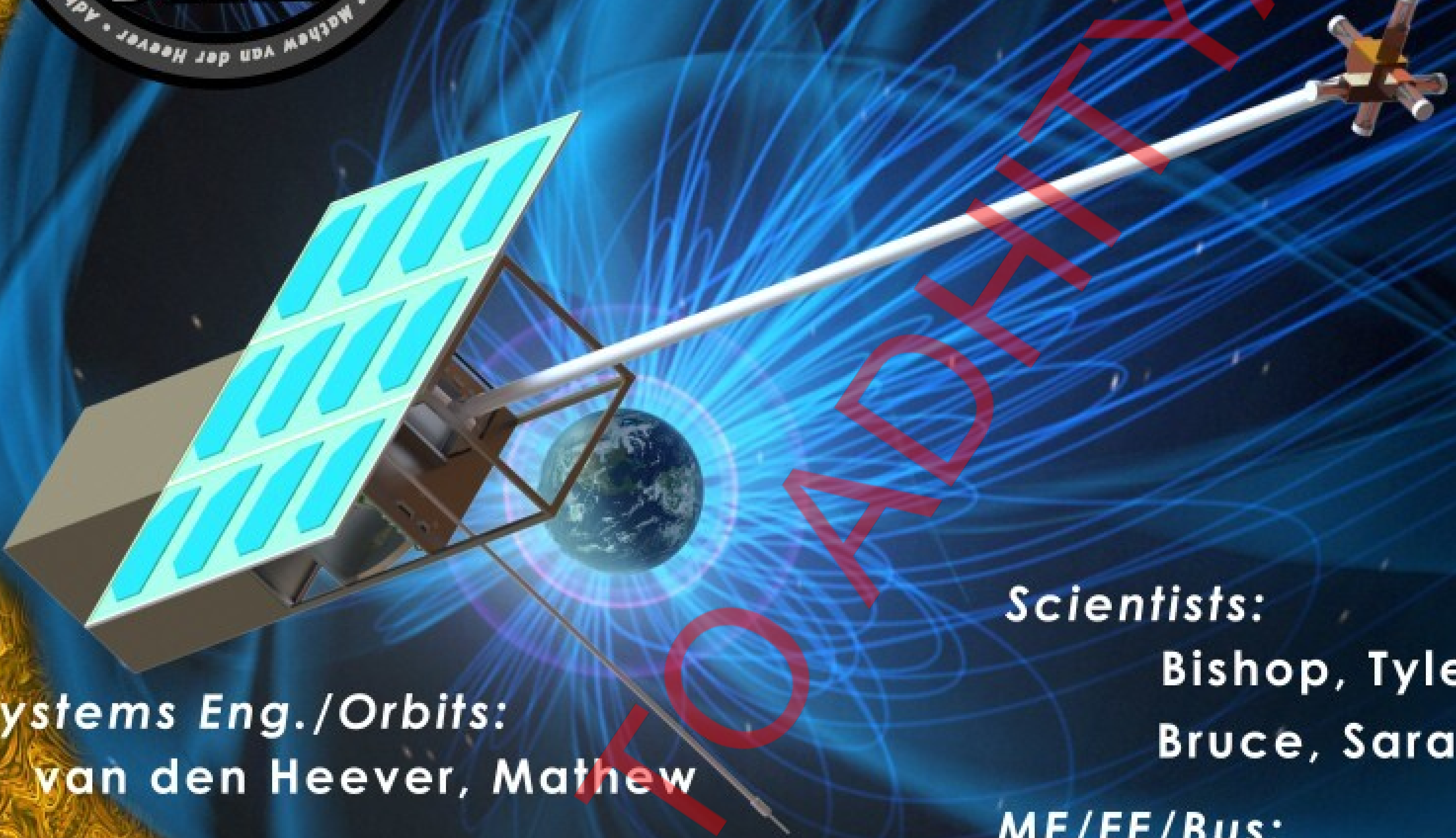
A proposal submitted in response to ASEN/ASTR 5440/5780: Mission Design & Development for Space Science



Scientists:

Bishop, Tyler

Bruce, Sarah

Systems Eng./Orbits:

van den Heever, Mathew

ME/EE/Bus:

Farr, Emily

Instruments:

Sripennem, Adhitya

DELTA

DENSITY EXPLORER TRIPLET ARRAY

University of Colorado Boulder

Contents

1 D. Science Investigation

1.1 D.1. Executive Summary:

The Density ExpLorer Triplet Array (DELTA) mission will explore the mysteries of Earth's magnetosphere by flying through and measuring the plasmasphere. Historically, magnetospheric research has prioritized the higher energy regions, such as the Van Allen Probes observations of the radiation belts or the Magnetospheric Multiscale Mission exploring the magnetotail. The plasmasphere has received less attention due to its dynamic complexity and the technological challenges in implementing it in models. This region is a crucial component of our space environment, the magnetosphere impacts earth bound space weather and geomagnetic storms. Advancements in CubeSat technology and space-based instrumentation make this an opportune moment to study the plasmasphere. As the amount of space-based activity increases, advancing understanding of space weather impacts becomes more crucial for keeping near Earth satellites and astronauts safe. Enhancing our knowledge of the plasmasphere is critical to predicting aspects of space weather, such as the dynamics of geomagnetic storms and their impacts on Earth's magnetic field. This current knowledge gap affects humanity's ability to protect space-based and terrestrial technological systems.

