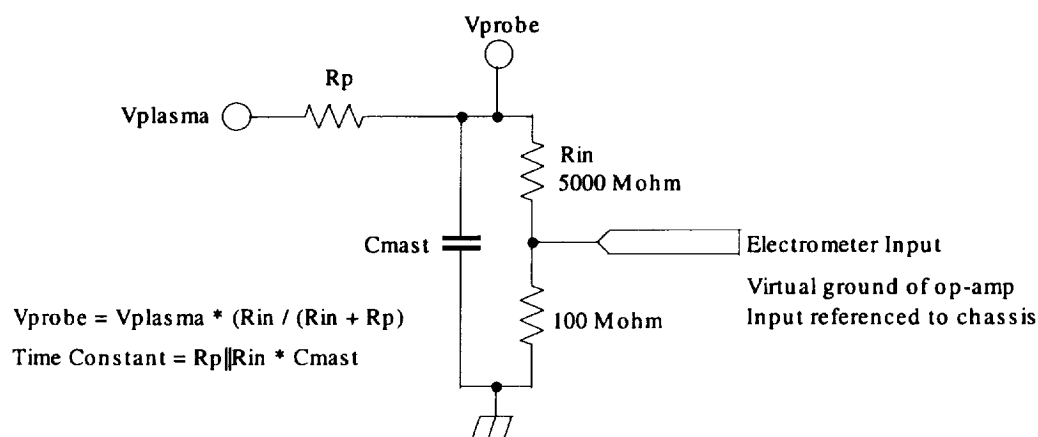
Figure 3.2-2 Voltage Sense Equivalent Input Circuit

The plasma resistance (Rp) and the LPSP input impedance (5000 MΩ) form a voltage divider that cause the measured probe voltage to be lower that the actual plasma potential according to the equation shown in Figure 3.2-2. The parallel resistance of Rp and 5000 MΩ along with the mast capacitance (Cmast) form a low pass filter with a time constant as shown in Figure 3.2-2

The estimated measurement errors caused by the probe input impedance are shown in Table 3.2-2 for different plasma densities, as can be seen the errors at the lowest density become fairly large (>25%). Errors calculated by modeling the plasma as series resistance only apply for large voltage differences between the probe and plasma, ideally the probe should be at the same potential as the plasma to make voltage measurements. The large capacitance of the triaxial mast and cable used for the langmuir probes results in long measurement settling time constants at lower plasma densities. Table 3.2-3 shows the measurement time constants for all 3 probe tips, it also show the measurement time constant for the 2 additional voltage segments on each mast.

Table 3.2-2 Spacecraft Potential Measurement Errors vs Plasma Density.

Plasma Density (Ions / cm^3)	Plasma Resistance (ohms)	Measured/Actual Voltage Ratio
1×10^3	1.68×10^9	0.74809
1×10^4	1.68×10^8	0.96742
1×10^5	1.68×10^7	0.99664
1×10^6	1.68×10^6	0.99966
1×10^7	1.68×10^5	0.99997

Table 3.2-3 Spacecraft Potential Measurement Time Constants

Plasma Density	Measurement Time Constant (ms)

(Ions / cm^3)	LPA C=1800pf	LPB C=1700pf	LPC C=2550pf	VS2,3 C=80pf
1 x 10^3	2267.23	2141.27	3211.90	100.77
1 x 10^4	293.20	276.91	415.36	13.03
1 x 10^5	30.21	28.53	42.79	1.34
1 x 10^6	3.03	2.86	4.29	0.13
1 x 10^7	0.30	0.29	0.43	0.01

LPA – C refer to the probe tips
VS2,3 refer to the 2 voltage only measurement channels on each mast.

The probe tips provide the primary spacecraft measurement function because they are the most likely segment to be outside the spacecraft plasma sheath, and they also have the lowest measurement noise due to the triaxial wiring. The probe measurement noise is typically a factor of 10 lower than the other segments. The probes pay for the low noise reading with long measurement time constants (See Table 3.2-3). This means that the probes will not be able to track rapid changes in plasma potential. At a plasma density of 10^3 cm^{-3} the probes 3db bandwidth will be approximately .05 to .07 hz., this increases rapidly as plasma density increases. The other two measurement channels were added to the mast to help determine the plasma sheath dimensions, they also have much higher bandwidth than the probe tip and will be able to track rapid changes in spacecraft potential better. Due to the low bandwidth of the probe tip the LPSP can't switch rapidly between Langmuir probe current measurements and voltage measurements. Langmuir probe measurements require the probe to be driven to ±10V of the spacecraft potential while it must float to make spacecraft potential measurements. The LPSP 60 and 80 second operating sequence perform LP measurements during a 20 second interval, the rest of the time the probes are allowed to float so spacecraft potential measurements can be made. When the LPSP makes the transition from LP current measurements to SP voltage measurements the probes are allowed to float 50ms before the 1st voltage segment (LP A probe tip) is measured. This may cause the 1st reading to be lower than the actual spacecraft potential because the mast capacitance hasn't had time to charge up. The LPSP electronics voltage sense accuracy will be checked by driving the voltage measurement segments with a power supply through a series resistance of 10 MΩ. The LPSP electronics will meet the specifications in Table 3.2-4 over its operating temperature range.

Table 3.2-4 LPSP Spacecraft Potential Measurement Accuracy

LPSP Probe Tip Measurement Accuracy		
Spacecraft Potential	Average Accuracy	Standard Deviation
+100 to –450V (±500 V FS)	±1% Full scale	±0.2% Full scale
-450 to –5000V (±5000 V FS)	±0.4% Full scale	±0.2% Full scale
LPSP Segment 2 and 3 Measurement Accuracy		
Spacecraft Potential	Average Accuracy	Standard Deviation
+100 to –450V (±500 V FS)	±3% Full scale	±2% Full scale
-450 to –5000V (±5000 V FS)	±1% Full scale	±1% Full scale

The accuracy measurements are based on the average and standard deviation of at least 130 voltage measurements. Segment 2 and 3 refer to the voltage sense pad near the middle and closest to the pivot of each mast.

3.2.1.3.2 Spacecraft Potential Timing

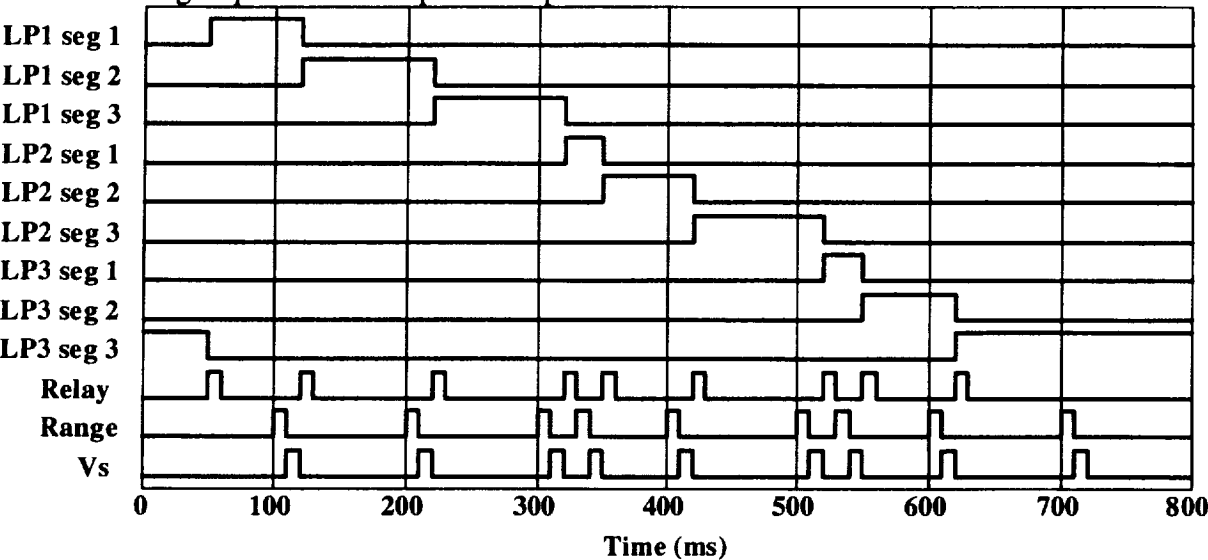The timing sequence of the spacecraft potential measurements is shown in

Figure 2.3-3. The measurement of all 9 segments requires about 700ms to complete.

3.2.1.4 Primary Power Specifications

The LPSP will operate with primary and deploy power voltage of 28 ± 6 Vdc over the operating temperature range of –40°C to +60°C. The maximum LPSP input power shall be as specified in 2.4.2.2.

3.2.1.5 Grounding and Isolation

The LPSP flight hardware shall be electrically bonded to the spacecraft mounting interfaces. All primary power and signal returns will be electrically isolated from each other and from chassis by a direct current resistance of one meg-ohm or greater. The LPSP electronics secondary returns will be connected by design to the spacecraft chassis. This is a requirement for proper operation of the sensors.

3.2.1.6 Shields

The interconnecting cable between the LPA sensors and LPSP electronics shall use a triaxial cable to the LP and shielded twisted pair for all other connections. The shields of these cables will be connected to chassis ground by connecting to the connector back shell and/or by connecting to connector pins that are connected to chassis. The harness to the LP mast and release mechanism shall be covered with an addition braided shield to provide additional protection from the Delta's 3rd stage rocket exhaust. This shield will be grounded to the connector back shell.

3.2.1.7 RF Bypassing

The LPSP electronics primary power returns may be bypassed to the chassis using a 0.1 μF or smaller capacitor.

3.2.1.8 Electrical Bonding

Bonding shall comply with the Specifications of MIL-B-5087. The Specifications and methods of class R bonding shall apply to all metal-to-metal mating surfaces on the sensor assemblies and on the LPSP electronics assembly. A maximum bonding resistance of 2.5 milliohms shall be maintained. Clean conductive mating surfaces shall be provided on the component case and the surface of the connector shells where connectors are installed on the sensors and electronics assembly. When rectangular connectors are used, captive nut plates shall be used to maintain proper compression at the bonding surface and preclude unsecured nuts within cases.

Only electrically conductive coatings shall be used on mating surfaces. Conductive coating as specified in MIL-C-5541D (Alodine) for aluminum shall be used for treatment of bare surfaces. Nickel plating is also acceptable.

3.2.1.9 Electro-Magnetic Compatibility Specifications

The LPSP instrument shall be designed and tested to meet the EMC requirements detailed in ProSEDS RVC and LPSP IRD Documents. These requirements define modified levels of a subset of the MIL-STD-461C compatibility requirements. Verification of the instrument performance shall be done at MSFC as part of system level EMC testing.

3.2.2 Mechanical Design Specifications

3.2.2.1 Quasi-Static Design Load Factors

The LPSP shall be designed to withstand the quasi-static loads defined in ProSEDS RVC and LPSP IRD Documents.

3.2.2.2 Strength

The allowable material property data sheets for the LPSP shall be obtained from the most recent revision of MIL-HDBK-5G. Type A basis material properties (99% probability and 95% confidence) or equivalent shall be used for components.

The following safety factors shall be applied to the materials selected for use in the design of the instrument:

Yield Factor of Safety	=	1.65 x limit load
Ultimate Factor of Safety	=	2.0 x limit load
Test Factor of Safety	=	1.25 x limit load

3.2.2.3 Stress Analysis

A stress analysis shall be performed for the LPSP Electronics assembly and for each sensor where it is attached to the spacecraft to demonstrate conformance to the Specifications of

this specification. The analysis may be based on finite element models or classical analysis methods and shall include margins of safety.

3.2.2.4 Stiffness

The LP assembly (probe/mast) with the deployment mechanism shall have a minimum natural frequency greater than or equal to 35 Hz when constrained at the Delta II interface. The LPSP electronics box should have a minimum natural frequency greater than 200 Hz when constrained at it's mounting interface.

3.2.2.5 Random Vibration and Shock

The LPSP will conform to random vibration and shock requirements as specified in the ProSEDS RVC.

3.2.2.6 Mass

The LPSP Mass shall be as specified in Section 2.5.2.

3.2.2.7 Venting

All components of the LPSP shall be vented so that hardware can withstand the Delta II launch fairing internal pressure profile as specified in the ProSEDS RVC.

3.2.3 Thermal Specifications

3.2.3.1 LPSP Sensor Specifications

The thermal specifications imposed are for survival of the functionality of the sensors mounted on the instrument masts. Operational temperature range is –75 to +170 °C, survival –75 °C to +170 °C. Mast release and pivot: operational temperature range, -53 to +82 °C, survival, -55 °C to +82 °C prior to deployment of the mast. After deployment of the pivot and release have a maximum operation / survival temp limit of –55 to +170 °C.

