COMMAND, CONTROL, AND TELEMETRY FOR UTAH STATE UNIVERSITY'S SCINTILLATION PREDICTION OBSERVATION RESEARCH TASK (SPORT) MISSION

by

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ABSTRACT

Command, Control, and Telemetry for Utah State University's Scintillation Prediction Observation Research Task (SPORT) Mission

by

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Utah State University, 2019

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The Scintillation Prediction Observation Research Task (SPORT) is a joint United States of America (USA) and Brazil 6U CubeSat mission to address the further understanding of the preconditions leading to equatorial plasma bubbles. Utah State University (USU) is supplying four instruments towards this SPORT mission, specifically two Electric Field Probes (EFP), one Sweeping Langmuir Probe (SLP), and one Sweeping Impedance Probe (SIP). These four instruments will allow measurements of the electric field and plasma density in the ionosphere which will help understand what gives rise to plasma bubbles in the ionosphere.

This thesis will discuss the command, control, and telemetry communications needed to operate the SPORT USU instruments. It will cover an overview of the instruments involved, how the instruments are controlled specifically, what commands were needed to run the instruments, what telemetry data was produced and how it was transmitted to the ground station, and how the data is made useful. The design process, challenges, and solutions to this system and project will also be discussed.

(77 pages)

PUBLIC ABSTRACT

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To the love of my life for listening to my technical talk until she has started to understand it, and to my parents for their constant encouragement and love.

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I would like to thank my dad, for helping me find the engineering path, and always being there when I needed him and my mom for her interest in all aspects of my life, big or small.

Most importantly, I want to thank my loving wife Aimee, for all the times she lovingly understood and supported all the long hours, rough assignments, and occasional rants about whatever I was not happy with that day.

Jordan Haws

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ACRONYMS

ADC	Analog-to-Digital Converter
APID	Application Process IDentifier
ASSP	Auroral Spatial Structures Probe
C&DH	Command and Data Handling
CCSDS	Consultative Committee for Space Data Systems
DAC	Digital-to-Analog Converter
DICE	Dynamic Ionosphere CubeSat Experiment
EFP	Electric Field Probe
FFT	Fast Fourier Transform
FIFO	First In First Out
FPGA	Field Programmable Gate Array
NCO	Numerically Controlled Oscillator
PID	ProportionalIntegralDerivative
PPS	Pulse Per Second (related to PDS)
RF	Radio Frequency
RTC	Real Time Clock
SDL	Space Dynamics Lab
SIP	Sweeping Impedance Probe
SLP	Sweeping Langmuir Probe
SPI	Serial Peripheral Interface
VHDL	VHSIC Hardware Description Language

CHAPTER 1

Introduction

The Ionosphere is a layer of earth's atmosphere that extends from about 90 km to 1000 km above the earth's surface and is composed of neutral and charged atoms. Short wavelength photons, such as x-rays and UV-light, are emitted from the sun and absorbed by the Earth's atmospheric gases. The neutral gas atoms are broken apart into a free electron and a corresponding positive ion. These free-floating electrons, ions, and neutral gas atoms are collectively called plasma. The ionospheric plasma generally peaks in density at about 350 to 450 km. Traditionally it is categorized into three different layers, the D layer, the E Layer, and the F layers according to how these layers vary over the day night cycle and their ability to reflect radio signals. Each of these layers are influenced by the activity of the Sun and can vary greatly based on the Sun's current state.

The ionospheric plasma will either reflect or refract radio waves based on the frequency of the waves and the density of the plasma. The reflection of radio waves has been used to communicate over long distances since Marconi's first transatlantic demonstration of December 12, 1901. Radio wave signals can repeatedly reflect between the ionosphere and the Earth and become guided around the curved earth to distant locations. The effectiveness of the ionosphere in guiding radio wave signals depends upon its uniformity. If the plasma density is not uniform over a given region, the desired reflection or refraction of radio waves can be disrupted. Higher frequency radio waves pass through the ionosphere but are still affected by its refractive properties. A practical example of refraction is the GPS satellite signal, which originates above the ionosphere. Ideally, the signal would travel line of sight to the receiver but instead the Earths ionosphere refracts and bends the signal path. This additional path length must be considered by the receiver on the ground to accurately determine position. If the ionospheric plasma is not uniform, then this variability can show up in the receiver on the ground as position errors that change with time.

A specific type of disturbance in the uniformity of ionospheric plasma is called a plasma bubble. Plasma bubbles occur at low latitudes, in the band of $\pm$ 30 degrees latitude [1], and consist of a pocket of lower density plasma rapidly rising up through the more dense ionospheric plasma layers. They generally form a few hours after sunset and their disturbing effects can last throughout the night. A plasma bubble and its turbulent after effects refract radio signals passing through the ionosphere and cause constructive and destructive interference patterns at the receiver called radio scintillations. In severe scintillation cases, the signal's power is dispersed, and communication is not possible. The effects of plasma bubbles on radio signals have been observed since the 1930s, but relatively little is known about how they are triggered.

1.1 SPORT Mission

The Scintillation Prediction Observation Research Task (SPORT) is a CubeSat mission that is geared toward learning and understanding more about what gives rise to these plasma bubbles and how scintillations are caused by the ionosphere. The mission is a joint science mission between the United States of America (USA) and Brazil. In the USA, Utah State University (USU), University of Dallas Texas (UTD), Marshall Space Flight Center (MSFC), Goddard Space Flight Center (GSFC), and Aerospace are all organizations that are developing and flying instruments and payloads to better understand the conditions that give rise to plasma scintillations. In Brazil, the Instituto Tecnológico de Aeronáutica (ITA) and Instituto Nacional de Pesquisas Espaciais (INPE) organizations are providing the spacecraft, flight computer, and communication capabilities from the ground. A CAD model of the SPORT CubeSat is presented in Fig 1.1.

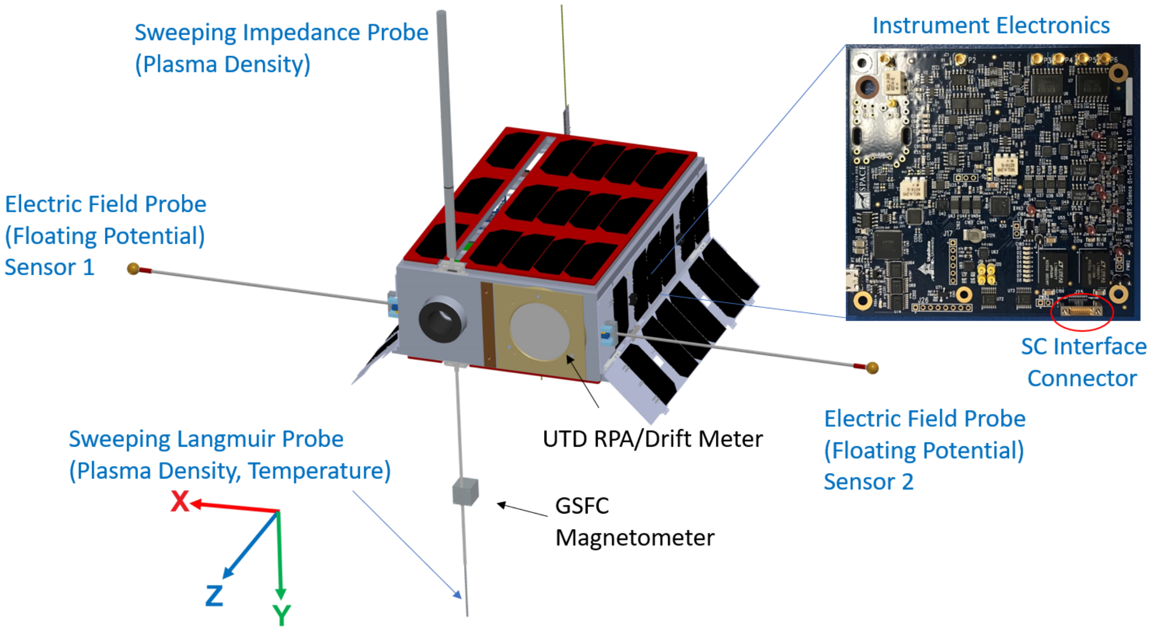


Fig. 1.1: SPORT CAD Model

The SPORT program was selected by NASA HQ in December of 2016 for implementation and funding was made available to the US partners in the fall of 2017. Funding for the Brazil portion of the program occurred in early 2018. The required U.S.-Brazil Framework Agreement was ratified in April 2018 and NASA's Office of International and Interagency Relations worked with the U.S. Embassy in Brazil to press for conclusion of the Implementing Arrangement in early 2019. Delivery of the completed US instruments to Brazil is expected in the fall of 2020 with launch of the spacecraft in early 2021.

The diagram in Fig 1.2 shows how the different organizations and payloads connect to make up this mission.

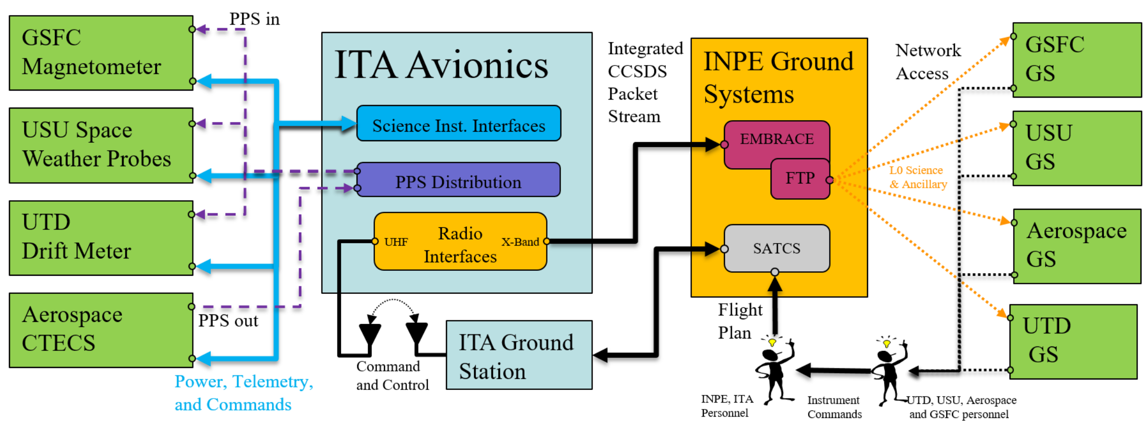


Fig. 1.2: SPORT Data Flow Concept

The US science instruments and payloads are seen on the left of Fig 1.2, and the data is passed to the ITA flight computer. Brazil manages and operates the main ground station as well, which both sends commands and receives telemetry from the satellite. The telemetry data is distributed to the instrument developers for analysis and processing via the File Transfer Protocol (FTP). Any instrument developer that needs to send a command can communicate with the ground station operator, who can initiate the proper command when the satellite comes within range next.