DELTA seeks to bridge this gap by deploying a fleet of three CubeSats into low Earth orbit at a semi-major axis of 4 R_E, strategically positioned to study the spatial structure and behavior of the plasmasphere. The DELTA mission aligns with NASA's strategic goal to **"detect and predict extreme conditions in space,"** as a comprehensive understanding of the plasmasphere is central to advancing space weather forecasting. The plasmasphere's influence on wave-particle interactions and neighboring particle populations, such as the ring current and radiation belts, highlights its significance. DELTA's mission is to provide insights into the mechanism behind these interactions, shedding light on electron density dynamics influenced by various types of plasma waves. Through this exploration, DELTA aims to advance our understanding of space weather and contribute vital data for the protection of space-borne assets. Additionally, DELTA complements previous missions like NASA's Van Allen Probes and the European Space Agency's Cluster mission. These collaborations enable comprehensive coverage of Earth's magnetosphere, enhancing our overall understanding and predictive capabilities of space weather phenomena.

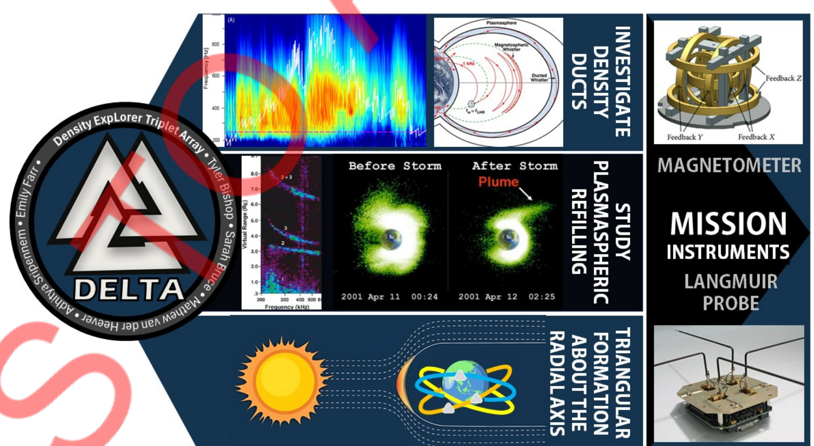


Figure 1: Mission Summary Image

1.2 D.2. Science Goals and Objectives:

The plasmasphere, as a vital element of Earth's magnetospheric system, plays a significant role in shaping space-related phenomena by modifying plasma waves and altering energy exchange rates between particles and waves in its environment. The energy exchange couples the plasmasphere to other parts of the magnetosphere, such as the radiation belts, a source of high-energy particles that cause the aurora. Such processes not only influence the operation and safety of satellites but also present potential risks to astronauts operating in near-Earth space. The effects of geomagnetic storms can lead to widespread technological implications on Earth, affecting integral systems such as power grids and communication networks. Deciphering the mechanisms governing the plasmasphere is not merely a pursuit of scientific curiosity; it is paramount for ensuring safe and informed operations of technological assets in space and understanding the broader impacts on our planet's magnetospheric system.

An important objective outlined in the Heliophysics Decadal Survey is to **"Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere."** The plasmasphere is directly coupled to the ionosphere, receiving material from that region during refilling, following geomagnetic disturbances. The plasmasphere experiences an average of 3 large geomagnetic storms per month, and a number of smaller storms[1]. A primary objective of DELTA will be to study how the plasmasphere refills following geomagnetic storms. Studying plasmaspheric refilling is essential to grasp how Earth's space environment recovers post geomagnetic storms, which can affect satellite communications and navigation systems. Additionally, there are density structures located within the plasmasphere, called density ducts and cavities, which are regions of enhanced or depleted density. Density duct behavior within the plasmasphere plays a pivotal role in influencing electromagnetic wave propagation, directly impacting space weather effects. An increased understanding of these density variations is needed to model space weather and to accurately forecast radiation belt dynamics. DELTA's science goals address these factors to help ensure the safety and success of current and future space missions:

(1) Determine the mechanisms governing refilling of the plasmasphere.

(2) Understand the importance of density ducts and cavities.

These questions directly relate to NASA's Science Mission Directorate (SMD) goals: "**Develop the knowledge and capability to detect and predict extreme conditions in space to protect life and society and to safeguard human and robotic explorers beyond Earth.**" Modeling the plasmasphere is needed for reliable space weather forecasts, as the density of cold plasma determines the rates of wave-particle interactions and magnetic reconnections. Currently, the general circulation models often speculate details about the plasmasphere or exclude it entirely, leaving a notable and potentially hazardous gap in our understanding.

1.2.1 D.2.1. Mechanisms Behind Plasmaspheric Refilling:

The plasmasphere undergoes periodic changes in response to geomagnetic storms as seen in Figure 2 [2]. During storms, an electric field pointed from dawn to dusk forms across the magnetosphere. This electric field causes convection of the plasma due to E×B drift, eroding the plasmasphere and producing a dayside plume. After the end of the storm, the plasmasphere slowly refills by outflows from the ionosphere, this is the phenomena that DELTA aims to examine [3].

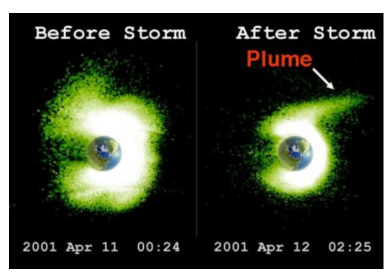


Figure 2: Plasmasphere before and after a storm. Shows erosion on the nightside and a dayside plume.

Several models have been developed to describe the refilling process. Hydrodynamic models, which treat the plasmasphere as one or multiple fluids, usually result in the formation of shock waves which cause plasma to accumulate at the equator before moving to the poles [4], [5], [6], [7]. On the other hand, models that include kinetic effects often show a smooth, gradual refilling process with no shocks [8], [9]. Due to the difficulty of solving the Boltzmann equation, there is no model of the plasmasphere which is fully kinetic. The current kinetic model offers a detailed approach, improving over previous hydrodynamic models by producing smoother flow profiles without discontinuities during refilling. However, while it shows high potential, it is essential to address the kinetic model's challenges and data gaps to refine its predictions and align them closer to real-world observations [8]. No model includes all kinetic effects and so there are a variety of predictions.