3.2.3.2 LPSP Electronics Specifications

The LPSP will be mounted on the ProSEDS instrument panel. During operation, the thermal design shall be capable of rejecting all the electrical dissipation appearing as heat by conduction through the baseplate to the mounting surface. Operational temperature range, -40 to +60 °C, survival, -40 to +85 °C.

3.2.3.3 Thermal Analysis Model

The LPSP only dissipates and average power of about 0.9 watts with the maximum power dissipation of < 100 mW in any one component mounted on the printed circuit board. Because of this low power dissipation a detailed thermal analysis at the component level isn't necessary.

The only component in the LPSP that may dissipate some power for an extended period of time is the transistor that drives the 150V cleaning supply. Under maximum load this transistor may dissipate 0.65 W for 6 minutes. This transistor is mounted to the LPSP lower deck wall with Thermaloy Thermalcote as a thermal joint compound. A simple but conservative

thermal model for this transistor has a 0.003" thick joint of thermalcote and assumes all the heat is conducted through a 0.75" long section of the aluminum box wall with a cross sectional area of 1.00" x 0.035" to the LPSP mounting foot. With these assumptions thermal resistance from transistor junction to the LPSP mounting foot is 12.4 °C/W. This gives a 12.4 °C/W * 0.65 W = 8.1 °C junction rise.

The LPSP maximum operating temperature of 60 °C gives a maximum junction temperature of 68.1 °C, the maximum de-rated junction temperature for the transistor is 100 °C.

3.3 Analysis and Test Specifications

3.3.1 General Test Specifications

3.3.1.1 Electrical Functional Test

This test for the LPSP shall verify the functionality of the flight hardware using the LPSP GSE. Component interfaces shall simulate those of the spacecraft as nearly as practical. Initial measured parameters are recorded and compared against component design specifications. These initial measurements will be used as a baseline for comparison of subsequent functional tests. A function test shall be performed before and after each environmental exposure. Data from these functional tests will be checked for changes from the baseline or possible trends that may lead to a later failure.

3.3.1.2 Testing Sequence

LPSP Electronics Test Sequence
1. Functional test module over temperature per 075-3217. This procedure verifies all component operation over required temperature range.
2. Apply conformal coatings to unit and stake all components
3. Test high voltage operation per 075-3219. This procedure verifies high voltage operation of the LPSP electronics and masts in a vacuum ($< 10^{-4}$ torr). The LPSP is tested to 750V which is 250V higher than the 500V LPSP measurement requirement.
4. Thermal vacuum temperature cycle per 075-3201. The LPSP electronics receives 8 cycles from min to maximum operational temperature extremes at pressures below 10^{-4} torr. The operated in ProSED 60 second operating mode at each temperature extreme. Functional operation is verified at each temperature extreme.
5. Perform spacecraft potential calibration test procedure over temperature per 075-3218. This test verifies correct operation of LPSP electronics and masts over their required operating temperature range, and provides calibration data for the spacecraft potential measurement function.

LPSP Masts and Release Mechanisms
1. Complete assembly of Masts and Release mechanisms
2. Test high voltage operation per 075-3219. This procedure verifies high voltage operation of the LPSP electronics and Masts in a vacuum ($< 10^{-4}$ torr). The LPSP is tested to 750V which is 250V higher than the 500V LPSP measurement requirement.

3. Perform vibration and shock testing on LPSP Masts and Release Mechanisims

4. Perform thermal temperature cycling per 075-3225. The masts receive 8 temperature cycles from min to max operatiing temperature range at one atmosphere. The masts are deployed 4 times at each temperature extreme during the test. The mast and release mechanism receive 1 temp cycle in vacuum with 1 deployment at each temperature extreme.

5. Perform spacecraft potential calibration test procedure over temperature per 075-3218. This test verifies correct operation of LPSP electronics and masts over their required operating temperature range, and provides calibration data for the spacecraft potential measurement function.

3.3.2 Mechanical Test Requirements

3.3.2.1 Sine Vibration

The LPSP mast and release mechanism will be tested to the sine vibration requirements listed in the ProSEDS RVC. The LPSP electronics will be tested after delivery after it is mounted on the ProSEDS instrument panel.

3.3.2.2 Random Vibration

The LPSP mast and release mechanism will be tested to the random vibration requirements listed in the ProSEDS RVC. The LPSP electronics will be tested after delivery after it is mounted on the ProSEDS instrument panel.

3.3.2.3 Shock

The LPSP mast and release mechanism will be tested to the Shock requirements listed in the ProSEDS RVC. The LPSP electronics module will be tested after delivery after it is mounted on the ProSEDS instrument panel.

3.3.2.4 Mass Properties

The mass of each of the LPSP sensors, the cable, and the electronics assembly of the LPSP shall be as specified in 2.5.2.

3.3.3 Thermal Test Specifications

3.3.3.1 Thermal Vacuum Testing

The LPSP electronics will receive 8 thermal vacuum cycles over its required operating temperature range. The Masts and Release mechanism will receive 8 temperature cycles over their required operating temperature range at one atmosphere and 1 temperature cycle in vacuum.

3.3.3.2 Survival Cycle

No testing over the survival temperature extremes will be performed.

3.3.4 EMC Test Requirements

EMC qualification testing of the LPSP will be done during system level testing and MSFC per the requirements of the ProSEDS RVC..

4. LPSP GSE Technical Specifications

The specifications for the ground support equipment (GSE) are presented in the following sections. The ground support equipment will be used for operations at MSFC and the launch pad at Cape Canaveral. Figure 4-1 shows the equipment needed.
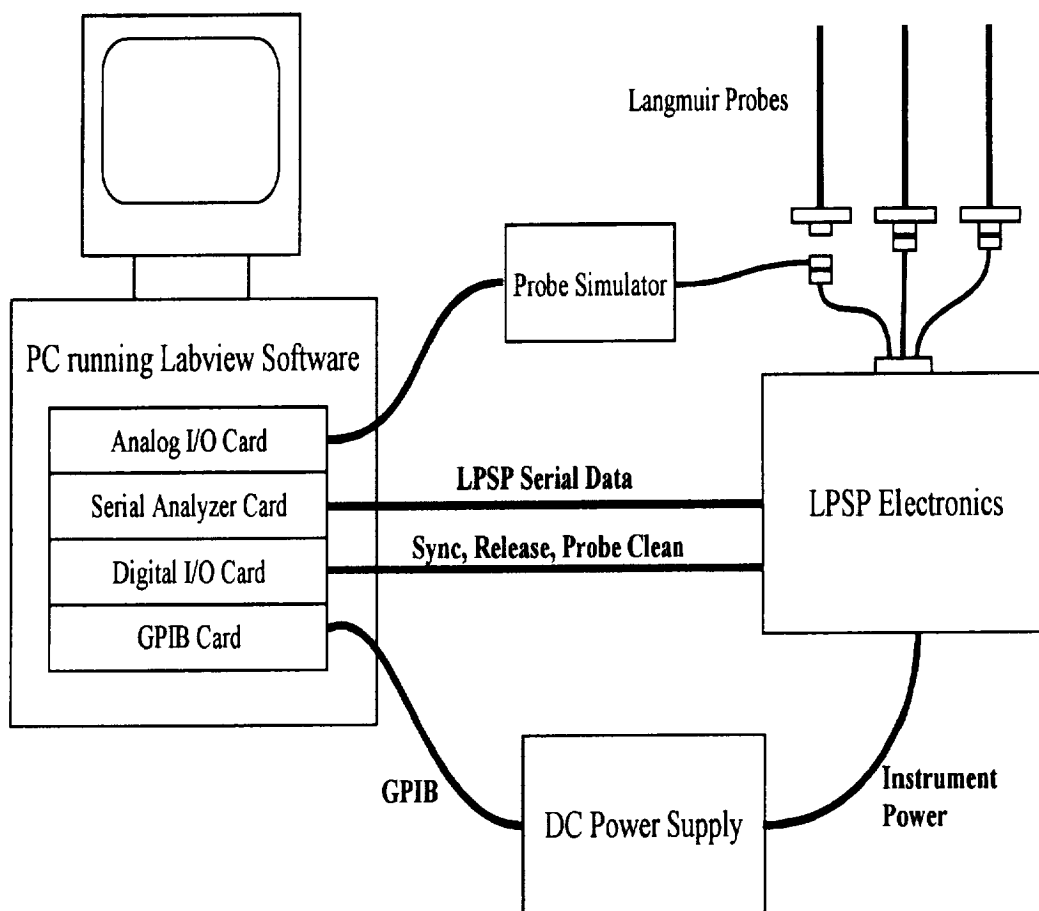

Figure 4-1 Ground Support Equipment at MSFC for Hangar Operations

4.1 Spacecraft/Sensor Simulator GSE

The major hardware components included for testing of the LPSP are described below with appropriate substitutions allowed:

1. A 200Mhz (min) Pentium computer having the following I/O boards installed:
   Ethernet Network Interface
   IEEE 488
   RS-422 serial interface card
   The computer shall include a 17 inch color VGA monitor, serial RS232, parallel printer ports, 64 MBytes of RAM minimum and a keyboard.
2. A Tektronix PS2520G Power Supply
3. LPSP GSE test box 076-3168
4. An LP simulator to provide signals simulating the LP volt-ampere flight characteristics for purposes of performing functional tests of the experiment hardware and software.
5. AC power distribution for the above equipment. The GSE shall operate from a source of 115VAC 60 Hz power of less than 10 amperes.
6. A shipping container for the above listed equipment.
7. A cable to connect the GSE to the power and data connectors on the LPSP electronics. These cables shall include the appropriate cable/connector savers.

4.1.1 GSE Calibration Requirements
   None

4.1.2 GSE Grounding Requirements
   The LPSP control box power supply return should be referenced to earth ground.

4.2 LPSP Experiment Shipping Container
   When transferring the flight-experiment hardware from one facility to another, an appropriately designed shipping container shall be used. The shipping case shall be able to withstand statics load that may be placed on the container during shipping.

4.3 Mechanical Support Equipment
   A list of mechanical support equipment will be provided to the ProSEDS when available.

4.3.1 Shipping Container
   The instrument provider will provide shipping containers for the LPSP assemblies and all associated GSE. Provisions shall be made for shipping container storage at the MSFC's facility.

4.3.2 Handling and Lifting Equipment

   None required

5. References

1. Brace, L. H., R. F. Theis, and A. Dalgarno, The Cylindrical Electrostatic Probe for Atmosphere Explorers C, D and E, *Radio Science*, 8(4), 341, 1973.

2. Krehbiel, J. P., L. H. Brace, R. F. Theis, W. H. Pinkus, and R. Kaplan, The Dynamics Explorer Langmuir Probe Instrument, *Space Sci. Inst.*, 5, 493-502, 1981.

3. Krehbiel, J. P., L. H. Brace, R. F. Theis, R. Cutler, W. H. Pinkus, and R. Kaplan, *IEEE Trans. Geosci. and Remote Sens.*, **GE-18**, 1, 49, 1980.

4. Mott-Smith, H. M., and I. Langmuir, The Theory of Collectors in Gaseous Discharges, *Phys. Rev.*, 28, 727-763-1926.

5. Hoegy, W. R., and L. E. Wharton, Current to a Moving Cylindrical Electrostatic Probe, *J. Appl. Phys.*, **44**, 5365-5371, 1973.

6. Shugg, W. Tillar, Handbook of Electrical and Electronic Insulating Materials, 2nd edition, IEEE Press, 1995.

7. Brace, L. H., W. R. Hoegy, and R. F. Theis, Solar EUV Measurements at Venus Based on Photoelectron Emission from the Pioneer Venus Langmuir Probe, *J. Geophys. Res.*, **93**, 5461, 1988.

8. Brace, Larry H., "Langmuir probe measurements in the ionosphere," Measurement Techniques for Space Plasmas, AGU Geophysical Monograph 103, 1998.

APPENDIX

A. THE MEASUREMENT TECHNIQUES

A Langmuir probe (LP) is a metal collector that is immersed in a plasma to measure its density and temperature, and to measure the potential of the spacecraft with respect to the surrounding plasma. To assure that the measurements are made beyond the disturbance zone surrounding the spacecraft, each collector is placed at the end of a rod that provides both mechanical support and electrical connection. The length of the mounting rod is great enough to require that the probe be folded down against the spacecraft and deployed after the spacecraft is injected into orbit.