1.2 The USU Space Weather Instrument Contribution to SPORT

Utah State University is providing a suite of three instruments for measuring density and temperature of the Earths ionosphere. The three instruments are integrated into a single electronics module with a shared instrument controller to exchange data with the spacecraft. The USU instrument consists of two Electric Field Probes (EFP), a Sweeping Langmuir Probe (SLP), and a Sweeping Impedance Probe (SIP). In addition, in the USU instrument includes a small magnetometer integrated circuit and a Real Time Clock (RTC) to provide ancillary data and timing. The payload also monitors the voltage, temperature, and current of the instrument for validating the quality of the science data and to provide status of the payload health.

The two Electric Field Probes will be deployed on booms on opposing sides of the spacecraft to measure the electric potential difference from the tip of each boom to the spacecraft body. The electronics consist of two very high input impedance voltmeters such that the current collated from the ionosphere does not change the potentials on the probes. Combining the data from the magnetometer with the EFP will allow the calculation of the electric field in a single axis of the spacecraft. Individually each probe observes relative spacecraft charging. This data will be used to correct the measurements of the SLP for changes in spacecraft charging induced by its measurements sweeps.

The Sweeping Langmuir Probe operates by altering the electrical voltage on the tip of the SLP boom and measuring the current collected from the ionosphere by the sensor. A sensitive current monitor reads the current flow at a given voltage level applied by the SLP, and that data will be used to identify both the temperature and the relative plasma density around the spacecraft. The SLP will have an operating range of +2 Volts (V) down to -3 V and will attract or repel electrons and ions respectively. The instrument operates in two different modes. In the DC mode, the voltage applied to the SLP sensor will be held at a constant +2 V and the current measured. In the Sweeping mode, the instrument will perform a structured voltage sweep down to -3 V, and back up to +2 V in 500 steps with the current measured at each step.

The Sweeping Impedance Probe will be used to determine electron density by monitoring the current supplied to a short monopole antenna when driven with a low-voltage RF signal. The probe length is a fraction of the free space wavelength of the 2 to 30 MHz RF signals applied to the probe. The first order of the impedance of the probe is capacitive but also dependent on the average dielectric properties encompassed by the near fields that exist between the probe and the spacecraft. Essentially the probe and spacecraft form a complex geometry capacitor that is filled with the ionospheric plasma. The dielectric properties of the ionosphere modify the capacitive impedance of the probe giving it several resonances over frequency. One resonance occurs at the upper hybrid frequency of the ionosphere, which is directly related to electron density. The probe operates two different modes to find this frequency. One mode is a sweep where the resonance can be identified in the impedance curve consisting of 500 different frequency steps. The second mode is an active tracking mode where the resonance condition is identified and the local oscillator is locked onto it.

1.3 Thesis Statement and Research Task

The USU Space weather instruments consist of analog circuits for applying potential and RF signals on sensors deployed away from the SPORT spacecraft and immersed into the ionospheric plasma. The observed voltage or current signals on these probes are then processed with operational amplifier circuits and digitized using analog to digital converters. The analog circuits are be controlled and sampled using digital to analog and analog to digital converters in real time using state machines implemented in a FPGA. The FPGA is interfaced to a processor for communication with the SPORT spacecraft fight computer. This thesis presents both the engineering formulation, development, and implementation of the command, control, and telemetry systems of the USU space weather instruments. The thesis statement for this effort is:

Can an integrated, low-power instrument controller be developed for the USU space weather instruments that satisfies SPORT mission science objectives and engineering requirements?

The efforts needed to address the thesis research topic required the formal engineering development of sampling requirements for each instrument from the science objectives. It involved developing concepts for the on-board instrument data handling and processing necessary to meet the science requirements as well as the specific formatting and processes of transmitting and retrieving the telemetry data and instrument commands from the spacecraft. It also covers the requirements and needs of command and control of the payload and instruments to allow for flexibility and adaptivity in flight. The design process for meeting these requirements will be discussed, as well as specific challenges faced and the decided upon solutions.

This thesis addresses the research and development effort of how the mission science requirements were met through instrument sampling and how the data is filtered and averaged to achieve the needed data rates and sizes. There is also a discussion of how the data is organized, time stamped, packetized and transferred to the flight computer. Finally, details are presented of how the data will be retrieved, stored, interpreted, corrected, and visualized from the Brazil developed spacecraft. Included is how the commands are used for instrument testing, calibration, and flight of the payload.

This thesis describes and documents the designs and decisions made with respect to the above topics as well as describing the implementation and testing done on the USU space weather probes that is related to the functioning of the command and control and spacecraft interface.

1.4 Literature Review

Command and telemetry schemes are central to every satellite mission and can be generalized as simply a network of computers exchanging data. Sending and receiving data in complex systems is usually done using packets of varying sizes and purposes. The packet structure relies on a standard header that specifies the packet size and type as well as a time stamp. The specific data to be transferred follows the header, which is followed by some type of verification data to determine if the packet has been corrupted during exchange. This generic model can be expressed in many ways but is at the heart of the development effort for the SPORT space weather instruments. The programs most recently undertaken by USU and related to the SPORT mission are the Auroral Spatial Structures Probe (ASSP) sounding rocket mission and the Dynamic Ionosphere CubeSat Experiment (DICE). Both of these missions included instrumentation similar to the USU Space Weather Probes and involved an instrument controller and packetized data systems. The command, control, and telemetry systems will be reviewed here to better understand the heritage and needs for the SPORT mission.

1.4.1 ASSP

The Auroral Spatial Structures Probe (ASSP) was a mission that deployed in 2015 and included Electric Field Probes, Langmuir Probes, magnetometers, and a Sweeping

Impedance Probe as a main payload [2]. It was designed and developed at USU and Space Dynamics Lab (SDL), and is the most recent iteration of USUs Impedance probe.

Because ASSP was a sounding rocket mission instead of a satellite mission, the telemetry scheme was a live telemetry channel transmitting data via UART to the ground [3]. There was some synchronizing reference data sent up to the rocket and its payloads for timing purposes, but these were minimal.

The ASSP data structure consisted of Sub Frames, nine sixteen-bit channels where the data for a specific frequency would be transmitted. A Major Frame consisted of 32 Sub Frames, and four Major Frames would be enough data to complete a full frequency sweep on the Impedance probe.

1.4.2 DICE

The Dynamic Ionosphere CubeSat Experiment (DICE) was a mission that deployed in 2011 and included an Electric Field Probe, a Langmuir Probe, and a magnetometer similar to what is used in the SPORT mission [4]. It was designed and developed at USU and is a large part of the flight heritage of SPORTs hardware and software.

The DICE mission consisted of two 1.5 U CubeSats to "study space weather phenomena that occur in Earths ionosphere during geomagnetic storms." [5] The DICE science instruments interfaced with an FPGA, and then that FPGA interfaced with a Command and Data Handling (C&DH) subsystem that would then interface with the radio to send down data.

The telemetry of the DICE mission consisted of Consultative Committee for Space Data Systems (CCSDS) headers, granules of data packed together into data packets, and a 16-bit fletcher checksum. A granule of data is a set of data taken from various instruments at a given time, and so is grouped together in a data packet. Three different data granules were used, each with an individual header byte to indicate which type of granule it was. These granules were grouped together into packets that were 542 bytes long, and those data packets represented a single seconds worth of instrument data.

The data was sent from an antenna from a CubeSat down to a receiver at Wallops, VA. The data packets were then turned into a data stream by a software-defined radio, and then processed and stored on a ground station computer.

DICE used 16 different commands, most of which were one byte each, to control the mission in flight. One of the commands was two bytes, and one was three bytes in length, but all others were a simple byte command. These commands control modes, sampling speeds, power on and off options, and several other functions on the satellite. These commands would go through the antenna, C&DH subsystem, and then the FPGA would make the needed alterations.

1.5 Thesis Outline

This thesis is organized into four chapters.

Chapter 1 lays out the introduction to the ionosphere and the SPORT mission. An overview of USU's contribution to SPORT and the literature review is also presented.

Chapter 2 covers the needs and objectives of the USU Space Weather Probes and the specific requirements imposed on them by the SPORT mission. The mission requirements are broken down into instrument and then telemetry requirements. The concept of operations of the Space Weather Probes from the spacecraft instruments though to the ground station and data analysis is presented.

The design decisions and implementation of subsystems to meet the requirements and constraints are found in Chapter 3. The science and housekeeping telemetry is outlined for each instrument mode, and packet. The state, calibration, and configuration commands are outlined to properly control the Space Weather Probes. The time stamping scheme and CCSDS packet protocol are presented and their implementation is discussed. Major issues that were encountered are discussed, as well as the solutions that were decided on.

Chapter 4 covers the tests, calibrations, and results of the Space Weather Probes. Clock correlation is specifically addressed, and the calibration results are shown. Because commands and telemetry are inherent in all instrument testing, successes in functionality occurred throughout the development process.

A discussion of the success of development and suggestions for future implementations of the space weather probes can be found in Chapter 5.

CHAPTER 2

Requirements and Concept of Operations

2.1 SPORT Science Requirements

The Scintillation Prediction Observations Research Task (SPORT) has two specific science objectives phrased as questions to be answered by the mission. The first question is: What is the state of the ionosphere that gives rise to the growth of plasma irregularities that extend into and above the F-peak? This question focuses the mission on identifying any predictors of plasma bubbles. Identifying the conditions that consistently give rise to plasma bubbles will greatly improve the ability to predict them before they form. The second question is: How are plasma irregularities at satellite altitudes related to the radio scintillations observed passing through these regions? Answering this question will increase the understanding of how radio waves are effected by plasma bubbles. By measuring the conditions in situ of the plasma before, during, and after plasma bubbles with accompanying radio wave measurements, radio wave disruptions can be correlated more closely with plasma disturbances.

Answering these scientific questions requires observations of plasma drifts, density and the presence of scintillations to occur in specific locations and times in the Earths ionosphere. This flows down to requirements for specific instrumentation, sensitivities, and sampling rates. Table 2.1 provides the traceability from the science question to the measurement requirements through the mission functional requirements for SPORT. This information was developed according to the concept of a minimum mission science requirements set, such that if these requirements are achieved then progress can be made on the science questions. The USU Space weather probes are tasked with producing data on the plasma density and electric fields in the Earth's ionosphere that achieves the required performance listed in Table 2.1. To do this the USU space weather instrument must meet the performance requirements presented in Table 2.2 which were derived by the instrument scientist.