Apart from theoretical difficulties, there is also observational evidence suggesting the refilling process to be complex. Refilling may occur in stages, and the refilling rate might also be mass dependent [3], [10]. To help answer these science questions, a major science objective for DELTA will be to characterize the refilling processes by making measurements of density at multiple locations, ideally along the same magnetic field line. This setup requires multiple spacecraft, detailed in the sections below.

1.2.2 D.2.2. Ion Trapping Mechanisms:

When ionospheric plasma refills the newly emptied flux tubes, the pitch angle of the particles must increase to trap ions at the equator and prevent them from entering the conjugate hemisphere. Several ion trapping mechanisms have been proposed, including perpendicular ion heating by plasma waves, and thermalization of shock waves. DELTA will assess the contributions from both of these mechanisms.

1.2.3 D.2.2.1 Perpendicular Ion Heating:

A potential ion trapping mechanism proposed by M. Singh [7] suggests that refilling ions can be heated perpendicular to the magnetic field via resonance with plasma waves near the ion cyclotron frequency. This includes magnetosonic and other equatorial waves in the magnetosphere with any near ion cyclotron resonance, such as electromagnetic ion cyclotron waves that contribute to perpendicular heating. DELTA will look for evidence of these waves to determine their importance in trapping ions during refilling. DELTA will also investigate whether these waves are modified by the presence of density ducts, which are already known to enhance whistler waves and the implications for refilling.

1.2.4 D.2.2.2 Shock Thermalization:

When interhemispheric flows collide while refilling a flux tube, shock waves could be produced. The existence and extent of these shock waves are model dependent, with both one stream and two stream hydrodynamic models predicting shock waves [11], while semi-kinetic models do not [8]. The existence of shock waves could be tested by observing abrupt changes in the magnetic field strength, which DELTA will be capable of measuring using its magnetometer.

1.2.5 D.2.3: Understanding the Importance of Density Ducts and Cavities

In addition to the mystery of plasmaspheric refilling, another topic of recent interest is the existence of density ducts and cavities within the plasmasphere. Density ducts are enhancements in the local density which are aligned along the magnetic field. These ducts are known to guide and enhance whistler waves, a type of electromagnetic plasma wave, especially at the boundary of the plasmasphere where there is a steep density gradient [12]. Whistler waves are guided along the duct, parallel to the magnetic field, similar to a photon traveling through an optical fiber. The power of these waves can also be enhanced, leading to density ducts having a pivotal role in wave-particle interactions. Inside the radiation belts, whistler waves can interact with electrons, accelerating them to relativistic speeds before they collide with the atmosphere and produce an aurora. As there are limited observations of wave enhancement within ducts, DELTA will help to answer how often this occurs. Density ducts can have a variety of shapes, and the distribution and abundance of these ducts are not fully known.

In opposition to density ducts, there are also density cavities, which are depletions in the local density. There is evidence that these cavities can enhance magnetosonic waves [13], which are an important ion-trapping mechanism and also contribute to equatorial noise and heating in the plasmasphere. Based on the images obtained from S.T. Loi [14], ducts and cavities can also appear together, which would majorly influence the propagation of waves as they pass through alternating ducts and cavities. By measuring whistler waves and magnetosonic waves, DELTA will assess the frequency and magnitude of the occurrences.

1.3 D.3. Science Requirements Traceability

The Science Traceability Matrix (STM) illustrated in Figure 3 outlines how DELTA will address the objectives set forth in the Heliospheric Decadal Survey. In order to address its science objectives, DELTA must be capable of measuring the DC and AC magnetic field, and the plasma density. To measure the whistler waves guided by density ducts, DELTA shall measure frequencies up to 9 kHz. This value is obtained by computing half the electron cyclotron frequency, which is estimated to be as high as 18 kHz in the region of the plasmasphere DELTA will be located in. The frequencies of magnetosonic waves are much lower, thus the same magnetometer will be used to measure waves between frequencies between 1 and 100 Hz.

Based on a previously observed density duct using the Van Allen Probes [15], where the plasma density increased from 10 cm^{-3} to 20 cm^{-3}, DELTA is required to measure the electron density with 10% resolution, which will allow DELTA to measure the 1 cm^{-3} variations in density needed to observe the shape of the duct. The DC component of the magnetic field will be used to characterize rapid changes in the magnetic field, indicative of shock waves. Based on previous observations [16], DELTA will need to measure the DC magnetic field with a resolution of 5 nT to observe changes across the shock front.

Per DELTA's mission requirements, three satellites will be deployed in a linear formation. These spacecraft traverse circular orbits with matching radii and are inclined at 5 degrees for a duration of 2 years. To ensure the spacecraft lines up correctly, we must calculate how closely two DELTA spacecraft can get to the same magnetic field line.

We use the L shell coordinate system to describe Earth's magnetic field, such that a single magnetic field line has a constant L value, where the number assigned to L is the location where the magnetic field line intersects the equatorial plane, in units of Earth radius. If λ is latitude and r is the distance, the relationship between r and L shell is r = $Lcos^2(\lambda)$. If the spacecraft is located at a distance R, the L shell of the spacecraft is $Rsec^2(\lambda)$; this means the difference in L shell between the spacecraft is ΔL = $Rsec^2(\lambda)$ - R = $Rtan^2(\lambda)$. DELTA's orbital parameters are R = 4 R_E, $\lambda = 5°$, so we can calculate that ΔL = 0.038. In the equatorial plane, this corresponds to 243 km. Density ducts are usually 0.035 - 0.07 L shells in width or 223 - 446 km [15], so DELTA is able to align its spacecraft within the same density duct most of the time.