The Langmuir probe design proposed here is based on similar experiments used on the Atmosphere Explorer[1], Dynamics Explorer-2[2], and the Pioneer Venus Orbiter[3] spacecraft. The measurements are made by sweeping the collector voltage and measuring the current that is produced as electrons and ions strike the collector surface and are neutralized. N_e, T_e, and the spacecraft potential, V_s, can be derived from the resulting volt-ampere curves. N_i measurements are also possible, but they will not be as straightforward in the secondary ion sheath as they are in the ionosphere itself, as will be described later. The theory of the LP measurements is outlined below.

A.1 Theoretical Basis for the LP Measurements

A simplified block diagram of an LP experiment and a theoretical volt-ampere curve are shown in Figure A-1 to illustrate the method. The technique uses all three regions of the curve; (1) the ion saturation region in which I_i is proportional to N_i, (2) the electron retardation region whose width is proportional to T_e, and (3) the electron saturation region in which I_e is proportional to N_e. V_s is derived by recording the voltage required to drive the probe to the plasma potential, V_p, which is identified as the inflection point between the retardation and acceleration regions. The measurements rely on the use of the Langmuir probe equations given below.

N_e *Measurements.* The electron saturation current for an orbital motion limited cylinder[4] is given by equation (1)

$$I_e = n_e A q \frac{2}{\sqrt{\pi}} \left(\frac{kT_e}{2\pi m_e} \right)^{\frac{1}{2}} \left(1 + \frac{qV}{kT_e} \right)^{\frac{1}{2}} \quad \text{for} \quad \frac{qV}{kT_e} < 0 \tag{1}$$

where
: A = probe area
  e = electron charge
  q = electron charge
  k = Boltzmann constant
  m_e = electron mass
  T_e = Temperature of electrons in Kelvin

V = probe potential relative to V_p
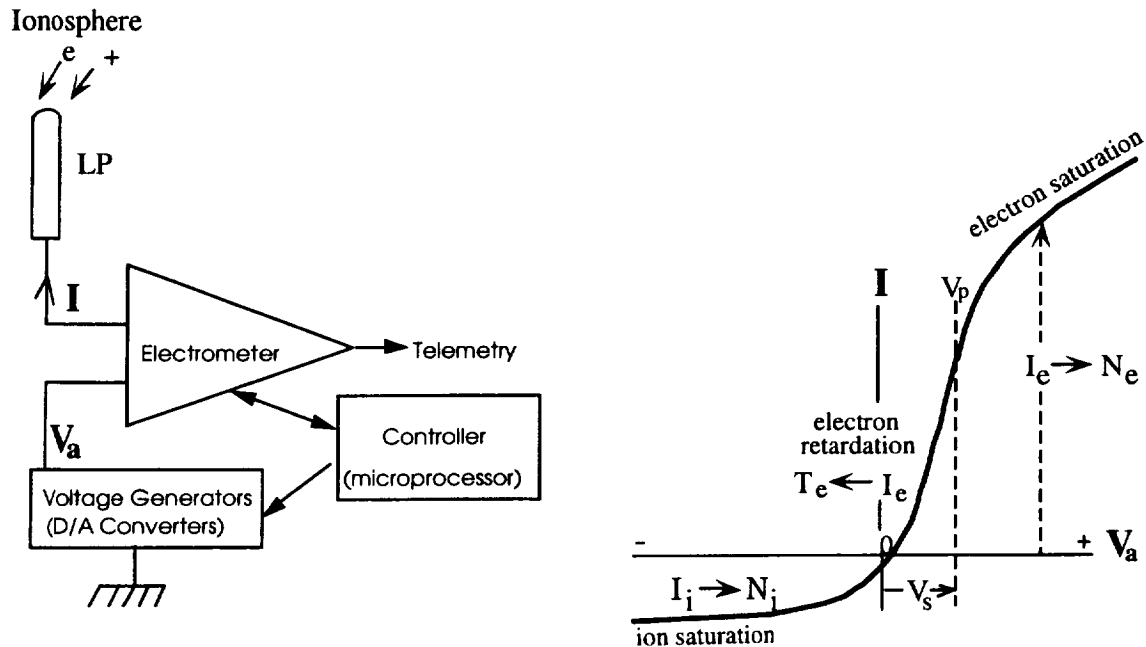
N_e = Density of electrons

Figure A-1. Diagram illustrating the LP measurement technique. An electrometer measures the probe currents that are produced by stepping its voltage, V_a, through a suitable range. The method is illustrated by the theoretical volt-ampere curve shown at the right. N_i is obtained from the amplitude of ion current in the ion saturation region. T_e is derived from the width of the electron retardation region. N_e is obtained from the amplitude of the electron saturation region. V_s is obtained by observing the Va that must be applied to drive the probe to the plasma potential, V_p, which is identified as the inflection point between the electron retardation and acceleration regions.

At large positive applied voltages ($eV/kT_e \gg 1$), the T_e terms cancel, and equation 1 can be simplified to the following,

$$I_e = N_e \, A \, e/\pi \, (2eV/m_e)^{0.5}, \tag{2}$$

whose simplicity illustrates an advantage of cylindrical probes; i.e., that N_e can be derived without requiring knowledge of T_e. This equation is particularly useful when operating a probe at a fixed positive potential to obtain the high N_e spatial resolution required to follow the build up and decay of the plasma cloud when the thrusters are turned on and off.

Equations 1 and 2 apply to long cylindrical collectors. They do not accurately describe the electron current to the shorter collectors that are typically used in space. In practice, the collector

length, l, is limited by physical strength considerations and by the desire to limit the magnitude of the voltage that is induced in the collector (**vxB•l**) by its motion through the geomagnetic field. The reason for this is described later in the section on measurement errors. To correct for the resulting "end effects" that short collectors suffer from, a somewhat higher power relationship is used, such as that given in equation 3,

$$I_e = N_e \, A2 \, (e/\pi^{0.5})(kT_e/2\pi m_e)^{0.5}(2eV/m_e)^{0.75} \qquad (3)$$

The empirically determined exponent (0.75) works well at low accelerating potentials and at typical ionospheric densities where the Debye length in the plasma is comparable to the collector length. Empirically, the exponent grows toward unity at low densities and should actually be a weak function of N_e rather than a constant. However, equation 3 works well enough at small applied potentials and should work very well at the higher densities of the secondary plasma cloud.

The Ni Measurements. N_i is derived from the ion saturation current[5]. When the probe axis is kept perpendicular to the ion velocity vector, the ion current, I_i, is given by equation 4,

$$I_i = N_i \, A\pi^{-1} \, q_i \, v_i \, (1+kT_i/m_i v_i^2 + 2eV/m_i v_i^2)^{0.5} \qquad (4)$$

where: q_i = ion charge
v_i = ions drift velocity in the spacecraft rest frame
T_i = ion temperature
m_i = ion mass

The first term describes the component of I_i that is produced by ions swept out on the side of the collector. In ionosphere applications, v_i is essentially the spacecraft velocity, since the ion drift velocity is usually negligible by comparison. The second and third terms describe the additional ion current caused by the ion thermal velocity and the attracting potential of the probe.

The Te Measurements. T_e is derived from the Langmuir equation for retarded electrons[4]

$$I_e = A \, N_e \, e \, (kT_e/2\pi m_e)^{0.5} \exp(eV/kT_e), \quad eV/kT_e<0 \qquad (5)$$

To obtain T_e, the electron retarding region is fitted using a linear approximation to the ion saturation current and an exponential representation of the electron current, as shown in Figure A-1. I_e is measured relative to the measured level of I_i. Knowledge of N_e is not required to obtain T_e, since it lies outside the exponential along with the other constants, A, e, π, and m_e. The power of the exponential depends only on T_e.

A.2 LP Measurement Errors and Surface Cleaning.

Three factors are critical to the success of the Langmuir probe measurements, particularly for the T_e measurements. They are: (1) employing a collector having acceptably low work function patchiness, (2) reducing surface contamination of the collector, and (3) minimizing the induced voltage in the collector. For the ionospheric measurements, we propose to use a collector whose surface consists of highly oriented rhenium (or molybdenum) crystals that are grown on a suitable metal mandrill which serves as the body of the collector. After centerless grinding and polishing, the electrical patchiness of such collector surfaces has been shown to be very small (<5 mv), thus permitting the ionospheric electrons to see essentially a single potential as they approach the probe. This feature reduces the "energy spreading" and lowers the limit for accurate temperature measurements. Typical polycrystalline surfaces should not be used for low T_e measurements because the difference in the potentials of their crystal faces (~100 mv) produces an energy smearing that is comparable to the mean electron energy in most regions of the ionosphere.

The maintenance of clean surfaces is also important to avoid large T_e errors, especially in the application proposed here in which the plume plasma and material sputter from the thrusters can be expected to leave deposits on the collectors. Solar EUV radiation can transform surface contaminants into insulating layers which reduce the electrical contact with the plasma. This effect becomes particularly evident in regions of high electron densities where the currents are large enough to produce significant voltage drops across insulating layers. The charging time constant of the surface can be comparable to the LP sweep period, thus distorting the volt-ampere curves and yielding falsely high T_e values. In addition, non-uniformity in the insulating layers induces additional work function patchiness that smears the electron retarding region

For these reasons, provisions will be made to clean the collector by electron bombardment. This is done by applying +150V to the collector for brief intervals. At this potential, the collector will draw large fluxes of energetic electrons from the ionosphere. This technique is used routinely in the laboratory and was demonstrated in space in the DE-2 Langmuir probe experiment. It can be shown, assuming one electron per contaminant molecule, 100 layers of contaminants, and 250 µA current that the contaminants are removed in a few minutes, which is consistent with previous flight experience.

Finally, the accuracy of the T_e measurements is affected by the potential gradient (vxB•l) that is induced in the collector by its motion through the geomagnetic field. The amplitude of the induced voltage should be kept small relative to kT_e to avoid energy smearing, since this imposes the same kind of limit on the low temperature measurements as does surface patchiness and contamination. At ionospheric altitudes the magnitude of the induced voltage is of the order of 3 mv/cm, so a short probe is required.

1 Introduction

This document describes the High Voltage Control and Monitor (HVCM) tether monitor and load control specifications for the ProSEDS payload on the Delta-II spacecraft. The document is serves as the <u>End Item Specification</u> for the HVCM.

<u>ProSEDS Goals</u>
The overall goal of the ProSEDS flight experiment is to demonstrate and validate the aspects of electrodynamic-tether technology required for applications in electrodynamic propulsion. Details of the ProSEDS Mission Objectives are found in other documentation, but in general the following objectives support this overall goal.

Primary Objectives. The primary objectives of the ProSEDS experiment are: (1) to demonstrate significant, measurable electrodynamic-tether thrust in space, and (2) to measure the current-collection performance of a "bare electrodynamic tether" under varied ionospheric conditions and determine its scalability for future applications.

Secondary Objectives. The secondary objectives of the ProSEDS experiment include: (1) to demonstrate the regulation, storage, and use of tether-generated electrical power; (2) to determine system performance during the extended mission phase (begins after first day); (3) to assess tether survivability in atomic oxygen (AO), meteoroid, and orbital-debris environments; (4) to assess tethered system dynamics during electrodynamic operation.

<u>Approach</u>
The approach to Primary Objective 1 will be to use the electrodynamic tether to generate electrical power. This will induce electrodynamic drag thrust ("magnetic brake"), which is in the direction opposite of orbit-raising thrust, but operates on the same physical principals. Using the induced drag force to demonstrate electrodynamic propulsion rather than thrust will allow (1) the use of the generated power to recharge batteries, and (2) a savings in payload mass since no bias-reversing, high-voltage power supply is required. If the system conducts an average current of 1 A, the Delta–II second stage and attached-tether system will drop from an initial altitude of 400 km and reenter within approximately 10–14 days. The same system without the tether-induced electrodynamic drag would remain in orbit for more than six months.

The approach to Primary Objective 2 will be to reduce the system impedance to a minimum and collect the maximum possible current for short periods during the mission while characterizing as much about the electrodynamic-tether system as possible including background ionospheric plasma conditions. The resulting tether current levels can then be compared with the predictions of theoretical models of the bare tether collector. The ProSEDS demonstration should also be compared with the results of the TSS–1R mission, which used an insulated tether with a conducting end-body collector.

The approach to the Secondary Objectives will be to conduct current over a period of many days and observe electrodynamic performance and its effect on dynamic motion and system stability.