Table 2.1: Top level requirements for the SPORT mission

The Scintillation Prediction Observation Research Task		**Instrumentation**	**Spacecraft**
Observational Approach	Science Measurement Requirements	Instrument Approach	Space System Requirements
1) What is the state of the ionosphere that gives rise to the growth of plasma irregularities that extend into and above the F-peak?			
Observations in the 1700 to 0100 LT sector over -30 to 30 latitude Height profiles of the plasma density to specify the magnitude and height of the F peak density in the EA Vertical ion drifts at or below the F peak in the EA	Plasma Density Profile 1) 140 to 450 km alt 2) 104 to 107 p/cm3 range 3) 20% p/cm3 accuracy 4) 1000 km along track sampling Ion Drifts (Earth Reference Frame) 1) 800 m/s Range 2) 20,m/s precision & accuracy 3) 10 km along track sampling	GPS Occultation Observe GPS satellite occultation along and to the sides of the orbit plane to obtain line of site TEC Ion Velocity Meter Observe vertical ion drifts by angle of arrival of heavy ions at detector	Satellite Orbit 1) 1 year mission life 2) 40 to 55 inclination 3) 350 to 450 km altitude 4) 10 km eccentricity Spacecraft 1) 515 Ram Pointing 1 2) 1 km position knowledge 3) 10 ms timing
2) How are plasma irregularities at satellite altitudes related to the radio scintillations observed passing through these regions?			
Observations in the 2200 to 0200 LT sector over -30 to 30 latitude Observations of irregularities in electron density and E-field power spectral density in slope from 200 km to 200 m	E-Field (Earth Reference Frame) 1) 45,mV/m range 2) 1.1 mV/m precision & accuracy 3) 1 km along track sampling 4) 10 km - 200 m along track waves Plasma Density 1) 103 to 107 p/cm3 range 2) 103 p/cm3 precision & accuracy 3) 1 km along track sampling 4) 10 km - 200 m along track waves B-field 1) 56,000 nT range 2) 100 nT precision and accuracy 3) 1 km along track sampling	E-Field Double Probe Observe probe floating potential for AC E-fields from irregularity GPS Occultation S4 scintillation index Langmuir/Impedance Observe DC and AC probe response for relative and absolute electron density and observe irregularities Three Axis Magnetometer Support VxB computation for ion velocity and E-Field measurements	Spacecraft Mechanisms 1) 0.6 m tip-to-tip booms Attitude (Post Flight Knowledge) 1) 0.05 1-uncertainty

2.2 Space Weather Probes Instrumentation Requirements

The Space Weather Probes provided by USU consists of an Electric Field probe, a Langmuir Probe, and an Impedance probe. Additionally, the probes must produce information on the state of health of the instruments, timing, and observations of the Earths magnetic field to support the impedance probe measurements. The magnetometer provided by USU will only be a support measurement to the space weather probes and does not replace the science magnetometer being provided by GSFC.

Table 2.2: Space Weather Instruments Requirements

Parameter	**EFP**	**SLP**	**SIP**
Scientific Measurement Requirements	Electric Fields 1) 45 mV/m range 2) 1.1 mV/m precision 3) 1 km sampling,Waves 4) 10 km - 200 m sampling	Plasma Density 1) 103 to 107 p/cm3 range 2) 103 p/cm3 precision 3) 1 km sampling,Waves 4) 10 km - 200 m sampling	Plasma Density 1) 103 to 107 p/cm3 range 2) 103 p/cm3 accuracy 3) 200 km sampling
Measurement Objectives	0.1 to 500 mV/m, 1% Vi (derived): 20 m/s	Ne : 10 to 107,cm-3, 5% Ni: 103 to 109,cm-3, 5% Te : 200 to 5000 K Vf : 10 mV to, 12 V Vp: 10 mV to, 12 V	Ne : 10 to 107 cm-3, 1% 1 km sampling
	DC-40 Hz	DC-40 Hz, 25 s/sweep	DC-40 Hz, 25 s/sweep
	16 spectrometer ch. 20 Hz to 15 kHz	16 spectrometer ch. 20 Hz to 15 kHz	

Table 2.2 describes the specific requirements of each instrument, and Fig 2.1 presents the concept of how the data produced from those instruments will flow.

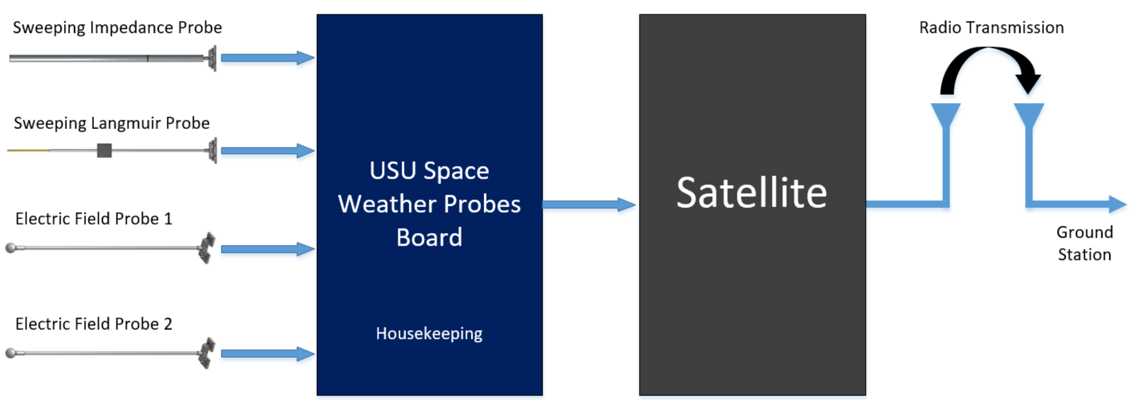


Fig. 2.1: Data Flow Concept

The instruments required to meet the science objectives can be seen on the left side of Fig 2.1, and the data produced from each instrument flows into the Space Weather Probes board. This data is combined with housekeeping data monitoring the payload health and is transmitted to the satellite. The satellite uses its radio to relay the data to the ground where ground stations can monitor and store the data.

The requirements from Table 2.2 were further refined to specific telemetry channels, with associated rates and word sizes to meet the instrument requirements in Table 2.3. The Rate column is how often a measurement is taken per second. The Word Size column indicates the number of bits that each individual measurement takes. The Wd/Samp column indicates how many words constitutes a full sample for each measurement. The bit rate, sample period for both orbit and distance calculations are shown in the final columns.

Channel Name	Rate Hz	Word Size bits	Wd/Samp Words	Bit Rate bits/s	Sample Period #/Orbit	Sample Period spatial (km)
Electric Field Probe V1S	100	20	1	2000	555346	0.077
Electric Field Probe V2S	100	20	1	2000	555346	0.077
Wave Power	10	18	64	11520	55535	0.767
Electric Field Probe Sweep V1S	0.0083333	20	1052	175	46	920.236
Electric Field Probe Sweep V2S	0.0083333	20	1052	175	46	920.236
Langmuir Probe DC high gain	100	20	1	2000	555346	0.077
Langmuir Probe DC low gain	100	20	1	2000	555346	0.077
Sweeping Langmuir Probe high gain	0.0083333	20	1052	175	46	920.236
Sweeping Langmuir Probe low gain	0.0083333	20	1052	175	46	920.236
Tracking Impedance Probe	100	32	1	3200	555346	0.077
SIP Magnitude	0.0083333	20	512	85	46	920.236
SIP Phase	0.0083333	20	512	85	46	920.236
SIP Quadrature I	0.0083333	20	512	85	46	920.236
SIP Quadrature Q	0.0083333	20	512	85	46	920.236
Mag X-Axis	100	16	1	1600	555346	0.077
Mag Y-Axis	100	16	1	1600	555346	0.077
Mag Z-Axis	100	16	1	1600	555346	0.077
Mag Temperature	100	16	1	1600	555346	0.077
Rate collected on orbit		Total		30166	bits/s	

Table 2.3: Science Telemetry Channels

Table 2.2 shows the data channels and volume needed for USU's payload in SPORT. This information is used to inform the requirements for the command and data handling for the Space Weather Probes.

2.3 Command and Data Handling Requirements

Requirements for SPORT USU's Command and Data Handling are labeled as R1 through R8 below. Each requirement is stated and given a short description.

R1 Science telemetry data shall only be collected for operating instrument modes.

The Science data from the Space Weather Probes can be divided into two groups. The first group is the Sweeping Langmuir Probe and Electric Field Probes. These instruments work together to measure the relative density of plasma in the ionosphere. These instruments can either operate in a DC or sweep mode. In DC mode, the SLP will hold a constant voltage, and sweep mode will sweep the voltage across a range of +2 V to -3 V. The current collected in either mode is used to calculate the relative plasma frequency. The Sweeping Impedance Probe will similarly operate in either a sweep or a track mode. The SIP uses an AC signal and adjusts the frequency to measure the impedance of the plasma. It can either track the frequency of interest or else sweep through a range of frequencies from 1 to 30 MHz. Science data from all instruments and modes needs to be gatherable and deliverable out of the Space Weather Probes.

R2 The health and status of the Space Weather Probes shall be available for monitoring.

While science data is needed to directly accomplish the mission goals, housekeeping data is needed to monitor instrument health. This housekeeping data will consist of various voltage, current, and temperature measurements. These measurements will ensure the payload electronics are operating in acceptable parameters and will assist trouble shooting should anything go wrong.

R3 The instrument controller shall be capable of receiving commands to switch instrument modes while on orbit.

Each instrument will be able to be turned on and off for flexibility in power, bandwidth, and general operation. These commands will be able to switch an instrument into a different mode as discussed in R1.

R4 The instrument controller shall be capable of receiving commands for calibration and testing while on the ground.

Within each instrument mode there are parameters that can be changed to greatly improve the calibration and testing process. An example is controlling the sweep step, adjusting the time between data packets, or changing parameters of the on-board data processing. These parameters and commands are specific to the instrument implementation and testing needed.

R5 The instrument controller shall be capable of receiving commands for changing instrument configuration while on orbit.

Instrument sweep tables will have the capability of being rewritten. This will allow adjustments to the focus of the instruments to be changed. This differs from R4 largely in terms of data volume. A configuration command will be crafted to adjust large-scale changes in instrument, as compared to the small adjustments used in calibration commands.

R6 Telemetry data shall be timestamped to 1 ms of the GPS time post flight.

Time stamping is essential to relating instrument data to physical location in satellite missions. Accurate time stamping is also used to correlate data from different payloads within a single spacecraft. If a time stamping scheme is not robust and accurate, data analysis can be difficult or impossible.

R7 The Space Weather Probes shall use the CCSDS packet protocol for both telecommand and telemetry.

The Consultative Committee for Space Data Systems (CCSDS) Space Packet Protocol[1] is standard data packet protocol often used in space missions. As a packet protocol, CCSDS contains a header with a packet ID, packet length, and sequence count among other information.

[1] See Space Packet Protocol Blue Book CCSDS 133.0-B-1 for more details.

R8 Data shall be placed in a MySQL database post flight.

The destination for the telemetry data is a MySQL database. MySQL is a popular database that can interact with a variety of programs for processing and analyzing the data. Matlab specifically can pull data from MySQL and process and visualize the data easily.