1.4 D.4. Science Traceability Matrix

Heliophysics Decadal Survey Science Goal	Science Goal	Science Objectives	Scientific Measurement Requirements		Instrument Requirements		Projected Performance	Instrument Used	Mission Requirements
			Physical Parameters	Observables					
Understand the dynamics and coupling of Earth's magnetosphere, ionosphere and atmosphere and their response to solar and terrestrial inputs	Characterize the Refilling Process	Characterize the steps of the refilling process	Electron Density	Spacecraft Potential	Density Range	10 – 800 cm-3	1 – 1000 cm-3	Langmuir Probe	Spacecraft pointing knowledge of 1 deg
					Density Resolution	10%	2%		
		Determine refilling mechanisms	Scalar Magnetic Field	DC magnetic field	Resolution	5 nT	5 nT	Hybrid Magnetometer	Mission Duration of 2 years
			Magnetosonic Waves	AC magnetic field	Frequency Resolution	0.1 nT	67 pT		
					Frequency Range	1Hz to 100 Hz	1 Hz to 10 kHz		
	Understanding the Importance of Density Ducts and Cavities	Determine wave altering properties of ducts and cavities	Magnetosonic Waves	AC magnetic field	Frequency Range	1Hz to 100 Hz			Three-Axis Stabilized Spacecraft
			Whistler Waves	AC magnetic field	Frequency Range	1Hz to 9 kHz			
		Determine the physical shape and distribution of density ducts and cavities	Density Profile	Density Gradient	Density	10 – 100 cm-3	1 – 1000 cm-3	Langmuir Probe	Constant North-South Constellation Pattern

Figure 3: Science Traceability Matrix

2 E. Science Implementation/ Instrumentation

2.1 E.1. Langmuir Probe

2.1.1 E.1.1. Measurement Concept and Design

The fundamental operational principle for the Langmuir probe involves the application of a varied voltage bias to a conductor exposed to a plasma environment. Accounting for the conductor's geometry, the specific current response to the applied voltage, and the underlying plasma theory, various plasma characteristics can be deduced. These characteristics include electron density, electron temperature, ion density, plasma potential, and floating potential.

The characteristics of a Langmuir probe [17], as seen in Figure 4, are depicted in the form of an I(V) curve. There are three main regions. The first region is the ion saturation region where ions are collected and electrons repelled. This allows the determination of ion density and temperature of the plasma. The second region is the electron retardation region where both ions and electrons are attracted toward the probe and electron temperature can be determined. The final region is the electron saturation region where the electrons are attracted and ions repelled, allowing the determination of the electron density[17].

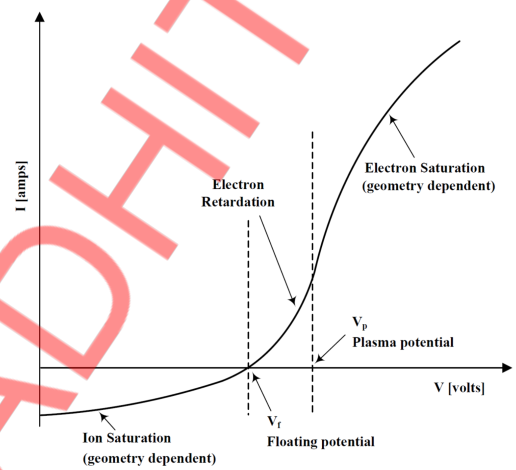


Figure 4: Ideal I(V) characteristic of a Langmuir probe

DELTA will operate in regions where the probe length is less than the Debye length. The Langmuir probe can measure the potential difference between the probe and the spacecraft, which can be used to infer the density [18], [12]. This method relies on the fact that the electric potential within a plasma falls off exponentially with the Debye length. Numerical simulations are needed to calculate the expected spacecraft potential due to the complexity of spacecraft charging effects. The block diagram in Figure 5 shows the probe-data pipeline.

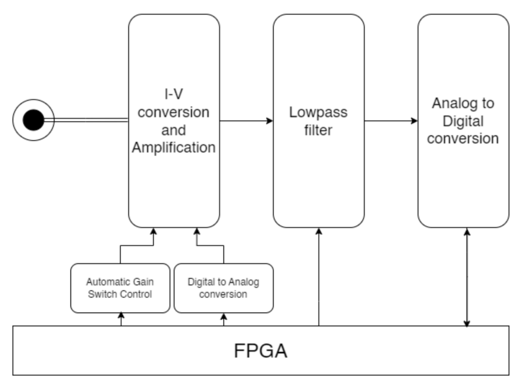


Figure 5: Block diagram on Langmuir Probe operation

2.1.2 E.1.2. Instrument physical design

DELTA shall use the Langmuir probe design previously flown on the SPORT CubeSat [19]. The Langmuir probe will be affixed to a 0.3 x 30cm boom directed in the nadir direction with 15-degree pointing control. Placing the probe in an area of undisturbed plasma reduces the interference from the satellite and other instruments to lessen measurement contamination risks. The spacecraft is designed with a minimized cross-section which is necessary for reducing drag in order to prolong the mission and preserve measurement accuracy. DELTA's layout positions all instruments away from the noise sources associated with the spacecraft bus.

Utilizing booms allows the probe to have minimal potential temperature influences from the spacecraft. Orbiting at a semi-major axis of 25512.5 km, the CubeSat and its instruments will be subjected to considerable thermal variation [19].