Mission Characteristics

ProSEDS will be a secondary payload on a Delta-II rocket. For planning purposes, it is assumed that, after deployment of the primary payload, the Delta–II second stage will be inserted into a circular orbit near 400-km altitude and approximately 32–36-degree inclination (final inclination is set after 2nd stage completes a depletion burn to empty its tanks; U.S. Air Force GPS satellite is the primary payload). The ProSEDS experiment will then deploy its end-body upwards from the Delta–II and the experimental operations will begin. Reentry is expected to occur within 10–20 days.

The physical and electrical characteristics of the HVCM instrument, on-orbit performance requirements, and interface with ProSEDS are discussed in this document. The document serves the role of an End Item Specification Document (EIS).

1.1 Definitions

The following definitions shall apply to the equipment types referred to within the body of this specification:

1.1.1 Flight Unit

Refers to the unique assemblage of hardware, firmware, and software designed for, and installed on, the Delta–II to satisfy the mission requirements.

1.1.2 Ground Support Equipment

Refers to non-flight support equipment that is required for servicing, testing, loading software programs, maintaining, and verifying operation of the flight configuration of the experiment. Additionally, ground support equipment (GSE) may also refer to equipment for storing and transporting the flight-unit elements. Some GSE such as test cables and storage containers are provided with the unit. Some GSE (e.g. test equipment and generic calibration boxes) are retained by the University of Michigan, but used as needed.

1.1.3 Acronyms and Abbreviations

The following acronyms and abbreviations are defined as references for use within the body of this specification:

C&DH	Command and Data Handling
EEE	Electronic, Electrical, and Electromechanical
EIS	End Item Specification
EMF	Electromotive Force
EMI	Electromagnetic Interference

EMC	Electromagnetic Compatibility
GSE	Ground Support Equipment
HCPC	Hollow Cathode Plasma Contactor
HVCM	High Voltage Control and Monitor
ICD	Interface Control Document
PC	Personal Computer
PROM	Programmable Read Only Memory
QA	Quality Assurance
RAM	Random Access Memory
RDY	Load Resistor
SEU	Single Event Upset
SW1	Switch 1: Short
SW2	Switch 2: Load Resistor
SW3	Switch 3: Battery Charging
TBD	To Be Determined
VAC	Alternating-Current Voltage
VDC	Direct-Current Voltage

1.2 Applicable Documents

1.2.1 Specifications and Plans

The following documents form part of this technical specification to the extent specified herein:

MSFC-RQMT-2901	ProSEDS Requirement Verification and Compliance Database (ProSEDS RVC)
MSFC-RQMT-2964	HVCM Interface Requirements Document (HVCM IRD)
MIL-STD-461C	Electromagnetic Interference Characteristics for Equipment
MIL-STD-462	Measurement of Electromagnetic Interference Characteristics of Equipment
MIL-B-5087	Bonding, Electrical, and Lightning Protection for Aerospace Equipment

1.2.2 Design Guidelines

The following documents shall be utilized as design guidelines as required by the ProSEDS sponsor:

GSFC Ref. Pub. 1124, Revision 2

Outgassing Data for Selecting Spacecraft Materials.

MIL-HDBK-5F   Metallic Materials and Elements of Aerospace Vehicle Structures

MIL-C-5541D   Chemical Conversion Coatings on Aluminum and Aluminum Alloys

1.2.3 Support Documents

- 068-1105 HVCM Relay Box Assembly Drawing
- 068-1107 HVCM Resistor Box Assembly Drawing
- 068-3033 ProSEDS Open-Circuit EMF Measurements
- 068-3232 HVCM Relay Stress Analysis
- 068-3233 Load Box Stress Analysis
- 068-3269 HVCM Relay Functional Test Procedure
- 068-3289 HVCM Relay High Voltage Test Procedure
- 075-3201 LPSP and HVCM Thermal Vacuum Test Procedure
- *Shock and Vibration Handbook* by Cyril B. Harris
- *Satellite Thermal Control Handbook* by David G. Gilmore

2 Electrical Measurements

The parameters that assist in describing the electrical behavior of the tether circuit are (1) the tether current at the base of the tether; (2) the open-circuit voltage, which is the motionally induced *emf*; (3) the voltage between the positive electrode and the ionosphere; and (4) the voltage between the negative electrode and the ionosphere. With some model assumptions, any one of these parameters can be calculated if the other three and the tether resistance are known.

With an insulated tether and collecting end-body, the open circuit emf can be measured using an instrument mounted on the end-body. This is simply not possible with a bare-wire collector because the potential changes along the tether. Fortunately, an "effective" voltage can be calculated provided the other three parameters listed in the above paragraph are known along with a good estimate for tether resistance along the tether.

The tether current and open-circuit *emf* are straight-forward measurements with a history based on TSS–1 and TSS–1R. The voltage between the negative end-body (the Delta–II) and the ionosphere is more difficult to determine. Unlike the measurements of the ambient ionospheric plasma characteristics, the Delta–II spacecraft potential must be measured during active current-flow operations. If the hollow cathode plasma contactor (HCPC) works as intended and without problems, we expect that the spacecraft potential will be limited to the order of –30 to –50 V. By itself, this would represent an error on the order of 5% in a Kirchhoff Voltage Law–like loop equation. However, if the HCPC does not work as expected, or if it suffers a failure or degradation, the spacecraft potential could approach the total tether-generated *emf*, which is on the order of –1000 V. Since this translates directly to an error in the calculated performance of

the electrodynamic tether, these are clearly not acceptable levels of error. The spacecraft potential should be measured accurately and reliably.

One limitation in estimating the open-circuit *emf* is due to the presence of some level of tether current even when the tether circuit is opened at the lower end via a switch. The presence of the long, bare tether means that some of the tether will be biased positive (top portion) with respect to the plasma and the lower portion will be biased negative with respect to the plasma. This means that the *emf* can drive current inducing a voltage drop along the tether. This situation has been analyzed (see UM 068-3033 on the VRC) and been shown that we cannot measure, using a voltmeter on the Delta–II end, that accounts for either the voltage drop along the tether nor the positive bias at the upper end. The analysis has shown that an error in *emf* estimate of 5–7% without compensating for these effects using models. Tether open-circuit currents are estimated to reach 50–100 mA causing 30–75 V of total voltage drop. It is also estimated that the "open-circuit" current can cause measurable altitude loss up to 2 km per day and a measurable change in orbit ellipticity.

3 HVCM Technical Requirements

3.1 Functional Configuration

3.1.1 General Description

The HVCM provides relay switches that switch the tether between open, short (spacecraft ground), resistive load, and battery charging modes. The tether current and voltage are measured by the Current and Voltage Monitors. The physical location of the HVCM on the deployer tube is shown in Figure 3.1.1-1.
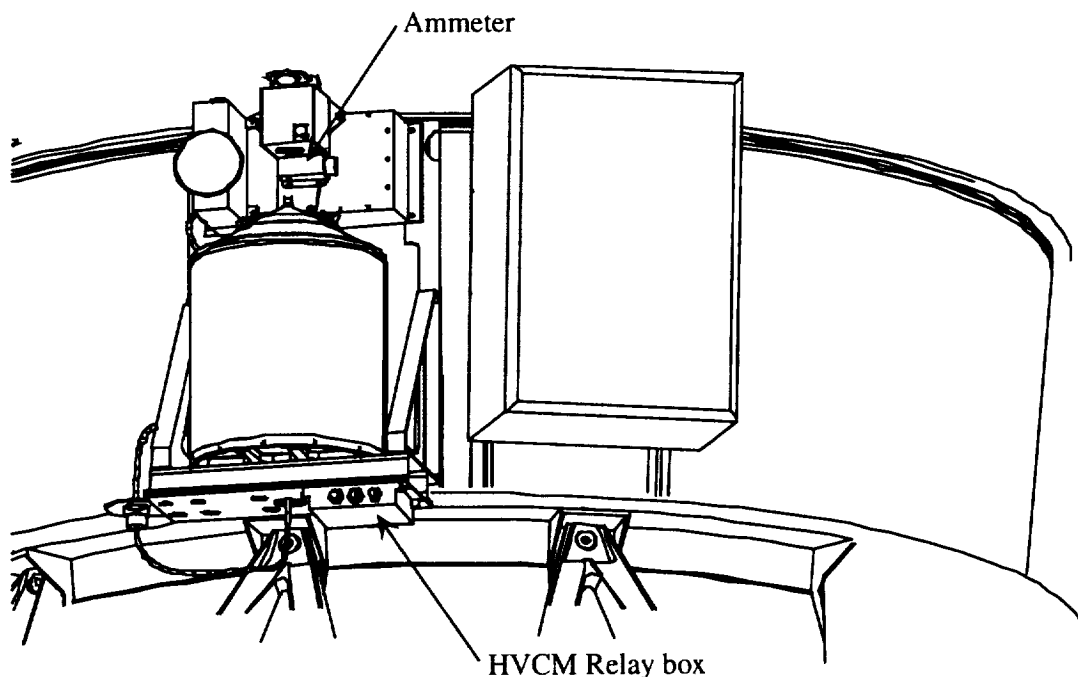

Ammeter

HVCM Relay box

Figure 3.1.1-1 View of the Delta showing HVCM relay box location
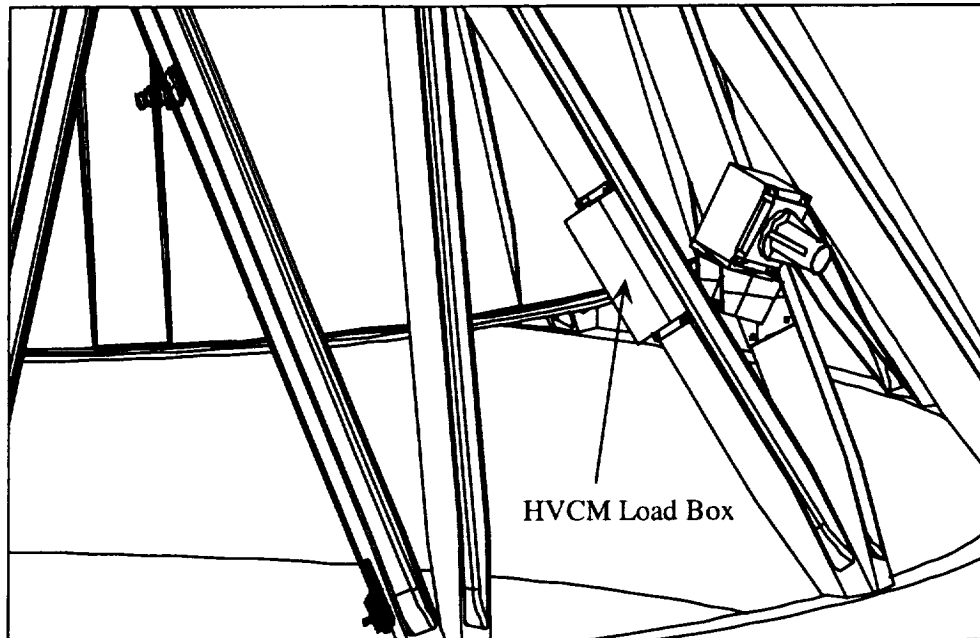

HVCM Load Box

Figure 3.1.1-2 View of the Delta showing HVCM load box location

3.1.2 System Functional Requirements

The primary goal of the HVCM is to provide control and monitoring functions that support the validation of the "bare" wire electrodynamic-tether technology in space. Previous electrodynamic-tether flights have used fully insulated tethers with spherical collectors as subsatellites (the end points), but collection by a thin, uninsulated wire may be more efficient than by a large spherical endmass. To properly assess the ProSEDS tether's electrodynamic performance, sufficient knowledge of individual element responses is needed. With the HCPC on, the tether circuit is completed with the ionospheric plasma—the situation to be explored. In order to validate this technology and compare it to theory, several measurements are needed. In support of these measurements, the HVCM will:

- Control the tether loads: open, shunt, load resistance, and battery charge;
- Support tether current measurement (separate current sensor);
- Support tether voltage measurements by providing a voltage access point;
- Provide temperature monitors;

3.1.3 System Modes of Operation

The operational sequences consists of four modes (Table 3.1.3-1): (1) open-circuit mode with no current flowing through the tether and HCPC not emitting plasma, (2) shunt-mode (max current) with the HCPC on, (3) resistor mode with the HCPC on, and (4) battery-charging mode with the HCPC on. Figures 3.1.3-1 through -3 show three operational timelines containing these modes. Mode 1 consists of modes 1a and 1b. In mode 1a, the plasma contactor is off and in mode 1b it is on; in both cases, the local plasma density and temperature of the ambient electrons and ions are measured. A sequence of one-minute duration will be repeated continuously after reaching full deployment for the first 3 orbits and then a modified sequence of 80 s will be repeated continuously as long as there is adequate power. The cycle is specified to assure adequate sampling of background ionospheric-plasma conditions which occur during the open-circuit period, mode 1a. The 30-s period for mode 1a is intended to allow adequate recovery of any spacecraft charging effects to accomplish background measurements. The various operational sequences are shown in Figure 3.1.3.