2.4 Theory of Operation

Using the requirements outlined previously, Fig 2.1 is expanded to include a more complete picture of how both the commands and data will flow as seen in Fig 2.2.

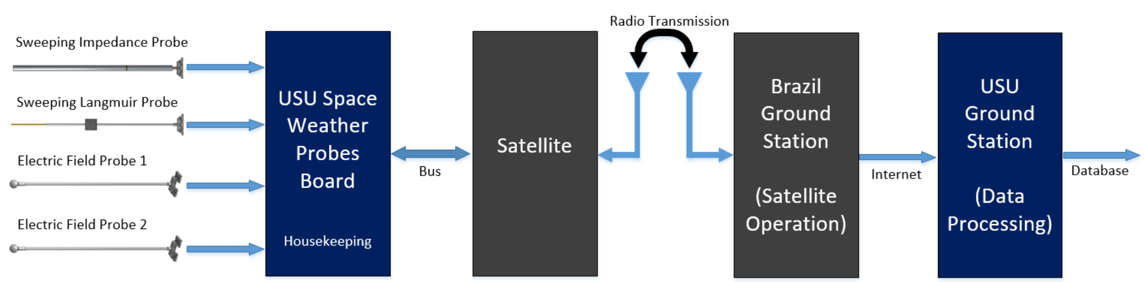


Fig. 2.2: Command and Data Flow Concept

Fig 2.2 presents the bi-direction communication concept from the USU Space Weather Probes board and the Brazil Ground Station. ITA and INPE are ultimately the groups in charge of the spacecraft launch, communication with the satellite, and flight computer for the entire mission. Thus, the commands will originate from the Brazil operation and ground station. USU will communicate with Brazil when adjustments and commands need to be sent, but the commands will be sent from the operation center, not USU.

The data generated by the Space Weather Probes will be grouped or packetized and held in on-board storage in the payload when the flight computer is busy with other payloads. Once the flight computer is ready to receive telemetry data, USU's payload will transmit the data across the satellite bus to the flight computer. The flight computer designed by the Brazilian organizations will then store and dump the data down to a ground station also maintained by Brazil. The data will then be made available to over the internet, and USU data will be transferred into a ground station computer at USU. The data USU receives from Brazil will be processed at USU, and the post processed data will be passed back to Brazil for distribution. This allows each group to process their individual sets of measurements then make the processed data available to the rest of the organizations involved. This step allows raw data to be processed as needed for future scientific analysis.

CHAPTER 3

Design and Implementation

This chapter outlines the design decisions made to fulfill the requirements for the command and data handling of the SPORT mission.

3.1 Science Telemetry

This section covers the design of the instrument data taken from the Space Weather Probes to meet R1.

3.1.1 Spacecraft Telemetry Interface

The USU Space Weather Probes communicate with the SPORT flight computer via a four-wire Serial Peripheral Interface (SPI) interface, in Motorola mode 0, and with two additional handshake signals. The interface is illustrated in Fig 3.1.

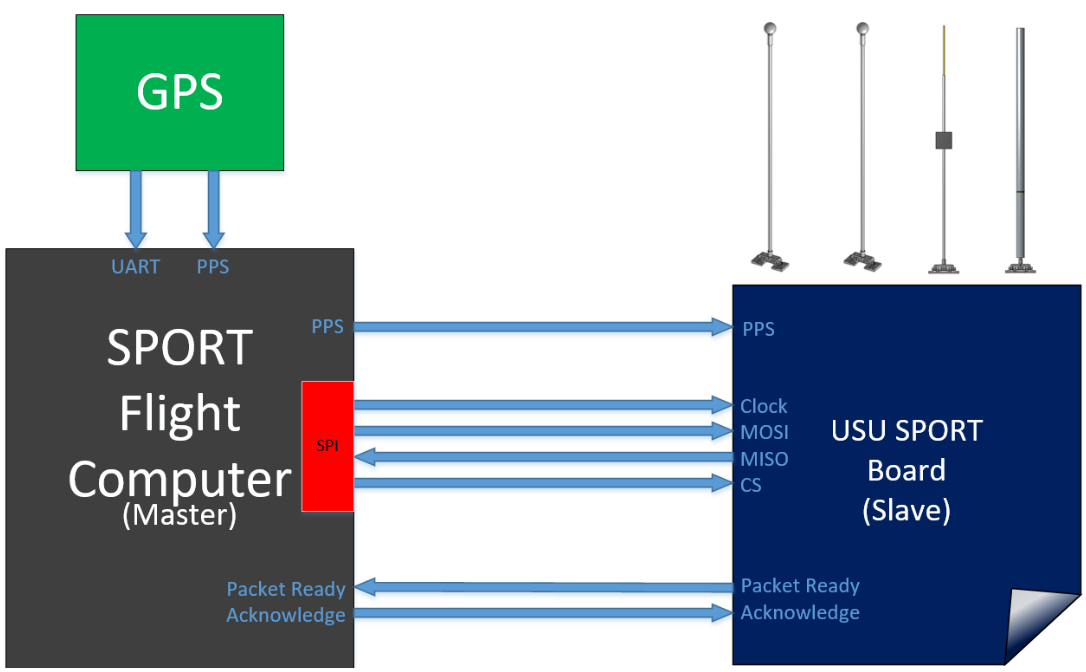


Fig. 3.1: USU and Flight Computer Telemetry Interface

A four wire SPI interface was chosen over other common protocols like I2C and CAN because of reliable use in heritage missions. SPI is a commonly supported protocol on many pieces of hardware, and SPI would also be used for various integrated circuits on the board itself. It made sense to try to stick to a single communication standard as much as possible throughout the payload.

In consideration of possible issues faced with a 4-wire SPI protocol, it was decided to only use the interface as half-duplex. Half duplex was chosen specifically because telemetry data coming from the Space Weather Instruments would neither be constant in size or timing. Implementing full duplex would have required extra attention to the SPI transaction, which would lead to many edge cases that would need to be accounted for. This half-duplex decision led to another problem of initiating data transfers from the slave side of the SPI bus.

Packet Ready and Acknowledge pins were added to initiate a handshake around the data transferred from the SPI. This would allow the slave to signal to the master that telemetry data was ready for transferring, and then the master to validate the data once received and signal back to the slave. These extra handshaking pins allowed for simple interface conditions with few edge cases that needed to be addressed.

A PPS signal is also shown as a separate pin connecting to the Space Weather Probes, and will be discussed in the time stamping section.

3.1.2 Telemetry SPI Timing

The USU Space Weather Probes acts as a slave to the Spacecraft in the SPI communication. In order for the USU Space Weather Probes to signal to the Spacecraft that it has data ready to send, the USU Space Weather Probes pulls the Packet Ready line high, until the packet has been sent and successfully received. The Spacecraft raises the Acknowledge line in order to signal to the USU Space Weather Probes that the packet was successfully received. This is illustrated in Fig 3.2.

If the acknowledge line is not raised before the next transaction the same telemetry data will be sent on the next transaction. To receive new telemetry packets the CS line

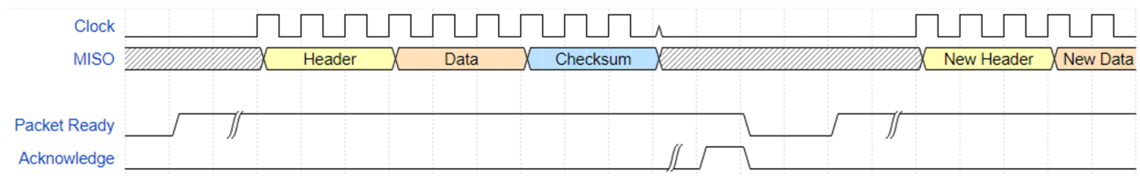


Fig. 3.2: Packet Ready and Acknowledge Pin Example

must be brought high between transactions.

3.1.3 Science Packet Breakout

The Science telemetry packet contains magnetometer readings, and the DC E-Field and Langmuir probes data. The magnetometer is a small integrated circuit that can measure the magnetic field in three axes as well as the temperature of the chip. GSFC is also providing a magnetometer that resides on the Langmuir Probe boom, and that magnetometer is the primary instrument used to measure the magnetic field in this mission. The small magnetometer in the Space Weather Probes is going to be used as a reference for the main magnetometer, and in post processing should eliminate much of the noise in the magnetic field due to the spacecraft. The small magnetometer also measures temperature, which can be used in connection with housekeeping data for a better understanding of the temperature gradient across the USU board.

The EFP data in this packet will measure the potential difference between the plasma and spacecraft body to either side of the spacecraft. This voltage can be combined with the magnetometer data to calculate the electric field along a single axis of the spacecraft. The EFP data also will be used as a reference for the SLP data. As the SLP does not change potential in DC mode (+2 V), deviations in the potential differences seen by the EFP should correspond to differences in the plasma itself. Thus if the plasma changes around the spacecraft while the SLP and EFP are in DC mode, both should register the changes in their respective measurements. The SLP has two almost identical channels, the only difference being a one of gain in the signal amplification. This was done because the resolution required with the low gain channel on this instrument could potentially become saturated on the high end. Ideally, the high gain channel will not be needed, but to ensure good data can always be produced, two channels were implemented.

In order to meet the data requirements for the science data described here, a simultaneous measurement of all the described instruments is stored together in a data granule. A data granule for any data packet is a grouping of related simultaneous measurements. A science granule will be produced every hundredth of a second during flight, and 100 granules will be aggregated into a science packet. Thus, a science packet will be produced at a rate of 1 Hz in order to meet the telemetry requirements.

A science granule can be seen in Fig 3.3. Here a row corresponds to a 16-bit word, and the four different measurements taken from the magnetometer fill a 16-bit word each. The data produced by the SLP's ADC is 16 bits, but on-board processing accumulates and filters 2000 samples together to both cancel noise and increase the resolution. The total packet size of the science packet is 1812 bytes.

Word Number	Bit Number															
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	Mag Temperature (16 bit)															
2	Mag X-axis (16 bit)															
3	Mag Y-axis (16 bit)															
4	Mag Z-axis (16 bit)															
5	EFP VS1 (MSB 16 bit)															
6	EFP VS2 (MSB 16 bit)															
7	SLP high gain (MSB 16 bit)															
8	SLP low gain (MSB 16 bit)															
9	SLP low gain (LSB 4 bit)				SLP high gain (LSB 4 bit)				EFP VS2 (LSB 4 bit)				EFP VS1 (LSB 4 bit)			

Fig. 3.3: Science Granule Breakout

Note that the numbers in green across the top of Fig 3.3 correspond to the bit index, where 0 is the least significant bit and 15 is the most significant bit.