2.1.3 E.1.3. Projected Performance

The electron density can be calculated from the spacecraft potential [21], given that the electron temperature is known through I-V curve characterization. Based on work done by Escoubet [20], density measurements derived from spacecraft potentials agree within a small margin of error with theoretical predictions. This method can be used to estimate densities as low as 0.1 cm^{-3}, well within DELTA's requirement.

Based on SPORT's voltage uncertainty of 10 mV [19], and approximating the electron density to be log $n_e \approx -2(\delta V) + 100$ cm^{-3} when n_e is measured in cm^{-3}, the resulting density resolution is 2%. This meets DELTA's density resolution requirement of 100 cm^{-3} up to densities of 500 cm^{-3}. At the highest expected densities of 1000 cm^{-3}, this corresponds to a density resolution of 20 cm^{-3}, which is more than sufficient.

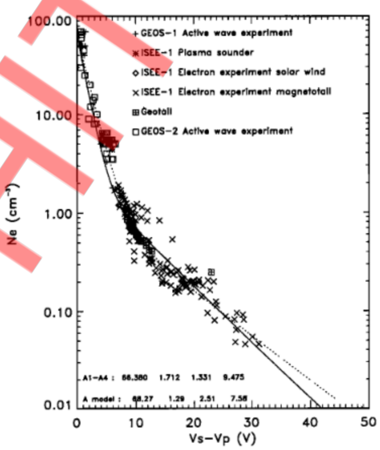


Figure 6: Demonstrating the method of determining densities from spacecraft potentials [20].

2.1.4 E.1.4. Environmental Effects

For Langmuir probes taking in-situ measurements like in the case of DELTA, photoemission of the probe itself poses a significant risk to data collection. When exposed to radiation and photons, the metal surfaces cause photoemission, where emitted electrons can be misinterpreted as plasma electrons, leading to errors in the accuracy of measurements. This can be resolved by taking base measurements and removing these inaccuracies through post-processing. Since we launch three CubeSats at the same time, this can be performed with minimal interruption to the science mission.

2.1.5 E.1.5. Instrument Heritage

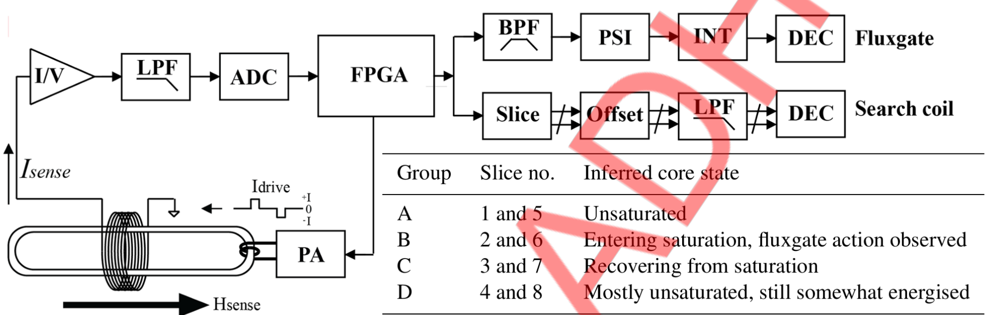
The instrument has a flight heritage as it is currently in orbit taking measurements. The SPORT mission has yet to publish any initial results but is expected to before the final review stage of the DELTA mission. Slight changes in the mounting and flight environment for the probe will allow DELTA to further advance the development of the instrument.

2.2 E.2. Magnetometer

2.2.1 E.2.1. Measurement Concept and Design

DELTA's Hybrid Magnetometer (HM) functions in accordance with Faraday's law of electromagnetic induction. The hybrid design here involves a fluxgate magnetometer core that is periodically driven into magnetic saturation to modulate the local magnetic field. By changing the core's permeability, it can change into the different modes of measurement [22]. It acts as a search coil when the core is unsaturated which achieves the higher sensitivity magnetic field measurements. When the core is in saturation, it acts as an air-core search coil and when the core is entering or leaving saturation, it acts as a fluxgate magnetometer. Using a field-programmable gate array (FPGA) and synchronizing the saturation of the core with the sampling of the sense coil, it is possible to separate the different measurements.

In the digital signal processing stage, the data is "sliced" into eight time series corresponding to the eight different phases in the magnetization loop of the core as shown in Figure 7. The frequency range requirement comes from the need to measure the Earth's magnetic field as well as the plasma waves. The instrument is picked with a high resolution and sensitivity to distinctly identify the shapes and features of the region surrounding density ducts. Figure 7 also depicts a block diagram of the setup for the DELTA HM. The HM is placed on a boom and connected to a pre-amplifier that amplifies the signal to be analyzed with the onboard computer.



Group	Slice no.	Inferred core state
A	1 and 5	Unsaturated
B	2 and 6	Entering saturation, fluxgate action observed
C	3 and 7	Recovering from saturation
D	4 and 8	Mostly unsaturated, still somewhat energised

Figure 7: Setup of Hybrid Magnetometer Design with slice number and corresponding state of saturation [22]

2.2.2 E.2.2. Instrument physical design

This design of the magnetometer core, depicted in Figure 7 is unique, as it is in the shape of a "racetrack" and is part of a technology demonstration on the production of lower noise fluxgate cores [23]. The racetrack core is formed on an Inconel bobbin with an 82.5mm long axis. It has three layers of a 100 μm foil spirally wrapped into the groove and attached with spot welds similar to (d) in Figure 8. The length of the solenoidal winding was roughly matched to the long axes of the racetrack core. This design is optimized for increased resolution, allowing DELTA to meet science goals.