Shunt mode (Mode 2) is intended to provide the highest current possible by connecting the tether to the electrical ground of the Delta–II which also has the HCPC connected. The Resistor mode (Mode 3) provides an additional load point which is discussed below. The Battery Charge mode is used to recharge the batteries. If charging is inadequate with the 80-s sequence, the system defaults to Mode 4 continuously until adequate charging levels are reached.

		Duration		
Mode	Mode Name/ Description	Minimum (sec)	Desired (sec)	Purpose
1a	Open circuit; HCPC off	25	30	Measure background plasma characteristics
1b	Open Circuit; HCPC on	3	5	Allow HCPC time to start operation, measure HCPC perturbation
2	Shunt	3	5	Measure maximum tether current capability; current/voltage measurement
3	Resistor	3	5	Alternate current/voltage measurement
4	Battery Charge (secondary battery)	Dependent upon subsystem power usage/time needed to maintain battery state-of-charge		Charge secondary battery; Additional alternate current/voltage measurement

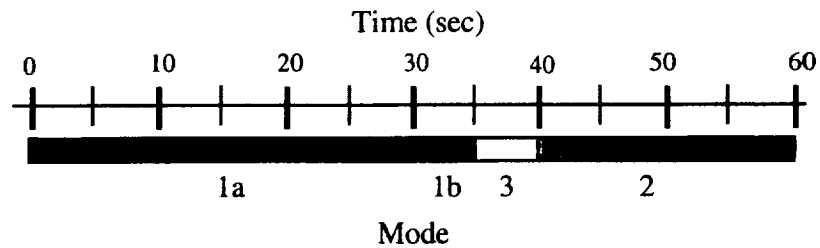**Table 3.1.3-1 ProSEDS Operational Modes**

Time (sec)

Figure 3.1.3-1 EPT Sequence 1 (60-s cycle) — Operation on Primary Battery
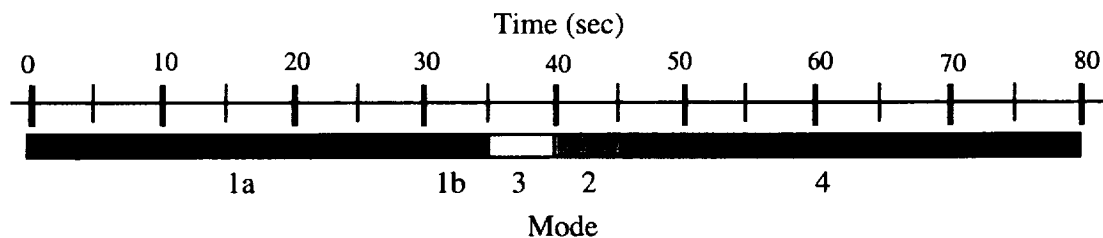
Time (sec)

Figure 3.1.3-2 EPT Sequence 2 (80-s cycle) — Operation on Secondary Battery

Time (sec)
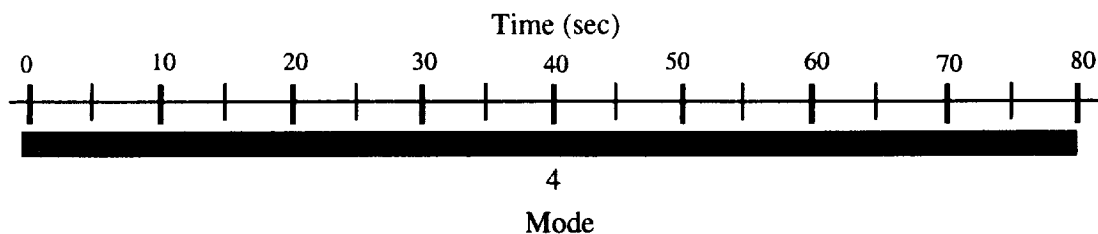
Figure 3.1.3-3 Battery Recovery Sequence (80-s cycle) — Operation on Secondary Battery

3.1.4 System Performance Specification

A functional circuit diagram of the HVCM is shown in Figure 3.1.4-1. Detailed specifications are summarized in Table 3.1.4-1. Note that the tolerance specifications for A1 and V1 in Table 3.1.4-1 are system level requirements [HVCM/Ammeter plus ProSEDS Data System (not shown in figure)] and require integrated testing and calibration.

Figure 3.1.4-1 Functional circuit diagram of the High Voltage Control and Monitor (HVCM) for ProSEDS

Monitor Parameter	Range	Tolerance	Sample Rate (Hz)	TM Rate (Hz)	# of Bits	Date rate (bps)
A1: tether current	0 to 10 A	±2% FS (RVC 3.9.8)	1	1	8	8
V1: tether voltage	-50 to −1400 V	±2 % (RVC 3.4.1.1.1)	1	1	8	8
Thermistor1 (Relay Box)	3 kΩ nom.	±1.0 °C	1	1	8	8
Thermistor2 (Load Box)	3 kΩ nom.	±1.0 °C	1	1	8	8
Total						32

Table 3.1.4-1 HVCM Specifications

3.1.5 Data Rate

Data from the HVCM includes current meter readings (A1), voltage meter readings (V1), and two thermistors. The total data rate from the HVCM is 32 bps.

3.1.6 Electrical Design Requirements

3.1.6.1 Voltmeter-1

This instrument measures the tether-generated *emf* with respect to spacecraft (Delta-II) ground. In order for the *emf* to principally appear across the voltmeter, this measurement must be made during open-circuit (no current flowing) conditions. The tether circuit will be opened for 30 s once per measurement cycle (60 or 80 s duration) to allow measurement of the full *emf* and the ambient plasma characteristics. The maximum *emf* produced by a 5-km conducting tether is –1.5 kV, but can also be on the order of a few hundred volts during portions of any given orbit. Overall accuracy is derived from a need for model validation. Assuming the use of differential GPS[1] and geomagnetic quiet-time period for the mission, predicted *emf* accuracy of slightly less than ±2% is possible. The open-circuit uncertainty likely will be no better than about ±2% unless a model is utilized to estimate the error. Thus, keeping other errors at a minimum is important to stay close to the expected modeling accuracy. One instrument range should be sufficient and eight-bit measurements will provide ±3 V resolution over the anticipated voltage range. For a typical voltage value of 500 V, ±3 V represents ±0.6%, an adequately small fraction of the overall error. Analysis of all error sources indicates that a ±2.5% of full-scale and ±3% of a 500V value are possible which is somewhat higher than desired. To achieve a beter full scale voltage accuracy it will be necessary to perform a voltage sense calibration over temperature and voltage of the HVCM relay and data system to compensate for system errors. One of the primary error sources could be the leakage currents in the protection diodes (see figure 3.1.4-1) on the V1 output to the data system. The leakage currents will depend on diode temperature and offset voltages between the HVCM relay and data system.

3.1.6.2 Design of Tether Voltage Measurements

The tether voltage monitor circuit consists of a resistive divider circuit with R1 located in the HVCM relay box and R2 located in the ProSEDS data system (Figure 3.1.7.2-1). The resistor R2 is located in the feedback loop of an inverting op-amp. A second op-amp inverts and level shifts the measured voltage such that –1500 to 0 V from the tether corresponds to 0 to +5 V, respectively, at the A/D converter. A pair of opposed Schottky diodes are placed between R1 and the op-amps internal to the HVCM relay box to ensure that if a corona should occur across R1 that the tether will be connected to ground through the diodes. In addition, a capacitor is placed across the diodes internal to the HVCM relay box to provide a 0.1 μF low-pass filter for the tether voltage measurement. The transfer function for this circuit is shown in Figure 3.1.6.2-2 and was obtained in a high-fidelity SPICE simulation. The frequency response of the tether voltage monitor circuit (Figure 3.1.6.2-3) has a 3-dB point of ~300 Hz. Inside the ProSEDS data system, the +5-V reference voltage is provided by a three terminal voltage regulator (National Semiconductor LM140).

---

[1] For differential GPS requires that the endmass and ProSEDS GPS receivers are locked up to the same satellites during the entire mission. This may or may not be possible and simulations will be done at MSFC to determine the feasibility.
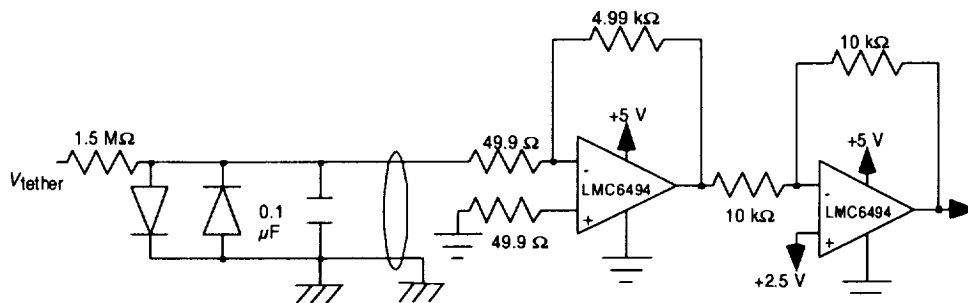
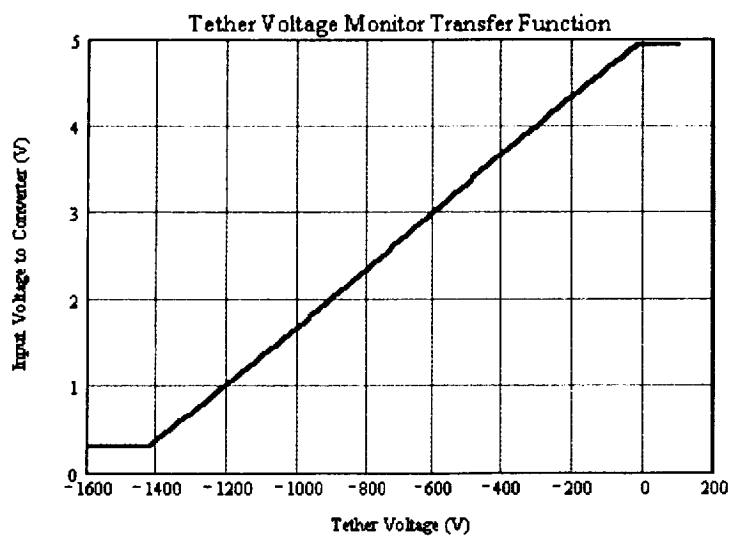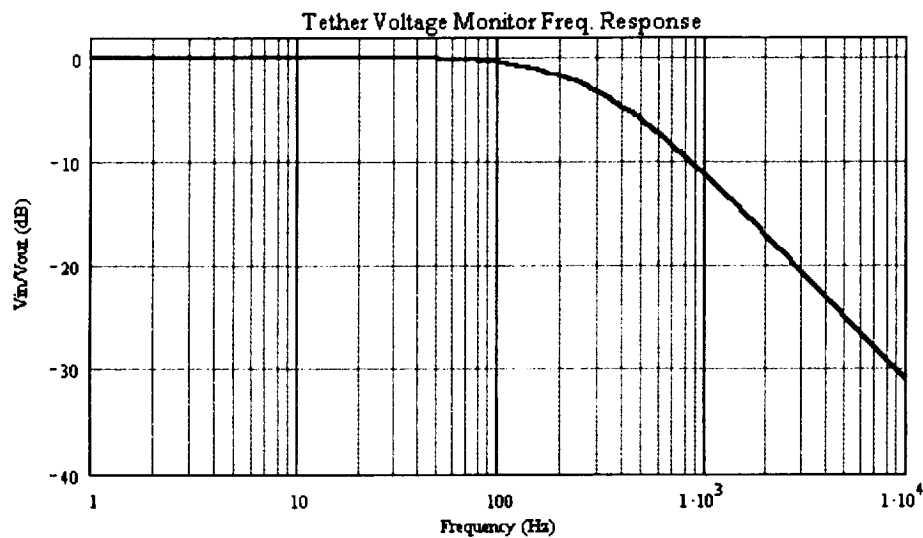**Figure 3.1.6.2-1 Tether voltage monitor resistive divider circuit**

Figure 3.1.6.2-2 Tether voltage monitor transfer function

Figure 3.1.6.2-3 Tether voltage monitor frequency response

3.1.6.2.1 Requirements

<u>Requirements for Resistor One</u>

Resistance:	1.5 MΩ
Temperature Range:	−40 to 80°C
Max Operating Voltage:	1.5 kV
Power:	1.5 W
Dimensions:	small as possible
Tolerance:	± 0.1% (at 25 °C)

<u>Requirements for Resistor Two</u>

Resistance:	5 kΩ
Temperature Range:	−40 to 80°C
Max Operating Voltage:	5V
Power:	10 mW
Dimensions:	small as possible
Tolerance:	± 0.1% (at 25 °C

3.1.6.2.2 Voltage Measurement Resistor

Resistor one is a Caddock MG721-1.5M-0.1% and is contained in the HVCM relay module. Resistor R2 is a 4.99K-0.1% and is contained in the data system.