3.1.4 Bit Organization across Telemetry Words

As can be seen in Fig 3.3, some values exceed the 16 bit word size for this telemetry scheme. When this happens in this and all other cases in SPORT, the Least Significant bits (LSb) are taken off the end of the data field and placed later in the granule. This is illustrated in Fig 3.4 and Fig 3.5.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
E Field V1S (MSB 16 bit)															
E Field V2S (MSB 16 bit)															
Blank												VS2(2LSB)		VS1(2LSB)	

Fig. 3.4: Packed Data Example

17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2
17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2
Blank												1	0	1	0

Fig. 3.5: Broken Out Data Example

Note that in Fig 3.5 the 0 corresponds to the LSb of the entire field, and 17 is the MSb of the entire field. This scheme was used in order to stay within the 16-bit word size and limit the amount of unused packet space in the telemetry stream. Color-coding is added to such figures to quickly see which chunks of data are part of the same value.

3.1.5 SLP Sweep Packet Breakout

The SLP Sweep packet differs from the science packet in that the Langmuir probe's voltage will be swept instead of held at a DC value. The SLP will measure current at each voltage step and will collect current accordingly. As the SLP is at varying positive voltages, it will attract extra electrons accordingly and a larger current will be measured. When the SLP is at varying negative voltages, it will repel electrons and only collect those that the probe collides with as the satellite moves through the plasma. Because the satellite moves significantly faster than the plasma, the plasma can generally be considered to be stationary from the viewpoint of the satellite. In addition, because of the significant size difference of ions and electrons in the plasma, ions can be considered to be stationary relatively to the moving electrons.

The EFP will again measure the voltage difference between the spacecraft and the plasma. When the SLP is sweeping voltage, however, the spacecraft's potential will change relative to the plasma in a short amount of time. The EFP data will be invaluable to help calibrate and understand how the SLP's voltage changes the charge of the spacecraft relative to the plasma at a given sweep step.

The sweep itself will consist of 1052 steps of voltage. It starts at +2 V and decrements by 10 mV down to -3 V, then increments again to +2 V, and finally holds at +2 V for 50 steps. Each step lasts for 50 μs and allows for settling time and eight measurements taken at each step. Accordingly, there are 1052 granules of data in the SLP Sweep packet, and the packet is 10532 bytes long. A granule can be seen in Fig 3.6.

Word Number	Bit Number															
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	EFP Sweep VS1 (MSB 16 bit)															
2	EFP Sweep VS2 (MSB 16 bit)															
3	SLP high gain (MSB 16 bit)															
4	SLP low gain (MSB 16 bit)															
5	SLP low gain (LSB 4 bit)				SLP high gain (LSB 4 bit)				EFP Sweep V2S (LSB 4 bit)				EFP Sweep V1S (LSB 4 bit)			

Fig. 3.6: SLP Sweep Granule Breakout

This packet takes 1.052 seconds to create, but will only be generated once every two minutes in flight. The rest of the time the SLP and EFP will be held in DC mode.

3.1.6 Wave Packet Breakout

The Wave packet contains post Fast Fourier Transform (FFT) data from both the E-Field and Langmuir probes. The E-field probes are looked at deferentially, so there is not two sets of data for those probes. The data will come in at 200 kHz through a 2 kHz FFT to leave 16 bins of both real (I) and imaginary (Q) data for each set of instruments. This is illustrated in Fig 3.7.

<table>
<tr><th>Word Number</th><th colspan="16">Bit Number</th></tr>
<tr><th></th><th>15</th><th>14</th><th>13</th><th>12</th><th>11</th><th>10</th><th>9</th><th>8</th><th>7</th><th>6</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th><th>0</th></tr>
<tr><td>1</td><td colspan="16">EFP Bin 1 I (MSB 16 bit)</td></tr>
<tr><td>2</td><td colspan="16">EFP Bin 1 Q (MSB 16 bit)</td></tr>
<tr><td>3</td><td colspan="16">EFP Bin 2 I (MSB 16 bit)</td></tr>
<tr><td>4</td><td colspan="16">EFP Bin 2 Q (MSB 16 bit)</td></tr>
<tr><td>5</td><td colspan="16">EFP Bin 3 I (MSB 16 bit)</td></tr>
<tr><td>6</td><td colspan="16">EFP Bin 3 Q (MSB 16 bit)</td></tr>
<tr><td>7</td><td colspan="16">EFP Bin 4 I (MSB 16 bit)</td></tr>
<tr><td>8</td><td colspan="16">EFP Bin 4 Q (MSB 16 bit)</td></tr>
<tr><td>9</td><td colspan="2">EFP Bin 4 Q</td><td colspan="2">EFP Bin 4 I</td><td colspan="2">EFP Bin 3 Q</td><td colspan="2">EFP Bin 3 I</td><td colspan="2">EFP Bin 2 Q</td><td colspan="2">EFP Bin 2 I</td><td colspan="2">EFP Bin 1 Q</td><td colspan="2">EFP Bin 1 I</td></tr>
<tr><td>10</td><td colspan="16">SLP Bin 1 I (MSB 16 bit)</td></tr>
<tr><td>11</td><td colspan="16">SLP Bin 1 Q (MSB 16 bit)</td></tr>
<tr><td>12</td><td colspan="16">SLP Bin 2 I (MSB 16 bit)</td></tr>
<tr><td>13</td><td colspan="16">SLP Bin 2 Q (MSB 16 bit)</td></tr>
<tr><td>14</td><td colspan="16">SLP Bin 3 I (MSB 16 bit)</td></tr>
<tr><td>15</td><td colspan="16">SLP Bin 3 Q (MSB 16 bit)</td></tr>
<tr><td>16</td><td colspan="16">SLP Bin 4 I (MSB 16 bit)</td></tr>
<tr><td>17</td><td colspan="16">SLP Bin 4 Q (MSB 16 bit)</td></tr>
<tr><td>18</td><td colspan="2">SLP Bin 4 Q</td><td colspan="2">SLP Bin 4 I</td><td colspan="2">SLP Bin 3 Q</td><td colspan="2">SLP Bin 3 I</td><td colspan="2">SLP Bin 2 Q</td><td colspan="2">SLP Bin 2 I</td><td colspan="2">SLP Bin 1 Q</td><td colspan="2">SLP Bin 1 I</td></tr>
</table>

Fig. 3.7: Wave Granule Breakout

Note that Fig 3.7 only shows a partial granule for the Wave packet. The Wave packet contains 16 bins for both SLP and EFP, so the granule is actually four times longer than what is shown in Fig 3.7. This was shortened for convenience in this document. The total packet size of the Wave packet is 1452 bytes, and is designed to be produced once every second.

3.1.7 SIP Sweep Packet Breakout

The Sweeping Impedance Probe can be thought of as a two-plate capacitor, with the boom serving as one plate, the spacecraft body as the other plate, and the plasma as the dielectric. An AC signal is created using a Numerically Controlled Oscillator (NCO) within the FPGA, that signal is routed out through the boom, and the signal is brought back into the FPGA and compared with the original AC signal. Because the plasma affects the dielectric of what can be thought of as a capacitor, differing plasma densities cause a differing impedance as seen by the AC signal. This impedance can be represented as either a pair of real and imaginary numbers in Cartesian coordinates, or a magnitude and phase that represents a vector form of the same measurement.

The phase response of a plasma looks similar to the phase response of a simple RLC circuit, as seen in Fig 3.8. As the AC signal affects the plasma, there are certain resonance frequencies that correspond to obvious changes in the phase response. The upper-hybrid frequency of the plasma occurs where the phase intercepts zero going from positive to negative. This frequency can be used to determine the absolute plasma density surrounding the spacecraft.

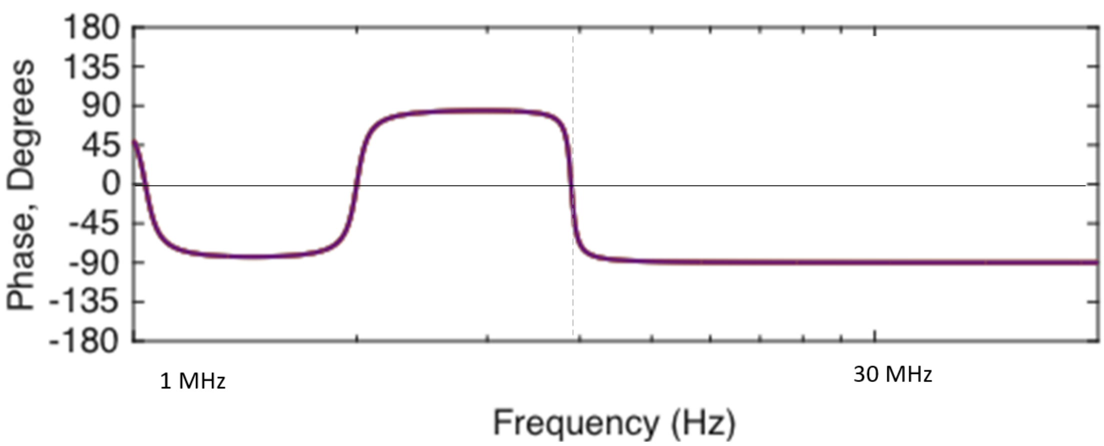


Fig. 3.8: Plasma Phase Response

The SIP Sweep packet contains both the real and imaginary, and magnitude and phase data for the difference between the generated and boom sinusoids. These are measured in 512 frequency steps from 1 MHz to 30 MHz. Each step takes 2.5 ms to settle and then take 32 measurements. The frequency sweep table to be used in flight has not yet been decided upon, and does not need to be linear as the SLP sweep is. Frequency steps can be bunched around places of interest to increase resolution and curve fitting in post processing. The packet contains 512 granules, and a granule can be seen in Fig 3.9.

Word Number	Bit Number															
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	SIP Magnitude (MSB 16 bit)															
2	SIP Phase (MSB 16 bit)															
3	SIP I (MSB 16 bit)															
4	SIP Q (MSB 16 bit)															
5	SIP Q (LSB 4 bit)				SIP I (LSB 4 bit)				SIP Phase (LSB 4 bit)				SIP Mag (LSB 4 bit)			

Fig. 3.9: SLP Sweep Granule Breakout

The total packet size of the SIP Sweep packet is 5132 bytes, takes 1.28 seconds to produce, and is designed to be produced once every two minutes.

3.1.8 SIP Track Packet Breakout

The SIP Track packet contains the frequency data of a PID controller that is tracking the upper-hybrid cutoff frequency. This is meant to be the primary mode of the SIP, and granules will be produced every 10 ms, the packet will contain 100 granules, and so the packets will be produced at a rate of 1 Hz. The granule can be seen in Fig 3.10.

Word Number	Bit Number															
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	SIP Track (MSB 16 bit)															
2	Blank				SIP Track (LSB 12 bit)											

Fig. 3.10: Track Granule Breakout

The total packet size of the SIP Track packet is 412 bytes.

3.1.9 Telemetry Flow through the Payload

The diagram in Fig 3.11 shows an overview of the payload USU is providing to the SPORT mission. All science data runs into the FPGA fabric after passing through any needed circuitry. This FPGA is the first clock domain that telemetry data passes through, and the ARM microprocessor is the second domain. Crossing this clock boundary was a major obstacle in creating a stable telemetry path. This path will be discussed more here to understand the design decisions made to reliably handle the science data.