2.2.3 E.2.3. Projected Performance

The DELTA HM was selected to satisfy broad frequency range requirements (1Hz to 10kHz) and higher resolution (5 nT). As a bonus, the DELTA HM has an overall high sensitivity accounting for the fact that it can switch between AC and DC measurements. The frequency requirement comes from the whistler wave measurements that go up to 10kHz. Having a DC measuring component to this also supports measuring shockwaves of 5 nT resolution. There will be three, 24-bit channels each able to take data at 100 samples per second. This particular instrument provides an outstanding performance by size and performance compared to low frequency, high sensitivity, large sized magnetometers launched so far. Work done by the University of Iowa shows the instrument meets the performance metrics shown here [22].

The noise floor of the HM based on its instrument heritage is 15 pT/Hz$^{1/2}$. The HM will measure waves up to frequencies of 10 kHz divided into 500 frequency bins, resulting in a bin width of 20 Hz. This corresponds to an instrument sensitivity of 67 pT.

2.2.4 E.2.4. Environmental effects

The environmental concerns for the HM are isolated to thermal variations. At lower temperatures, the error expected in the collected data will increase. DELTA will only eclipse for 6% of the total mission. In order to mitigate the thermal variation, a small heater will be added to the HM. In the event the heater fails, the eclipsing data will be discarded from the final results.

2.2.5 E.2.5. Instrument heritage

The instrument was designed and tested by Dr. D.M. Miles [22]. The HM was tested in their laboratory at The University of Iowa. It was designed for the purpose of space measurements and miniaturized for small satellites. The instrument shows significant promise in initial laboratory testing but has not yet flown. Further bench testing on the fully assembled instrument to assess for potential cross-talk in the design will be completed prior to controlled laboratory environmental evaluation. Performance characterization will be completed prior to integration into the DELTA CubeSats.

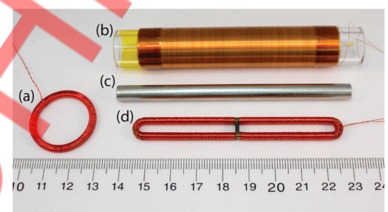


Figure 8: Depiction of different core designs and sense winding [22]

2.3 E.3. Science Mission Profile

Once a stable orbit is achieved, all DELTA CubeSats will continuously take data. DELTA completes one orbit every approximately 11 hours. Downlinks for each individual CubeSat will occur once every three orbits, with the ground stations connecting to one CubeSat every 11 hours. The ground stations will rotate sequentially through the CubeSats. In the event a CubeSat fails to connect, onboard memory can store up to 18 orbits, though the radio transmitter, assuming a 10 minute connection with the ground stations, can only transmit up to 12 orbits of data. Failure to connect to the CubeSat will not result in data loss unless the connection fails 3 or more scheduled connections in a row. The CubeSats will maintain the same orbital configuration and pointing throughout the mission, reducing the potential for alignment errors. To maximize the number of plasmaspheric refilling events, DELTA will launch in 2035, at the time of the next solar maximum, and operate for 2 years.

2.4 E.4. Data Sufficiency

Given a 2-year mission profile, DELTA will observe plasmaspheric refilling regularly, since the plasmasphere is in a constant state of flux. Geomagnetic storms are also of interest since they generate the largest depletion within flux tubes, followed by the largest refilling events. Since DELTA would like to observe more than a handful of events (> 10) over four local time sectors (dawn, dusk, day, and night), the mission would need to observe at least 40 storms to get a representative sample. At solar maximum, DELTA will probably experience around 3 geomagnetic storms each month where the DST index drops by 50 nT [1], for a total of 72 large events over its mission span. However, quiet time refilling is also of interest, which happens post geomagnetic storm. In addition to observing plasmaspheric refilling after a geomagnetic storm, DELTA will also observe the existence and properties of density ducts. To resolve the density duct, a minimum of 3 measurements are needed to see the relative increase in density, however, at least 10 measurements are required to resolve the shape of the duct. At $4R_E$, each spacecraft is traveling at 4 km/s. Taking the width of a duct to be 300 km [15], to make 10 measurements each instrument must have a sampling rate of at least 0.13 Hz, a rate well below the expected performance of both instruments.

3 F. Mission Implementation

3.1 F.1. Mission Implementation Summary

DELTA's three CubeSats will each carry two instruments, a Langmuir probe and a search coil magnetometer, both of which will be mounted on extendable booms. For communications, each DELTA spacecraft will use two radios, one for receiving and the other for transmitting. Amazon's AWS Ground Stations communications network will be used, which provides ample geographic coverage. The S-band and UHF band will be used for downlink and uplink operations, respectively. Deployable solar panels will be utilized to provide power for each subsystem, with a more detailed description provided in section F.4. To ensure each spacecraft remains in the correct orbit, each CubeSat will be equipped with a propulsion system and an Integrated Attitude Determination and Control System (ADCS), detailed in sections F.6 and F.7. DELTA's mission length is 2 years, after which the spacecraft will use their onboard propulsion systems to deorbit.

3.2 F.2. Mission Concept and Design

DELTA will launch eastward from Cape Canaveral Space Force Station on the 26th of November, 2035, and has a two-month launch window on either side of the scheduled launch date. This launch date was selected as it is near the next solar maximum. Once in a low earth orbit, the launch provider will perform an inclination change from 28.5 degrees to 0 degrees, as it crosses the equatorial plane of the earth. The launch provider will release the mothership, containing the three DELTA spacecraft. The Mothership will perform 3 maneuvers. The first is a burn to extend the apoapsis of each DELTA spacecraft's orbit to a semi-major axis of four earth radii. The second will transfer the orbit from an elliptical to a circular orbit by raising the periapsis altitude to match that of apoapsis. The Mothership will release the DELTA satellites at a reference right ascension of the ascending nodes (RAAN) of 0, 120, and 240 degrees respectively. Upon release, each of the DELTA spacecraft will perform its attitude determination and control sequences to ensure the satellite is not tumbling and is pointing correctly. Next they will perform an inclination change from 0 degrees to 5 degrees, which will require 344.9 m/s m/s of Δv. Each of the three spacecraft will stay in their orbit for the two-year duration of the mission before performing two deceleration burns to lower the orbit back to LEO where each DELTA spacecraft will continue to deorbit via atmospheric drag.