3.1.6.2.3 Specifications

<u>Resistor One Specifications</u>

Resistance:	1.5 MΩ
Temperature Range:	-55 to 125 °C (power derating begins at 125 ^{O}C)
Max Operating Voltage:	4 kV
Power:	2 W
Dimensions:	1" length, 0.24" diameter, 0.04" wire diameter
Tolerance:	± 0.1%
Temperature Coefficient	±80 ppm/^{O}C from −15°C to 105°C

<u>Resistor Two Specifications</u>

Resistance:	4.99 kΩ
Tolerance:	± 0.1%

3.1.6.3 Ammeter-1

This instrument measures the tether current. The ammeter is a magnetic sensor type (not in-line) and is capable of measuring currents in the range of 0 to 10 A. Eight-bit data will provide ±39 mA resolution over the anticipated current range. Overall accuracy is derived from a need for model validation. For a typical current of 1 A, ±5% is well within model accuracy. Therefore the required accuracy should be ±50 mA.

The steady-state current level is not expected to be rapidly varying, hence the measurement frequency can be relatively low; *e.g.*, in the range of 1 Hz. However, recent analysis of the TSS-1R data suggests that current extraction from the ionospheric plasma can be a highly unstable process that oscillates at a high frequency (much greater than 16 Hz). Therefore, a measure of *dI/dt* may be important, thus benefiting from higher sampling frequency at times.

3.1.6.3.1 Ammeter Baseline

The ammeter baseline is American Aerospace Controls Model number AAC S632-10-C (Figure 3.1.6.3-1). The ammeter interface is through a MS3113H-10 C6P connector.

Figure 3.1.6.3-1 Picture of AAC ammeter

Connector Pin Out

Pin	Function
A	Supply Voltage (+)
B	Supply Return
C	Output Signal (+)
D	Output Return
E	Case Ground

3.1.6.3.2 Ammeter Specifications

Physical Parameter	Value	Requirement
Current Range	0–10 A	RVC 3.9.8
Accuracy	±0.5% Full Scale (±50 mA)	RVC 3.9.8
Mass	8 ozs (0.23 kg)	
Dimensions	1.68 × 3.00 × 1.27 in.	
Supply Voltage	22 to 36 Vdc	
Power	0.4 W (max)	
Operational Temperature	–55 to 85 °C	
Survival Temperature	–55 to 85 °C	
Connector	MS3113H–10C6P	

3.1.6.4 Power Consumption

The only power consumed by the HVCM is the power required to energize the relay coils. The three relays used in the HVCM each have a coil resistance of 290Ω ± 10% at 25 °C. This gives a nominal power consumption of 2.7 W per relay when the coil is energized at +28 VDC.

The average power consumed by the HVCM relays is determined by the duty cycle each relay is energized. For the ProSEDS 60 second sequence the average power will be 2.03 W with the shunt relay energized 40 of 60 seconds and the load relay 5 of 60 seconds. The average power for the 80 second sequence will be 3.88 W with the relay energize time as follows: shunt, 75 of 80; load, 5 of 80; battery, 35 of 80.

The relay coil resistance varies significantly with coil temperature. Test have shown that the coil resistance changes approximately 1.12 Ω/°C, thus the power consumed by the HVCM will change significantly with temperature. A relay coil that is energized 100% of the time will have a coil temperature 50°C (at chassis of 70°C) to 70°C (at chassis of –40°C) higher than the HVCM chassis temperature.

3.1.6.5 HV Relays

The HVCM controls the electrical connection of the conducting tether and as such requires 3 relays in order to provide the switching functions. A typical current and voltage profile is shown in Figure 3.1.6.5-1. Switching will occur approximately once per minute and can occur at any time.
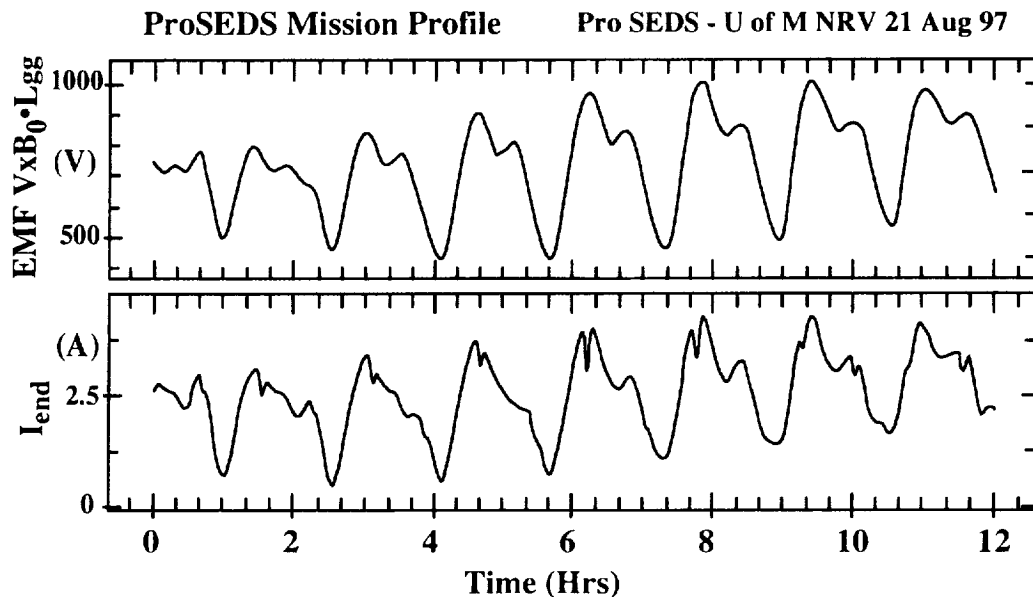
Figure 3.1.6.5-1 Typical ProSEDS voltage profile

3.1.6.5.1 Relay Requirements

1.	Mission life	1 day primary, 21 days secondary
2.	Make/Break cycles	SW1, SW3 - 1,200 primary, 25,000 secondary SW2 - 2,400 for primary, 50,000 secondary
3.	Absolute peak voltage	-1,500 V
4.	Absolute peak current	10 A
5.	Average current	1.7 A (SAO)
6.	Average Voltage	-750 V
7.	Contact resistance	< 20 mΩ
8.	Operate time	< 20 mS
9.	Release time	< 20 ms
10.	Coil voltage	22V to 34V
11.	Mass	< 60 gms

These specs apply to both normally open and normally closed relays.

3.1.6.5.2 HVCM Tether Switching Relays

The relays used in the HVCM are the Kilovac K41A (normally open) and the Kilovac K41B (normally closed). Specifications for each relay are shown in table 3.1.6.5.2-1.

Specification	K41A	K41B
Mechanical Life	2,000,000 Operations	2,000,000 Operations
Test Voltage	6 kV	6 kV

Continous carry Current, Maximum (dc)	30 A	30 A
Contact Resistance	0.02 Ω	0.02 Ω
Operate Time	10 ms	10 ms
Release Time	10 ms	10 ms
Pull-in Voltage	16 V	16 V
Drop Out Voltage	1 - 10	1 - 10
Coil Resistance	290 Ω ± 10%	290 Ω ± 10%
Latch / Non-Latch	Non-Latch (normally Open)	Non-Latch (normally closed)
Mass	28.3 g	28.3 g

Table 3.1.6.5.2-1 HVCM Relay Specifications

3.1.6.5.3 Latching vs. Non-Latching Relay Selection Criteria for the HVCM

Switches two and three (SW2 and SW3 respectively) were originally specified as latching relays in order to save power. However, the latching relay (Kilovac K41P) that was chosen could not survive the vibration testing required for the HVCM relay module. SW2 and SW3 were changed to non-latching normally open relays (Kilovac K41A) to accommodate the vibration requirement. The following paragraphs detail the decision process for choosing latching vs non-latching relays, for ProSEDS it is not possible to use latching relays, but future missions may be able to. The choice of latching vs. non-latching for SW1 (to ground) is not as trivial. Here we outline the pros and cons of each choice and make a recommendation for SW1 to be a non-latching relay.

3.1.6.5.3.1 SW1 as Non-Latching Relay

The major disadvantage of using a non-latching relay for SW1 is the power drain. The current relay selection (Kilovac K41 Series) has a coil operating voltage[2] of +28 V and a coil resistance of 290 Ω for a non-latching and 80 Ω for a latching version. Therefore, in a normally closed version, it would require a continuous power of 2.70 W in order to keep the switch open. SW1 must be open during RDY (load resistor operation) and battery charging operations.

On the other hand, a normally closed, non-latching relay would direct all of the current to Delta-II ground in the case of a several failure modes (see below). This would still allow the ProSEDS mission to acquire valuable current data for the lifetime of the batteries. Basic dynamics of the mission can also still be observed via radar tracking of ProSEDS re-entry.

3.1.6.5.3.2 SW1 as a Latching Relay

---

[2] Specifications call for an input voltage of 26.5 V but the ProSEDS data system has made 28 V available.

In the case of a failure, the use of a latching relay for SW1 could eliminate the possibility of getting any current measurements from the ProSEDS mission. Such a scenario will occur if the failure occurs while SW1 is open.

A latching version would save considerable power though. Instead of 2.7 W of continuous power draw to keep the SW1 open, a latching version would only require 100 milliseconds[3] at 9.8 Watts. It would also require 9.8 W for 100 milliseconds in order to close the relay.

3.1.6.5.3.3   Failure Modes

It is useful to consider possible failure modes that relate to SW1. Possible failures include:

- SEU or equivalent type software computer error that does not properly cycle SW1. This could mean not closing when it should or not opening when it should. Probably affects latching and nonlatching the same.
- Computer interface electronics failure which keeps relay open or closed permanently. Affects latching and nonlatching the same.
- SW1 failure such that it will not respond to commands. Probably affects latching and nonlatching the same.
- Any wire or connection to the relay could open or short. Could affect latching and nonlatching the same.
- The relay could fail internally, high contact resistance, mechanical failure leading to open or short. Could affect latching and nonlatching the same
- Loss of power to mission. Nonlatching would take tether to ground. Latching could be in either state, although data system could be configured to minimize the possibility of this.

3.1.6.5.3.4   Conclusions

The problem to the designer is a case of power conservation vs. reliability. The latching version saves power, but the non-latching version is likely to be more reliable in terms of mission success. Of the failure modes identified above, the major concern is the lack of charging current from the tether later in the mission. Since recharging of batteries from the tether has never been done before, there is significant uncertainty. This would result in the ProSEDS experiment ceasing to have active control of SW1 via its data system. If the batteries are depleted, then a non-latching, normally closed relay for SW1 will remain closed allowing current to continue to flow through the tether. The other failure modes are possible but have existed in many previous missions and are unlikely. Therefore, our conclusion is to leave the baseline as is with SW1 a nonlatching relay. Should power become critical later on, the option may still exist to change to a nonlatching relay.

---

[3] Kilovac spec is 6 milliseconds maximum, but extra time is allotted for signal processing and safety to make sure the switch operation is performed.

3.1.6.6 Grounding and Isolation

The HVCM flight hardware shall be electrically bonded to the spacecraft mounting interfaces. All primary power and signal returns will be electrically isolated from each other and from chassis by a direct-current resistance of 1 MΩ or greater. This requirement applies only to the HVCM electronics assembly without connections to the sensors. Once the HVCM sensors are attached and bonded to the spacecraft and connected to the HVCM electronics by means of the interconnecting cable, the experiment secondary returns will be connected by design to the spacecraft return. This is a requirement for proper operation of the sensors.

3.1.6.7 Wiring

The use of shielded twisted pairs for all power and signal leads is preferred.

3.1.6.8 Insulation Resistance

The insulation resistance of any low-voltage terminal to chassis and connector contact to connector housing shall be a minimum of 1 MΩ after application of 100 VDC. The insulation resistance of any high-voltage terminal to chassis and connector contact to connector housing shall be a minimum of 1 MΩ after application of 2,000 VDC for 10 minutes. This requirement applies to the sensor interface connections, all HVCM electronics interface connections to the spacecraft and the sensors, and to the interconnecting cable.