First In First Out (FIFO) modules are used to cross this clock boundary reliably for each set of measurements. State machines were made on the FPGA to funnel all of the related data into a FIFO, which can then be accessed by the microprocessor. These FIFOs were implemented on the FPGA and corresponded to granules in the packets as the data leaves the payload. Each FIFO has empty, full, almost empty, and almost full flags that are used by both the FPGA and microprocessor to properly handshake and pass the data on to where packets are organized. For some of the data, a synch word was added to the beginning of the data pushed into the FIFO to mark the beginning of a new packet from the FPGA's count. This keeps the packets together, and allows the processor to completely fill a packet before switching modes on a given instrument.

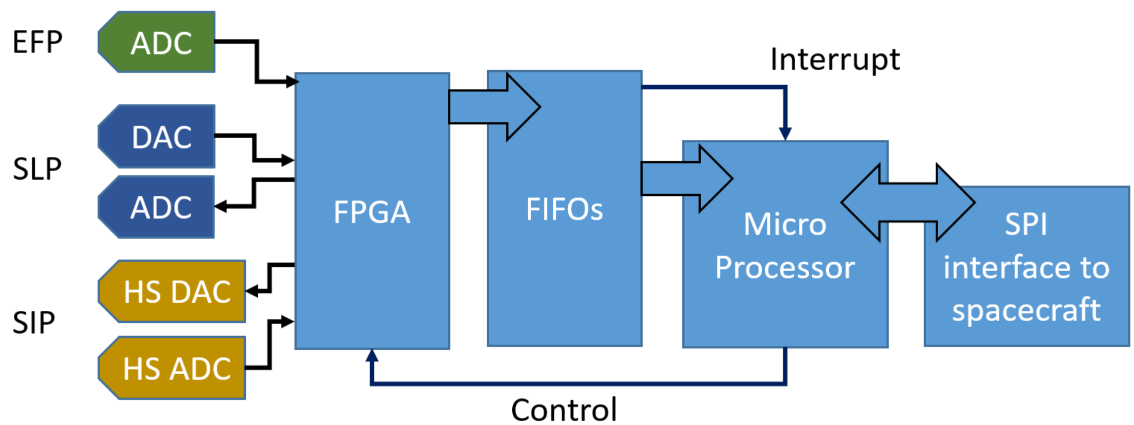


Fig. 3.11: High Level Block Diagram

The microprocessor uses these flags as interrupts, and after an initial configuration, runs a completely interrupt driven process to receive the data from the FPGA and deliver it to the flight computer. This interrupt driven microprocessor eliminated a need for real-time operating system and significantly reduced the complexity needed to organize and transmit the data.

Every time an FPGA process finishes producing a granule of data, that granule is loaded into the corresponding FIFO. The microprocessor sees that the FIFO is no longer empty and reads out a granule's worth of data from that FIFO. The microprocessor then stacks granules in an array until there are enough granules to form an entire packet. Once an entire packet is formed, a time stamped header and checksum are attached to the packet, and the packet is placed in a circular buffer before being transmitted to the flight computer.

In order to reduce the complexity of the circular buffer within the microprocessor, each packet type had its own circular buffer to hold completed packets. This took slightly more space to allocate within the microprocessor but made the process much simpler and more robust.

The interrupt driven microprocessor then raises the Packet Ready line to the flight computer when a packet was available to read out, and copies the packet into a dedicated SPI peripheral on the microprocessor. This dedicated peripheral then completes the transaction as soon the flight computer transfers of data. Once the data is read across the SPI lines into the flight computer, the checksum is recalculated to ensure no data has been corrupted during the data transfer. If it has, the flight computer would again read out the packet. Once a correct packet is read out, the flight computer raises the Acknowledge line and the microprocessor would transfer the next packet to the SPI peripheral.

3.2 Housekeeping Telemetry

This section describes how Requirement R2 is met by the implementation of a status packet.

3.2.1 Status Packet Breakout

The Status telemetry packet contains all time stamps and status information for the space weather probes. The first set of data is the Real Time Clock (RTC) data, which corresponds to the time when the packet was created. This data from the RTC has a byte allocated for each of the following time measurements: hundredths of seconds, seconds, minutes, hours, months, date, years, and day of the week. This can be seen in Fig 3.12.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
System Clock Milliseconds (32 bits)															
RTC Seconds (8 bit)								RTC Hundredths (8 bit)							
RTC Hours (24) (8 bit)								RTC Minutes (8 bit)							
RTC Months (8 bit)								RTC Date (8 bit)							
RTC Years (8 bit)								RTC Weekdays (8 bit)							

Fig. 3.12: Status Packet Time Stamp

The next section of data is the PPS clock data. This is the most recent correlated System, Real Time, and GPS data that corresponds to the last PPS signal received before the Status packet was sent. This is discussed more fully in the section on time stamping. This can be seen in Fig 3.13.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
PPS System Clock Milliseconds (32 bits)															
PPS RTC Seconds (8 bit)								PPS RTC Hundredths (8 bit)							
PPS RTC Hours (24) (8 bit)								PPS RTC Minutes (8 bit)							
PPS RTC Months (8 bit)								PPS RTC Date (8 bit)							
PPS RTC Years (8 bit)								PPS RTC Weekdays (8 bit)							
PPS GPS Week Number (16 bits)															
PPS GPS Milliseconds (32 bits)															

Fig. 3.13: Status Packet Correlated Time Stamp

The next section of data contains the housekeeping ADC measurements. Each housekeeping ADC contains a temperature sensor, and has an internal mux with four other inputs. The data field is color coded to correspond to each of the ADCs. The housekeeping ADCs monitor each of the voltages and currents of the analog and digital lines providing power to sections of the payload. Thus if a part is damaged in flight, a major deviation should be seen in the voltages or currents that will help troubleshoot remotely. This can be seen in Fig 3.14.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
5Volt (uint16)															
Pos1.8VoltA (uint16)															
Pos1.8VoltD (uint16)															
Pos4.5VoltA (uint16)															
5Curr (uint16)															
Pos1.8CurrA (uint16)															
Pos1.8CurrD (uint16)															
Pos4.5CurrA (uint16)															
LPSweep (uint16)															
Neg1.8VoltA (uint16)															
Pos3.3VoltD (uint16)															
Neg4.5VCurrA (uint16)															
Neg1.8CurrA (uint16)															
Pos3.3CurrD (uint16)															
Neg4.5VoltA (uint16)															
TempU60 (uint16)															
TempU55 (uint16)															
TempU48 (uint16)															
TempU49 (uint16)															

Fig. 3.14: Status Packet Housekeeping Data

The next set of fields contains data regarding command modes. A field indicates what current science mode the payload is operating in, when the most recent command was received, as well as a count of any command packets that did not have a valid checksum. This last mentioned field should help determine if a command was not received if it was an error in transmission, or was simply composed incorrectly. This can be seen in Fig 3.15.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Current Science Mode (uint8)								Bad Command Packet Count (uint8)							
System Clock Milliseconds at Received Science Mode Time (32 bits)															

Fig. 3.15: Status Packet Command Data

The final fields are error fields for lost data packets. If the on-board storage of the Space Weather Probes is filled with data packets ready to be sent, and more data is produced, the newest data will overwrite the oldest data in the buffers. These fields will be incremented with every overwritten packet. If an overflow ever does occur, this data should help determine what data was lost and how much was lost. There is also 16 bits of flags at the end that are used to monitor various FIFO flags and other things as needed. This can be seen in Fig 3.16.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Status Packet Count in Buffer (uint16)															
Science Packet Count in Buffer (uint16)															
SLP Sweep Packet Count in Buffer (uint16)															
SIP Sweep Packet Count in Buffer (uint16)															
Tracking Packet Count in Buffer (uint16)															
Wave Packet Count in Buffer (uint16)															
Status Packets Lost Count (uint16)															
Science Packets Lost Count (uint16)															
SLP Sweep Packets Lost Count (uint16)															
SIP Sweep Packets Lost Count (uint16)															
Tracking Packets Lost Count (uint16)															
Wave Packets Lost Count (uint16)															
Flag15	Flag14	Flag13	Flag12	Flag11	Flag10	Flag09	Flag08	Flag07	Flag06	Flag05	Flag04	Flag03	Flag02	Flag01	Flag00

Fig. 3.16: Status Packet Overflow and Flags

The total packet size of the status packet is 108 bytes, and is designed to be produced once every two minutes.

3.2.2 Telemetry Packets

Telemetry packets contain all the data sent down from the USU payload, both scientific and housekeeping. This data is tied directly with the instruments in the space weather probes. As such, each type of packet corresponds to a specific subset of data that an instrument produces. The Space Weather Instruments uses seven types of telemetry packets who's Application Identifiers (APID) can be seen in table 3.1.

Table 3.1: Telemetry APID Table

APID	Mnemonic	Description
0x020	STATUS	Health, timing, and error data
0x021	SCIENCE	Magnetometer, and DC SLP and EFP data
0x022	SLP_SWEEP	Sweep SLP and EFP data
0x023	WAVE	EFP wave power data
0x024	SIP_SWEEP	SIP sweep data
0x025	SIP_TRACK	SIP upper-hybrid frequency data
0x026	CONFIG	Echo of the configuration data

The significance of the APID field is covered more fully in the CCSDS section of this chapter.

3.3 State Commands

This section describes how Requirement R3 is met by the design of operational states and commands.

3.3.1 Operational Overview

The payload provided by USU operates in one of four states at a given time, and within each of those states, certain commands are available to control the instruments. This can be seen in Fig 3.17.

There are four operational states, Idle, Science, Calibrate, and Configure. The Space Weather Probes start in Idle mode, and from Idle, all other states can be entered. The Calibrate state is used mostly for development and testing purposes, and will not be used in orbit. The Configure state is used for uploading any new parameters to the configurable memory of the Space Weather Instruments.