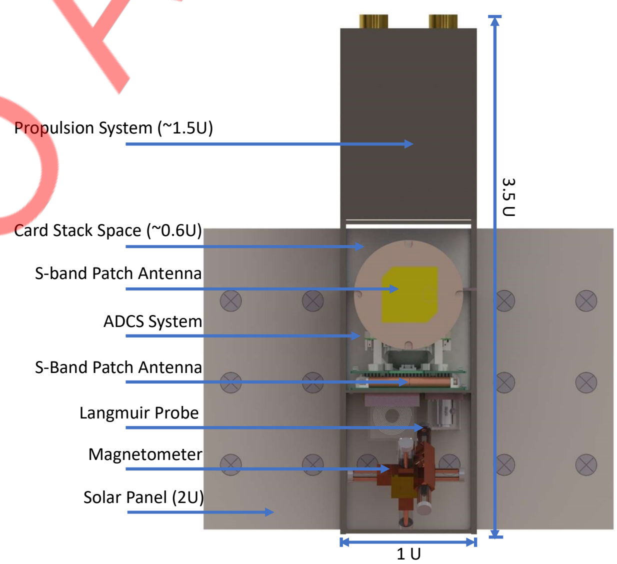


Figure 9: Spacecraft with subsystems labelled

3.3 F.3. Structures and Mechanisms

DELTA will be a 3.5U CubeSat, with a bus measuring 10 x 10 x 35 cm^3. It will house various subsystems, including two sections dedicated to boom deployment. The bus will be constructed from a 15mm aluminum alloy with a 30mm MLI insulation layer to ensure its ability to withstand temperature variation and high radiation [24]. As illustrated in Figure 9, the spacecraft's size has been chosen to accommodate all the necessary subsystems for its operation. However, for the sake of transparency, the figure displays all the subsystems except the spacecraft bus panels.

The solar panel deployment system utilizes a burn-wire resistor to release the solar panels. Additionally, the spacecraft features booms made of carbon fiber. These booms can be unwound to a length of 5 meters for the magnetometer and 30 centimeters for the Langmuir probe [25]. They serve to remove the instruments from electronic interference of the spacecraft, allowing for accurate data acquisition. Figure 10 offers a visual representation of the CubeSat in its deployed phase.

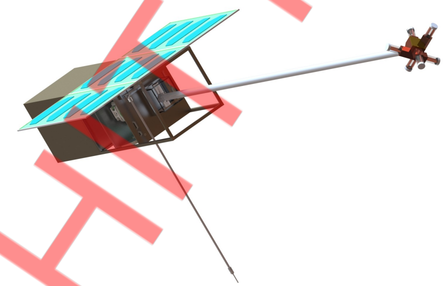


Figure 10: Spacecraft with instruments deployed

3.4 F.4. Power Subsystem

DELTA's power budget is provided in Fig. 11. To supply the required power, DELTA will use deployable solar arrays and batteries supplied by Blue Canyon Technologies. The power supplied by the solar panels is between 27 and 34 W, and the onboard batteries can store up to 100 Wh of energy with a 28V supply.

Subsystem	Usage (W)
Solar Panels	27
Electronics	-10
Communication	-7
Housekeeping	-2
Instrument Operation	-0.6
Heater	-1
Power Surplus	6.4

Figure 11: DELTA's power budget.

3.5 F.5. Communication Subsystem

DELTA carries two radios- one UHF configured for 450 MHz for all housekeeping, command, and control, and an S-band radio configured between 2.2 - 2.3 GHz supplied by ISISPACE for science data downlinks. DELTA will use the Amazon AWS Ground Stations narrowband communications. Amazon has S-band downlink capability from 11 geographically distributed ground stations, putting no constraints on the orbital range for DELTA.

3.6 F.6. Propulsion Subsystem

Each of the DELTA satellites will utilize a MICRO R^3 system from Enpulsion. These systems are flight tested within the Van Allen Belt, thus can survive within the relevant space environment for the DELTA mission. This off-the-shelf product includes all the necessary components of the propulsion subsystem, including thrusters, tanks, control electronics, and structural components. This system has a total impulse of 30,000 Ns, and can hold 1.3 kg of propellant. A total mission Δv of 4905.7 m/s is required. The inclination change each DELTA cube will preform requires 344.9 m/s of Δv. A 100% margin is budgeted for the inclination change, thus 689.8 m/s of Δv is reserved for each satellite. To deorbit each satellite, 1199.2 m/s is needed to lower the periapsis altitude to

1800 km, and 1611.4 m/s is required to lower the apoapsis altitude to 1800 km. Each of these has been given a 50% margin, thus the 4,215.9 m/s is reserved for each CubeSat to deorbit each DELTA CubeSat. Finally, 10 m/s is available to shift the equatorial crossing of each DELTA spacecraft up to 200 km within a single orbit. A total propellant mass of 0.35 kg is required to meet DELTA's Δv requirements, this gives each DELTA CubeSat a propellant margin of 260%.