3.1.6.9 Electrical Bonding

Bonding shall comply with the requirements of MIL-B-5087. The requirements and methods of class-R bonding shall apply to all metal-to-metal mating surfaces on the sensor assemblies and on the HVCM electronics assembly. A maximum bonding resistance of 2.5 mΩ shall be maintained. Clean conductive mating surfaces shall be provided on the component case and the surface of the connector shells where connectors are installed on the sensors and electronics assembly. When rectangular connectors are used, captive nut plates shall be used to maintain proper compression at the bonding surface and preclude unsecured nuts within cases.

Only electrically conductive coatings shall be used on mating surfaces. Conductive coating as specified in MIL-C-5541D (Alodine) for aluminum may be used for treatment of bare surfaces. Nickel plating is also acceptable, gold plating is preferred.

3.1.6.10 Electromagnetic Compatibility Requirements

The HVCM experiment shall be designed and tested to meet the EMC requirements detailed in ProSEDS RVC and HVCM IRD Documents. These requirements define modified levels of a subset of the MIL-STD-461C compatibility requirements. Verification of the instrument performance shall be done at MSFC as part of system level EMC testing..

3.1.7 Mechanical Design Requirements

3.1.7.1 Quasi-Static Design Load Factors

The HVCM shall be designed to withstand the quasi-static loads defined in the ProSEDS Systems Specification Document.

3.1.7.2 Strength

The allowable material property data sheets for the HVCM shall be obtained from the most recent revision of MIL-HDBK-5G. Type-A basis material properties (99% probability and 95% confidence) or equivalent shall be used for components.

The following safety factors shall be applied to the materials selected for use in the design of the instrument:

Yield Factor of Safety   =   1.65 × limit load
Ultimate Factor of Safety =   2.0 × limit load
Test Factor of Safety   =   1.25 × limit load

3.1.7.3 Stress Analysis

A stress analysis on the LPSP electronics box was provided by Lisa Barker from NASA-MSFC. Ms. Barker provided the University of Michigan a MathCad spreadsheet in which UM personnel modified in order to make a stress analysis of the relay and load resistors boxes. The margins of safety produced by each of these spreadsheets are reproduced below. All margins are positive.

3.1.7.3.1 Relay Box (Launch Loads):

Box to Plate
Bearing Yield   111.0
Bearing Ultimate   110.0
Shear Tearout   65.7

Cover to Box
Bearing Yield   2.70
Bearing Ultimate   2.66
Shear Tearout   2.56

3.1.7.3.2 Load Resistor Box (Launch Loads):

<u>Box to Plate</u>
Bearing Yield   20.4
Bearing Ultimate   20.2
Shear Tearout   15.5

<u>Cover to Box</u>
Bearing Yield   1.85
Bearing Ultimate   1.82
Shear Tearout   3.30

3.1.7.4   Dynamic Analysis

The HVCM electronics assembly shall have a fundamental natural frequency greater than 35 Hz. The following is a first order dynamic analysis of the relay box and the load resistors box (068-3215).

The first order issue in the dynamic analysis of the relay box is the resonant frequency of the relay bar. For the resistor box, the issue is the resonant frequency of the load resistors.

3.1.7.4.1 Relay Box

Assumptions:
- Relay bar was modeled two ways in order to bound the resonant frequency:
  1. As a bar with all relay mass at the center
  2. As a bar with relay mass distributed evenly through out the bar.

Calculations:

The first method was done using the formula found on page 7.5 of "Shock and Vibration Handbook" by Cyril B. Harris. The second method also used a formula from the same reference (page 1.13).

Calculations show that the first method gives us a lower bound on the resonant frequency . This lower bound is found to be comfortably above 2 kHz - well above the 35 Hz requirement.

3.1.7.4.2 Load Resistor Box

Assumptions:

- Resistor was modeled as a rectangular plate with two clamped edges and two supported edges.
- Poisson's ratio was unavailable for the resistor. Therefore, a minimum value of 0 was used.

Calculations:

Page 7.36 of "Shock and Vibration Handbook" by Cyril B. Harris has a formula for the natural frequency of a rectangular plate with our assumptions. Using this formula, the resonant frequency of each resistor is found to be 349 kHz, again well above the 35 Hz requirement .

3.1.7.5 Shock

The HVCM will meet shock environments as specified in the ProSEDS RVC.

3.1.7.6 Mass

The mass of each subassembly of the HVCM experiment shall not exceed those shown in table 3.1.7.6-1.

Table 3.1.7.6-1 HVCM Mass

Description	Max Weight (gms.)
Relay Box	410
Load Resistor Box	660
Load Harness	200
Load Thermistor Harness	139
Total	**1409**

3.1.7.7 Venting

All components of the HVCM shall be vented so that hardware can withstand the Delta II launch fairing internal pressure profile as specified in the ProSEDS RVC.

3.1.7.8 Thermal Requirements

The HVCM relay and load resistor shall be tested to the operational temperature limits of Table 3.1.7.8-1.

Table 3.1.7.8-1 HVCM Thermal Requirements

Module	Operational Temperature	Survival Temperature
HVCM Relay	-38 to 67 °C	-55 to 85 °C
HVCM Load	-67 to 77 °C	-67 to 180 °C

3.1.7.8.1 Thermal Analysis Model

The following is a first order thermal analysis of the relay and load resistor boxes.

3.1.7.8.1.1 Relay Box

Assumptions:

• Heat paths only exist through the bolted joint interface.
• Thermal coefficient of the bolted joint region is estimated at 200 W/(m-°C)—a very conservative estimate.
• Temperature difference between the relay box and the deployer tube is at a maximum

Calculations:

On page 4-33 of "Satellite Thermal Control Handbook" by David G. Gilmore, there is an equation for the heat transfer coefficient of the bolted joint region. Using this equation and

$$Q = h \times (T - T_0) \times \Pi \times (R^2 - R_0^2)$$

Where R is the radius of the contact area and R_0 is the bolt radius, we get an estimated heat dissipation of 8 W from the relay box to the Delta-II.

3.1.7.8.1.2   Load Resistor Box

Assumptions:

- Box is in thermal equilibrium with environment
- Albedo, Sun, Earth, and load resistors all contribute to heating of box
- Heating due to resistors is assumed to be a max (1.6 kW)
- Box is modeled as independent spacecraft

Calculations:

First a box temperature was found by accounting for the absorption and emission of the heat from all contributors. This can be easily done through basic physics equations

$$FluxIn = \alpha \times SF + \alpha \times Albedo \times VF \times SF + VF \times EF$$

$$Q_{inst} + (FluxIn \times A) = \sigma \times A \times e \times T^6$$

$$T = ((Q_{inst} + FluxIn \times A) / (\sigma \times A \times e))^{0.25}$$

Where α is absorption, SF is solar flux, VF is view factor, EF is Earth flux, Q_{inst} is heating due to load resistors, σ is Stefan-Boltzmann's constant, and A is box area.

Next, the heat conducted to the Delta-II is calculated via the strut:

$$H = k \times A \times ((T_2 - T_1)/L)$$

Where L is the length from the load box to the Delta-II along the strut. Such a calculation gives the Delta-II 285 W.

3.1.7.9   Radiation Requirements

Normal solar and Earth albedo TBD

3.2 Analysis and Test Requirements

3.2.1 General Test Requirements

3.2.1.1 Electrical Functional Test

This test for the HVCM shall verify the functionality of the flight hardware using the HVCM GSE. Component interfaces shall simulate those of the spacecraft as nearly as is practical. Initial measured parameters are recorded and compared against component design specifications. These initial measurements will be used as a baseline for comparison of subsequent functional tests. A functional test shall be performed after or as part of environmental exposure testing. Data from these functional tests will be checked for changes from the baseline or possible trends that may lead to a later failure.

3.2.1.2 Testing Sequence

HVCM Relay Test Sequence
1. Functional test module over temperature per 068-3269. This procedure verifies all component operation over required temperature range.
2. Apply high voltage coatings to unit and stake all components
3. Test high voltage operation per 068-3289. This procedure verifies that corona does not occur during high voltage operation over pressures from 1 atmosphere to 10^{-4} torr. The HVCM is tested at the maximum operating voltage.
4. Thermal vacuum temperature cycle per 075-3201. The HVCM relay receives 3 cycles from min to maximum operational temperature extremes at pressures below 10^{-5} torr. The unit is operated in maximum power dissipation mode and at near maximum voltage at each temperature extreme. Functional operation is verified at each temperature extreme.

HVCM Load Resistor Test Sequence
1. Complete assembly of unit and record resistance value.
2. Perform Vibration and Shock tests on load.
3. Measure and record resistance value.
4. Perform thermal vacuum temperature cycling per 075-3201. The load receives 8 cycles from minimum to maximum operational temperature extremes.   At each temperature extreme the load resistance value is recorded and maximum operational voltage is applied to the load per the ProSEDS 60 second operating cycle. The load receives 8 pulses (5 sec on/ 55 sec off) at maximum power dissipation at each temperature extreme.

3.2.2 Mechanical Test Requirements

3.2.2.1 Sine Vibration

The HVCM load resistor will be tested to the sine vibration requirements listed in the ProSEDS RVC. The HVCM relay module will be tested after delivery after it is mated with the deployer system.

3.2.2.2 Random Vibration

The HVCM load resistor will be tested to the random vibration requirements listed in the ProSEDS RVC. The HVCM relay module will be tested after delivery after it is mated with the deployer system.

3.2.2.3 Shock

The HVCM load resistor will be tested to the Shock requirements listed in the ProSEDS RVC. The HVCM relay module will be tested after delivery after it is mated with the deployer system.

3.2.2.4 Mass Properties

The mass of the HVCM, shall be estimated or weighed to an accuracy of $\pm 5\%$.

3.2.3 Thermal Test Requirements

3.2.3.1 Thermal Vacuum Testing

The HVCM relay will receive 3 thermal vacuum temperature cycles over its operating temperature range. The relay module will receive additional thermal vacuum testing at MSFC after it is integrated into the deployer system.
The HVCM load will receive 8 thermal vacuum cycles over its operating temperature range.

3.2.3.2 Survival Cycle

No testing over the survival temperature extremes will be performed.

3.2.4 EMC Test Requirements

EMC qualification testing of the HVCM will be done during system level testing and MSFC.

4 HVCM GSE Technical Requirements

The Ground Support Equipment (GSE) to be provided for the HVCM shall include a GSE Spacecraft/Sensor Simulator, the HVCM shipping container, and fit-check fixture(s). The requirements for each of these portions of the GSE are presented in the following sections of this specification.

4.1 Spacecraft/Sensor Simulator GSE

The major hardware components included in each of the two Spacecraft/Sensor Simulators are as follows:

1. A power supply capable of providing primary power for the experiment at the voltages defined in this specification.

2. AC power distribution and protection for the above equipments. The GSE shall operate from a source of 115 VAC, 60 Hz power of less than 5 amperes.

3. A control box to allow manual switching of the HVCM relays and monitor points for the tether voltage sensor and thermistors.

4. A cable to connect the GSE to the power and data connectors on the HVCM electronics. These cables shall include the appropriate cable/connector savers.

5. Test ladder for measuring HVCM connector signals if required.

4.1.1 GSE Calibration Requirements

4.1.2 GSE Grounding Requirements

The HVCM control box power supply return should be referenced to earth ground.

4.2 HVCM Experiment Shipping Container

When transferring the flight-experiment hardware from one facility to another, an appropriately designed shipping container shall be used. The shipping case shall be able to withstand statics load that may be placed on the container during shipping.

4.3 Fit-Check Fixtures

The University of Michigan provided fit check boxes for both the relay box and the load resistor box for use by NASA-MSFC.