The Science mode is the main mode that will be used, as it turns on and off the instruments. Each of the different instruments has different modes, which can be seen in

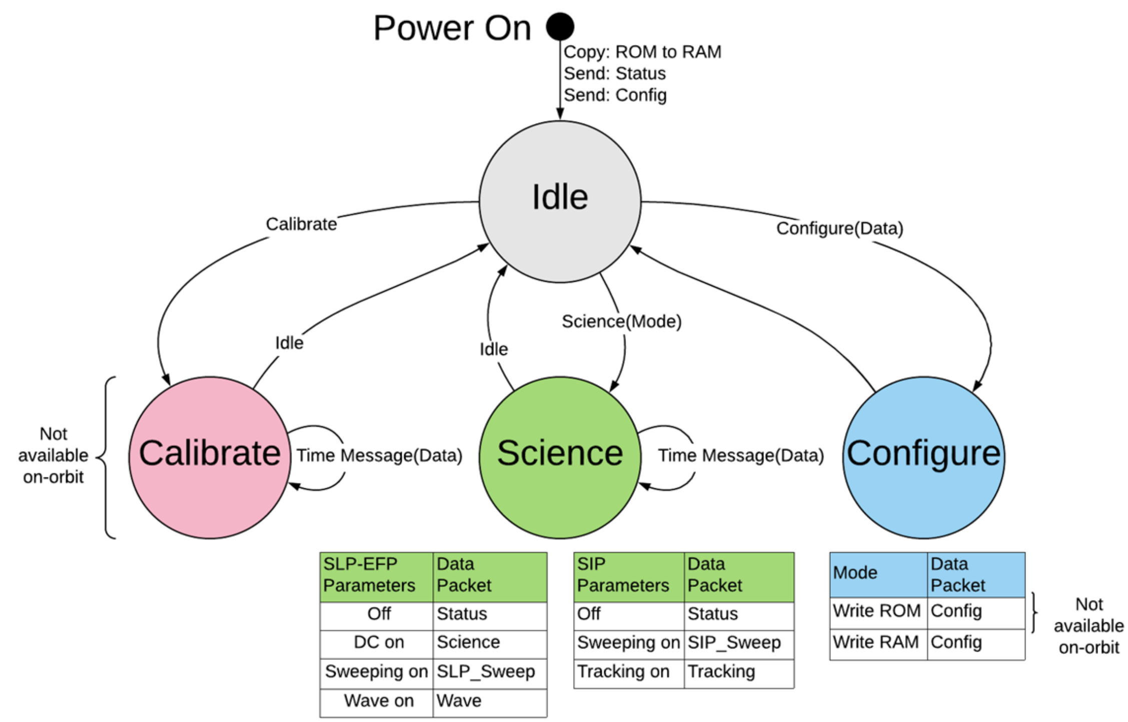


Fig. 3.17: USU Space Weather Probes Operational State Machine

the bottom of figure 3.17. These modes correspond to different packets being produced.

3.3.2 Command Packets

Command packets are the commands used to control the space weather probes. The packets are used to put the USU payload into different modes of operation as well as change various aspects of a specific mode. These packets are to be used for development and testing on the ground, calibration on the ground, as well as flight operation and adjustments.

Each command has a total length of 14 bytes (6 for the primary header, 6 for the data, and 2 for the checksum) except for the Configuration command packet. The opcode for the command is embedded in the packet header as the APID field, and a list of these can be seen in table 3.2. The data fields for packets with operands less than 6 bytes will include zeros for all unused bytes.

Table 3.2: Command APID Table

APID	Mnemonic	Description	Operand (Bytes)
0x110	SET_SCIENCE_MODE	Enter science mode	Mode(1)
0x111	SET_CONFIGURE_MODE	Set configuration	NA
0x112	SET_CALIBRATE_MODE	Enter calibration mode	NA
0x113	SET_IDLE_MODE	Enter idle mode	NA
0x114	TIME_GPS	GPS Timestamp	Time(6)
0x115	CONFIGURATION	System Config Data	Config(3200)

3.3.3 Science Mode Operand Description

The single byte operand in the science mode command packet defines each mode for each instrument. The breakout can be seen in table 3.3.

Table 3.3: Science Mode Operand Table

Bit	= 0	= 1
LSb, b0	SLP-EFP DC off	SLP-EFP DC on
b1	SLP Sweep off	SLP Sweep on
b2	Wave off	Wave on
b3	SIP Sweep off	SIP Sweep on
b4	SIP Track off	SIP Track on
b5	NA	NA
b6	NA	NA
MSb, b7	NA	NA

Thus, almost any combination of instruments can be turned on or off. If both the SLP-EFP DC and SLP Sweep are turned on, the instrument will spend most of a two-minute period producing Science packets, and produce one SLP Sweep packet. Similarly, if both the SIP Sweep and SIP Track are turned on, the instrument will spend most of a two-minute period producing Track packets, and produce one SIP Sweep packet. Note that the SLP Sweep packet cannot be turned on without the Science packet also turned on. USU expects to turn on all the instruments and their corresponding packets during flight, but instruments and packets can be turned off if needed.

3.3.4 Command Flow to the Payload

The command flow of data starts Brazilian ground station, where commands are set to be uploaded at the next available link to the satellite. A given command is received by the flight computer and sent via the SPI lines to the USU payload. Because the SPI operates in only half-duplex mode, any data transmitted to the flight computer when it is sending a command to the Space Weather Probes is disregarded and resent later. Commands are received from the flight computer by the microprocessor, and the appropriate changes are made.

3.3.5 Command SPI Timing

When the Spacecraft needs to send data to the USU Space Weather Probes, then the Spacecraft will initiate a master SPI transaction without the use of the additional pins. This is illustrated in Fig 3.18.

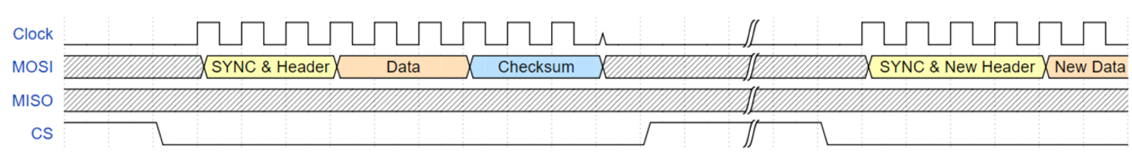


Fig. 3.18: Packet Ready and Acknowledge Pin Example

Command data can be sent at any time, even if the Packet Ready pin is high. Any data sent to the spacecraft computer during a command transaction is ignored.

3.4 Calibration Commands

This section describes how Requirement R4 is met by the implementation of calibration commands.

Calibration commands can be sent to the Space Weather Probes while in the Calibration mode. These commands contain information that adjusts values found in a register file on the FPGA. This register file is referenced in different parts of the state machines that control the data handling and processing. The register file is created so that more can be added and referenced when needed, and the values can be altered without re-flashing the FPGA. A description of the current register file values can be seen in Fig 3.19.

Address (Decimal)	Address (Hex)	Data Name	Data Width (bits)	Data Value	Comments
0	0x0000	Skip_DC	8	0	DC doesn't skip any samples
1	0x0001	Skip_Sweep	8	2	Sweep skips the first two always
2	0x0002	Sum_DC	16	2000	DC averages 2000 samples
3	0x0003	Sum_Sweep	16	8	Sweep averages 8 samples
4	0x0004	Shift_DC	3	0	Gather and mask uses this to decide which bits to save (0 corresponds to taking the lowest bits)
5	0x0005	Shift_Sweep	3	0	Gather and mask uses this to decide which bits to save (0 corresponds to taking the lowest bits)
6	0x0006	Increment	1	1	Increment can be changed to zero for calibration purposes
7	0x0007	Sweep_Set	16	0	Should be able to set the value - used for calibration
8	0x0008	Manual_Mode	1	0	Manual mode is 1 for calibration

Fig. 3.19: Register File Values and Description

These commands that alter the values in the register file, or in some cases only alter local variables within the microprocessor can be seen in Fig 3.20.

APID	Mnemonic	Description	Operand
Calibration Control (0x12)			
0x120	SET_SLP_SWEEP_STEP	Sets the SLP level, sweep or DC	2 Bytes
0x121	SET_STATUS_TIMING	Sets the generation time of Status Packets	2 Bytes
0x122	SET_SKIP_SUM_SHIFT_SLP_DC	Sets the Skip, Sum, and Shift values for the SLP DC mode	5 Bytes (2 Skip, 2 Sum, 1 Shift)
0x123	SET_SKIP_SUM_SHIFT_SLP_SWEEP	Sets the Skip, Sum, and Shift values for the SLP Sweep mode	5 Bytes (2 Skip, 2 Sum, 1 Shift)

Fig. 3.20: Calibration Commands

These commands are intended only for testing and calibration, and the ability to enter the calibration mode and sending calibration commands will be removed from the software before flight.

3.5 Configuration Commands

This section describes how Requirement R5 is met by the implementation of configuration commands.

Configuration commands can be sent to the Space Weather Probes while in the Idle mode. These commands contain the sweep tables for both the Langmuir and Impedance probes. A figure of the Configuration command packet can be seen in Fig 3.21.

<table>
<tr><th>Address</th><th>15</th><th>14</th><th>13</th><th>12</th><th>11</th><th>10</th><th>9</th><th>8</th><th>7</th><th>6</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th><th>0</th></tr>
<tr><td>0x0000</td><td colspan="3">Packet Version Number</td><td>Pac. Type</td><td>Sec. Hdr. Flag</td><td colspan="11">Application Process Identifier (See APID sheet)</td></tr>
<tr><td>0x0002</td><td colspan="2">Sequence Flags</td><td colspan="14">Packet Sequence Count or Packet Name</td></tr>
<tr><td>0x0004</td><td colspan="16">Packet Data Length</td></tr>
<tr><td>0x0006</td><td colspan="16" rowspan="3">1052 SLP Sweep Steps</td></tr>
<tr><td>...</td></tr>
<tr><td>0x083C</td></tr>
<tr><td>0x083E</td><td colspan="16" rowspan="3">512 SIP Sweep Steps</td></tr>
<tr><td>...</td></tr>
<tr><td>0x103C</td></tr>
<tr><td>0x103E</td><td colspan="16" rowspan="3">Magnetometer Configuration</td></tr>
<tr><td>...</td></tr>
<tr><td>0x105A</td></tr>
<tr><td>0x105C</td><td colspan="16" rowspan="3">Config Memory Data</td></tr>
<tr><td>...</td></tr>
<tr><td>0x1068</td></tr>
<tr><td>0x106A</td><td colspan="16">CheckSum</td></tr>
</table>

Fig. 3.21: Configuration Command

The SLP Sweep Steps referenced in Fig 3.21 are further outlined in Fig 3.22. Each step is a 16-bit value, and 1052 steps create the entire SLP Sweep table. This amounts to 2104 bytes of data.

<table>
<tr><th rowspan="2">Word Number</th><th colspan="16">Bit Number</th></tr>
<tr><th>15</th><th>14</th><th>13</th><th>12</th><th>11</th><th>10</th><th>9</th><th>8</th><th>7</th><th>6</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th><th>0</th></tr>
<tr><td>1</td><td colspan="16">SLP Sweep Step</td></tr>
</table>

Fig. 3.22: Configuration SLP Sweep Step

The SIP Sweep Steps are further outlined in Fig 3.23. Each step is a 28-bit value, and 512 steps create the entire SLP Sweep table. This amounts to 2048 bytes of data.

Word Number	Bit Number															
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	SIP Sweep Step (MSB 16 bit)															
2	Blank				SIP Sweep Step (LSB 12 bit)											

Fig. 3.23: Configuration SIP Sweep Step

The Config Memory Data is further outlined in Fig 3.24. This is an organized version of the data that can be changed in the Calibrate mode. This data amounts to 14 bytes of data.