3.7 F.7. Attitude Determination and Control Subsystem

The attitude determination and control subsystem for each of the DELTA spacecraft will be a Tensor Tech ADCS – 10m. This ADCS is designed for CubeSats up to 12U in size and is flight-tested. The Tensor Tech ADCS - 10m meets the pointing requirements of the DELTA mission, providing pointing knowledge of 0.1 to 1 degree, pointing accuracy of 0.2 to 1 degree in sunlight and eclipse respectively. This system has several automated modes that can be operated, including a sun-pointing mode, detumbling mode, safe mode, and fine pointing mode. The detumbling mode is critical during release from the mothership. The sun-pointing mode will be critical during the sun-lit portion of DELTA's orbit and will ensure the DELTA spacecraft's solar panels are able to capture sunlight.

3.8 F.8. Science Operations

Data Budget		
orbits per day	2.13	
measurement time per orbit	0.47	days
Langmuir Probe		
data depth	16	bits
sample rate	0.2	Hz
data per day	34.6	kB/day
Hybrid Magnetometer		
axes	3	
data depth	16	bits
frequency bins	500	
sample rate	0.2	
data per day	51.9	MB/day
Total data produced	**51.93**	**MB/day**
downlink time per day	5	min
downlink rate	4000	kbps
Total downlink capability	**150**	**MB/day**

Figure 12: DELTA's link budget.

DELTA satellites will observe continuously and are able to communicate data while observing. Plasma ducts are situated in no particular arrangement throughout the plasmasphere, so there need be no emphasis on any particular time or place of observation. With this layout, DELTA can be expected to regularly collect data on both plasma ducts and many large and small geomagnetic storms throughout its 2-year mission span. DELTA's detailed link budget is provided in Fig. 12.

4 G. Cost and Management

4.1 G.1. Schedule

Observed in Figure 13 is the Mission Timeline of DELTA. The mission timeline is proposed keeping in mind duration of instrument development and extensive testing. The period of the solar cycle required to take science measurements aligns with the launch date shown.

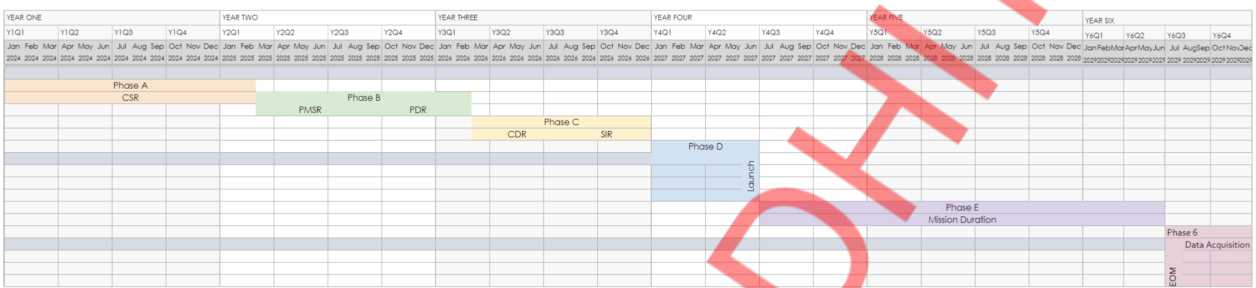
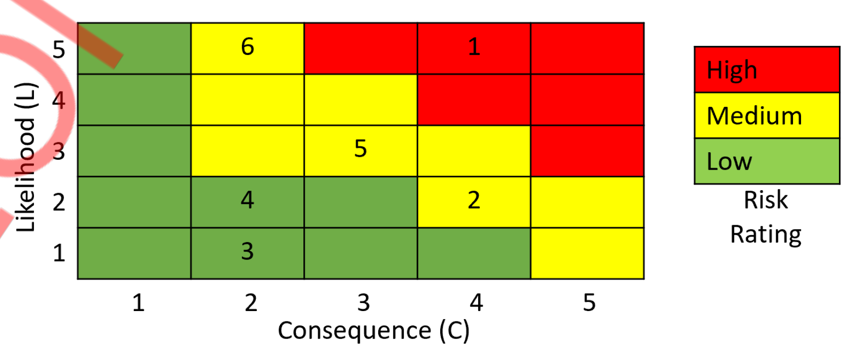


Figure 13: DELTA Mission Schedule

4.2 G.2. Risks and Risk Mitigation

The table below is DELTA's Risk and Risk Mitigation technique.

Rank/Category	Risk Description	L	C	Mitigation
1) Establishing initial communications contact with DELTA	If the AWS ground station is unable to establish initial contact with one or more of the DELTA CubeSats	5	4	Placing a small, minimal power draw beacon on each DELTA CubeSat to allow amateur radio operators to locate the CubeSats
2) Performance margins of the magnetometer	The magnetometer is in the final phase of development but has not completed testing. Potentially could fail to achieve science closure needs	2	4	An alternate magnetometer with a slightly lower performance will be kept in reserve
3) Mothership is unable to find the reference True Anomaly	A failure issue with the Mothership's GNSS could cause issues referencing True Anomaly	1	2	This will be mitigated by specific release timing from the mothership, based on the initial CubeSat release time
4) Environment of the Langmuir Probe	The probe has been tested at LEO but has not previously flown at the orbital height of DELTA	2	2	Additional testing in simulated environments will be conducted prior to launch to ensure performance metrics
5) Deployment of the instrument booms	Deployment of the instrument booms & Both of the instruments on DELTA require a boom deployment to accurately operate without interference from the spacecraft	3	3	Extensive testing of all six booms will be completed early in the timeline, allowing for adjustments or changes as needed to ensure full deployment
6) Magnetometer heater fails	Magnetometer fails due to bombardment of radiation	5	2	DELTA will omit data taken during eclipse



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