4.4 Test Equipment

4.4.1 Testing at MSFC

- High-voltage, high current power supply
- PC with data acquisition cards
- Low voltage power supply
- Multimeter and oscilloscope
- Test cables

4.4.2 Testing at KSC

- Signal generator
- Multimeter and oscilloscope
- Test cables
-

5 Load Resistance

The selection of the load-resistance value is based on the need to validate the electrodynamic-tether models as well as provide information to further refine the models. Figures 5.0-1 and 5.0-2 are used to predict the anticipated performance results and then to pick a load value that provides the most useful information. Assumed tether is 5 km long, circular cross-section with 0.7-mm diameter all Aluminum. Insulation at lower part of tether is not considered. Tether resistance is 208 Ω. 20-V negative bias with respect to plasma assumed at Delta II end. Plots generated by R. Estes, SAO
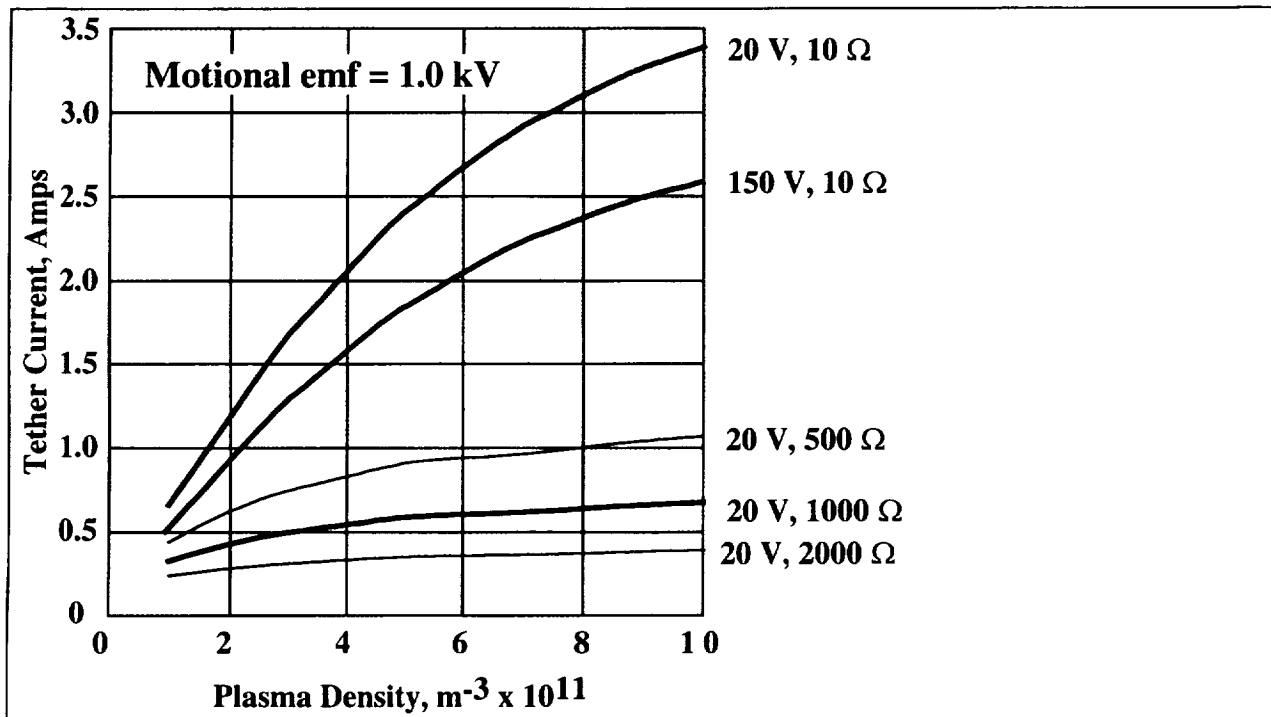

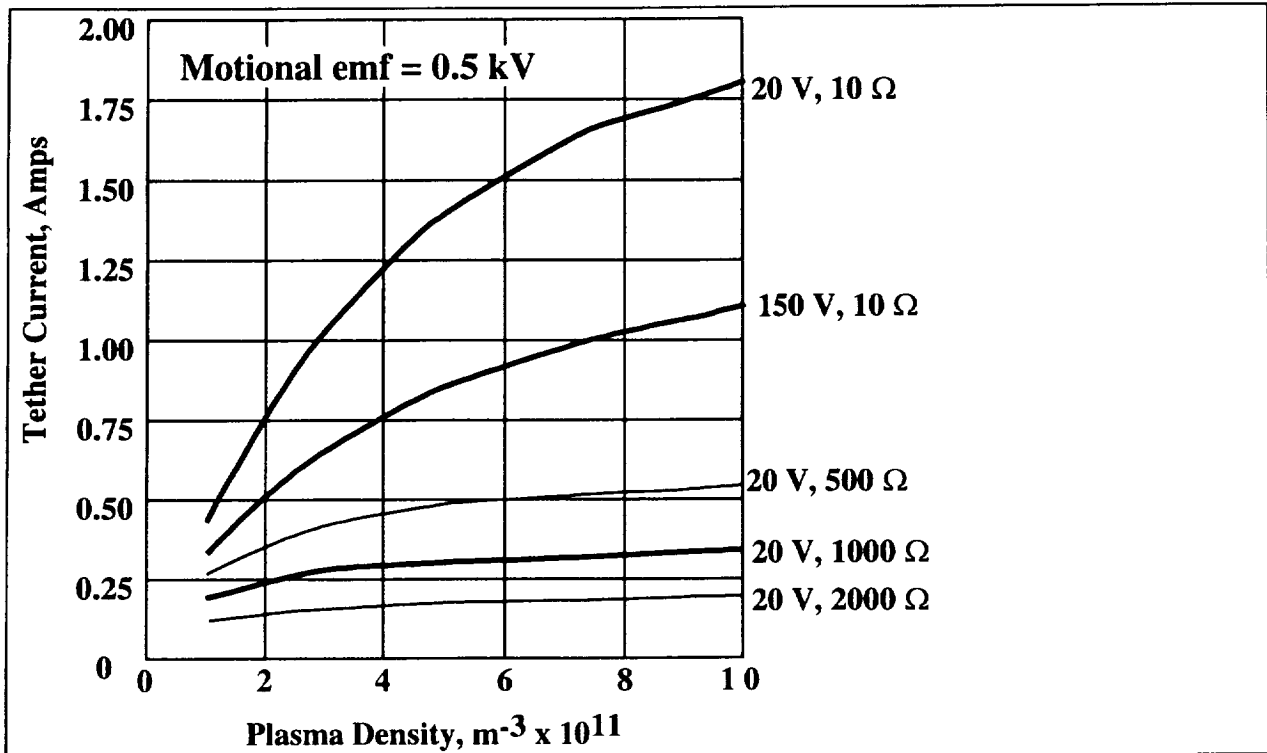**Figure 5.0-1 Predicted tether performance at a motional emf = 1.0 kV**

Figure 5.0-2 Predicted tether performance at a motional *emf* = 0.5 kV

The upper curves, labeled, "20 V, 10 Ω" in Figures 5.0-1 and 5.0-2 are the short-circuit case and provide the first data set for use in model validation and refinement. The middle curves represent the battery-charging mode and provide the "middle" data set. The resistor-load mode provides the bottom data set and 1000 Ω, was chosen as a "good" lower data set. In order to reduce the load resistor power the load was changed from 1000 ohms to near 2000 ohms. Due to resistor procurement lead time, a resistance value of 2320 ohms was chosen. Resistor power is then calculated as shown in Table 5.0-1, where Current = (Voltage − 20)/(Load Resistance + Tether Resistance). Instantaneous Power is Current^2 × Load Resistance and Average Power is Instantaneous Power × Duty Cycle.

Table 5.0-1 Load Resistor Power Calculation

Load Resistance	Tether Resistance	Typical Voltage	Typical Current	Instantaneous Power	Cycle Time	On Time	Duty Cycle	Average Power
Ω	Ω	V	A	W	s	s	%	W
2320	208	1000	0.39	348	60	5	8.3	29

5.1 Load Resistors

The Load Box contains two UXP 600 resistors in parallel to provide redundancy in case one should open.

5.2 UXP 600 Specifications

Resistance:	4640 Ω
Resistance Tolerance:	$\pm5\%$
Power:	600 W (1000 W for 10 seconds max)
Operational Temperature:	$-55°C$ to $150°C$

5.3 Maximum Power Calculation

The maximum resistor power is calculated using the maximum tether emf of 1500V and tether resistance of 208Ω. A tether resistance of 208 Ω represents a low value which might occur with a "cold" tether at nighttime. The UXP 600 resistor is capable of 1000 W for 10 seconds. or 600 W continuous. Therefore, two of these resistors are needed to achieve the maximum power.

A power calculation, using the 208-Ω tether resistance along with the2320-Ω load resistance, can be seen below.

$$V_{load} = [R_{load}/(R_{tether}+R_{load})]*V_{tether}$$
$$= 0.918*1.5\ kV = 1377\ V$$

$$P_{max} = V_{load}^2/R_{load}$$
$$=(1377)^2/2320 = 817\ W$$

The thermal load of the resistors, which could be conducted into the hardware it is mounted on, necessitated the separation of the resistors from the relay box.

6 Physical Characteristics

The expected physical and electrical characteristics are listed in Table 6.0-1.

Table 6.0-1. Physical Characteristics

Unit	Mass (kg)	Dimensions (in)
HVCM (Electronics Box)	0.400	5.1 x 4.0 x 1.175
Load Resistors Box	0.650	7.0 x 2.7 x 1.5
Total	**1.050**	

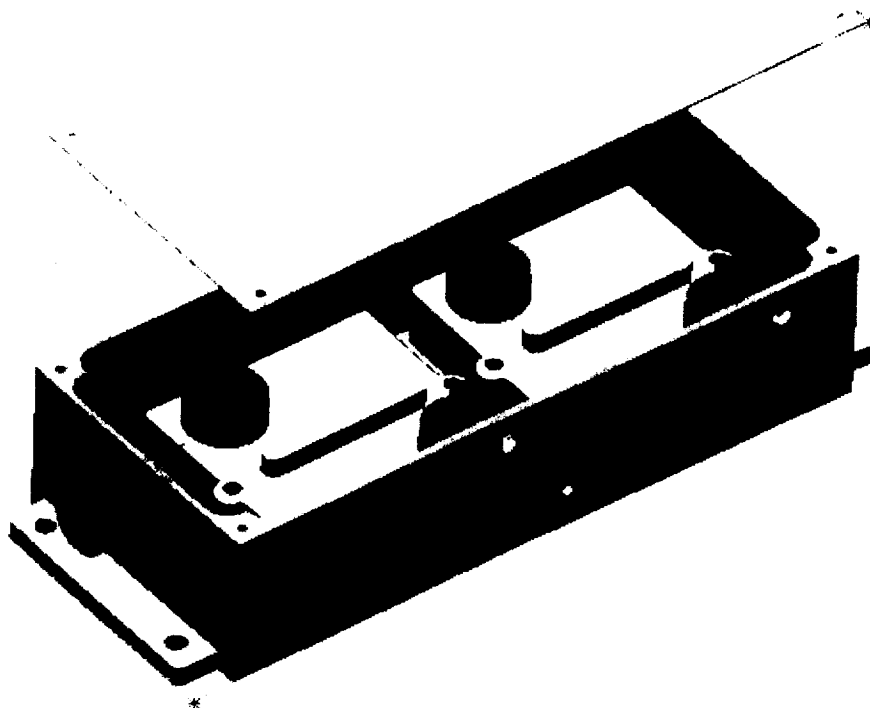**Figure 6.0-1 Exploded view of the HVCM relay box**

Figure 6.0-2 Exploded view of the HVCM load box

7 Operating Mode Command Requirements

The commanded relay states for each of the tether operating modes is listed in Table 7.0-1.

Table 7.0-1

Case	Relay 1	Relay 2	Relay 3	Results
1	open	open	open	open mode
2	close	open	open	shunt mode
3	open	close	open	resistive mode
4	open	open	close	battery charging

Relays 1, 2, and 3 correspond respectively to SW1, SW2, and SW3 from diagram 3.1.3-1.

The rule for switching between modes is "make before break" meaning that no relay will break a circuit until all other relays have set the circuit for the next mode. This, of course, allows for four transient states. Analysis has concluded that these transient states do not put the HVCM electronics at risk.

Commanding all relays requires +28 V. Relay 1 is non-latching, normally closed and therefore requires +28 V constantly in order to stay open. Note that this is required for three of the four defined modes. Relay 1 has a nominal coil resistance of 290 Ω and therefore a power of 2.7 W. Relays 2 and 3 are non-latching normally open and therefore requires +28 V constantly in order to stay closed. Relays 2 and 3 have a nominal coil resistance of 290 Ω and therefore a power of 2.7W

8   Spacecraft Design Factors

The HVCM is a relatively straight forward electronics box with the exception of the load resistor which will dissipate a maximum average power of 70W. This power will have to be conducted into the Delta II chassis, thus the resistor location needs to be able to maintain the Load box operating temperature limits while dissipating 70W average. The mounting of the Load box will require the use of thermal grease to assure adequate heat conduction out of the Load box.