Word Number	Bit Number															
	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	Skip Sweep								Skip DC							
2	Sum DC															
3	Sum Sweep															
4	Shift DC															
5	Shift Sweep															
6	Incrememnt															
7	Sweep Step															

Fig. 3.24: Config Memory Data

Similar to the register file mentioned in the Calibration section, both sweep tables are stored in RAM blocks on the FPGA. The SLP Sweep table consists of a RAM block that is 16 bits wide and has a depth of 1052. The SIP Sweep table consists of a RAM block that is 28 bits wide and has a depth of 512. The RAM blocks for both sweeps are filled with default sweep data upon booting, but this configuration packet will overwrite the RAM data. This packet can be used in flight to adjust the outlined data, but thorough testing might fine-tune the configurations so that the default is what is needed.

The Configuration Command packet is 4204 bytes long in total.

3.5.1 Magnetometer

The magnetometer configuration section is 30 bytes of data that is loaded into the magnetometer on boot-up. The magnetometer is capable of measuring the magnetic field in three axis as well as a temperature measurement. The magnetometer has built-in functionality to be over-sampled then filtered to achieve the desired resolution and frequency. The operational mode chosen for the magnetometer for this mission is the single measurement mode. This allows the FPGA to trigger a measurement when a new measurement is needed, so the data demand will never become out of sink with the supply. This was decided to be the most robust way of getting the measurements.

3.6 Time Stamping Data

This section describes how Requirement R6 is met by the implementation of a time stamping scheme.

3.6.1 Need for Multiple Clocks

Exact time stamping is needed to relate science data together and locate where the data was taken. A failure of good time stamping can result in confusing or even useless data because it cannot be accurately placed in reference to anything else.

The simplest time stamping can be implemented using a counter on an FPGA. This counter can roll over, but provides a simple and reliable way to organize data. This counter is internal, and so can be thoroughly tested and has no dependents besides the FPGA itself. This counter is implemented on the Space Weather Probes and is referred to as the System Clock. The issues with such a clock is that it needs to be correlated with a more accurate and universal time, such as GPS time. In addition, a power cycle will reset the counter, which could prove difficult in ordering power-cycled timestamps.

GPS time is accurate, common, and does not reset upon a power cycle. The SPORT mission does contain a GPS receiver, but creating the time stamping system entirely dependant on another organization's subsystem is a poor design. The GPS time can be correlated with the System Clock for a complete solution, but if the GPS fails, the System Clock would not be sufficient for time stamping.

The Space Weather Probes were designed to have both a System Clock, receive GPS time data, and uses a Real Time Clock chip to complete a robust time stamping scheme. This RTC has a backup power source in case of power cycling, can be used to help place when a System Clock rollover occurs, and is an acceptable but inferior backup in case the GPS fails.

3.6.2 Coordination of Time Stamping Sources

The System Clock is a one millisecond 32-bit counter that resides on the FPGA fabric. The System Clock is the way all data is timestamped before it is transmitted from the Space Weather Probes. This reference is subject to clock drift and does not record the time passage while powered down. The GPS time does not drift, and is used for the gold standard of time. The Real Time Clock data can be used as a local record of any time the payload spends in an unpowered state. The System Clock data can be corrected in post-processing to account for clock drift by capturing the System Clock value when a GPS value is sent. This coordination is stored in each Status Packet that is sent. The way these time stamps are presented in the telemetry is shown in Fig 3.25.

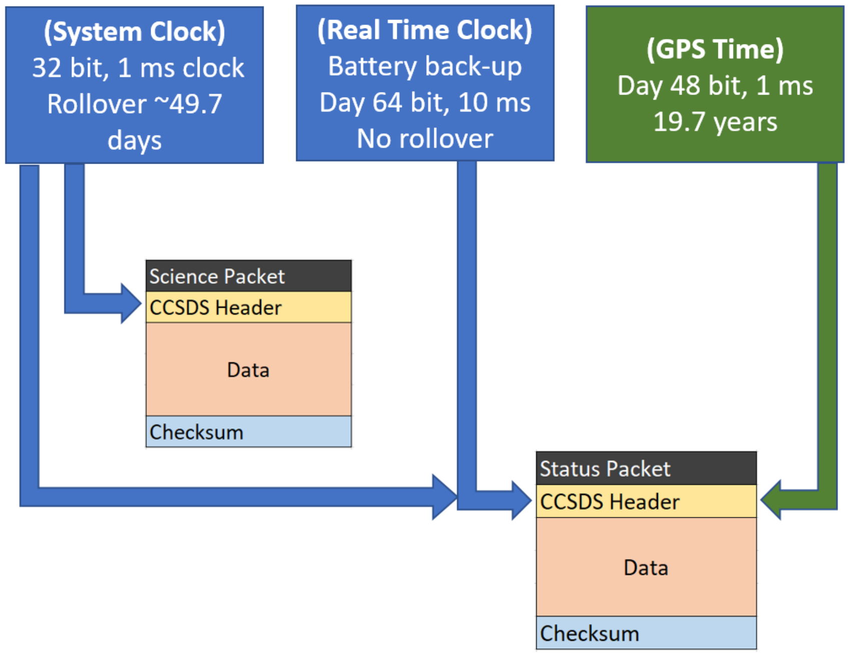


Fig. 3.25: Time Stamping of Telemetry Packets

The system clock is most convenient and is used in all telemetry packets, while the RTC and GPS time is coordinated within the Status packet for clock correction later.

These three time stamping systems provide redundancy for stitching the data back together on the ground. Once the data is corrected, it will be shared with the other payload providers to properly analyze answer the overarching science questions.

3.6.3 GPS Command Packets

All command packets listed in table 3.2 will be directly sent from Brazil's ground station except for the TIME_GPS packet. This packet will be relayed through the flight computer from another payload in the SPORT mission. To ensure accurate time stamping of the received GPS time, a Pulse Per Second (PPS) signal will also be employed in order to match the TIME_GPS packet with the local time stamp. Fig 3.26 shows the window that a TIME_GPS packet can be accepted in relation to the PPS signal.

The figure 3.26 shows that after a PPS signal is received, there is a window of 900 ms

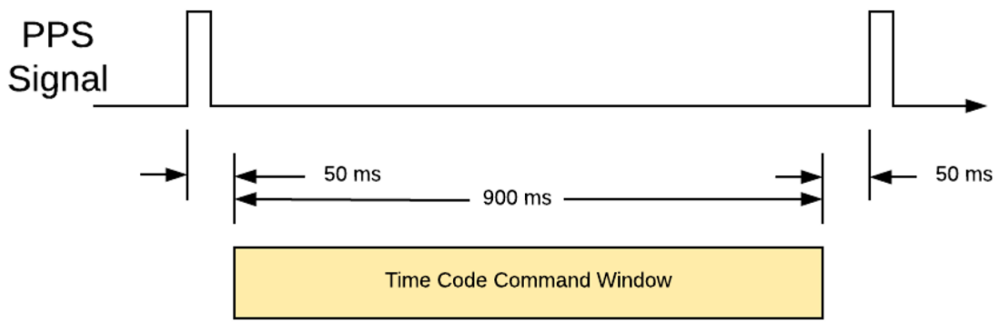


Fig. 3.26: Time Command Synchronization with the PPS signal

after that a valid TIME_GPS packet can be received and paired with the local time stamp that occurred on the PPS signal. This functions effectively as a beep, and then "The time at the beep was ____".

3.7 CCSDS Protocol

This section describes how Requirement R7 is met by the implementation of a CCSDS packet protocol.

3.7.1 General Telemetry Breakout

The general telemetry packet as used in USU's portion of the SPORT mission is formatted as seen in Fig 3.27. First a 6-byte CCSDS primary header. Second a 4-byte CCSDS secondary header (timestamp). Third, a series of N "granules" with a certain set of data. Forth, a two-byte Fletcher checksum.

Address	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0x0000	Packet Version Number			Pac. Type	Sec. Hdr. Flag	Application Process Identifier (See APID sheet)										
0x0002	Sequence Flags		Packet Sequence Count or Packet Name													
0x0004	Packet Data Length															
0x0006	System Clock Milliseconds (32 bits)															
0x0008																
0x000A	Granule 1															
0x000A + (1* granule size)	Granules 2 through N-1															
0x000A + (N - 1 * granule size)	Granule N															
0x000A + (N * granule size)	CheckSum															

Fig. 3.27: General Telemetry Breakout

As can be seen in the first row of Fig 3.27, a 16-bit word size was chosen for the command and telemetry packets used for SPORT. This was because many of the fields needed for the telemetry needs were 16 bits wide. This was a choice made early in the design process and has affected many of the details of the data system.

The fields in the CCSDS header are described as follows:

Packet Version Number The current CCSDS SPP version number is 000.

Packet Type This field distinguishes packets as either telemetry (from the spacecraft) or telecommand (to the spacecraft). 0 indicates telemetry while 1 indicates telecommand.

Secondary Header Flag This field indicates the presence of a secondary header if 1, or 0 indicates no secondary header.

Application Process ID Opcode for commands or telemetry (see APID Tables 3.1 and 3.2) .

Sequence Flags This field indicates that the user data is segmented across multiple space packets. All packets for the instrument will be unsegmented (indicated by 11).

Packet Count The count of this type of packet. Each different type of telemetry data has its own count that is unique for that particular type.

Packet Data Length The length is the offset of the last byte of the packet. This length does not include the Primary Header, but it does include the Secondary Header length in the count.

The system clock was chosen to be a 32-bit millisecond counter kept locally on the FPGA of the space weather probes board. The time interval was picked because most of the measurements recorded on any of the probes would take several milliseconds before the next measurement. This System Clock then, allows adequate time resolution between measurements and packets. The size of 32 bits was because it was a common size, and the counter would only roll over every 49 days. The decision to have the System Clock field in every telemetry packet was made to ease the data processing on the ground.

Finally, the decision to hold multiple measurements in the form of granules in each packet was made to reduce the overhead data for sending large amounts of packets. Most simultaneous measurements in the space weather probes consists of 10 to 20 bytes of data, and the combined header and checksum consists of 12 bytes. Because of the limited bandwidth allocated to the USU payload in SPORT, it was decided to greatly increase the data to overhead ratio as a precaution to meet the system requirements.

3.7.2 Packet Checksum

Each CCSDS packet has a 2-Byte Fletcher checksum as the last two bytes of the packet. The checksum serves the purpose of verification that the packet was not modified erroneously or corrupted for any other reason during transmission. This well-known checksum was also used in legacy missions to SPORT. The pseudo-code algorithm for computing the checksum is as follows:

$CK\_A = 0,\ CK\_B = 0$

$for(i = 0;\ i < n;\ i{+}{+})$

{

$CK\_A = CK\_A + Buffer[i]$

$CK\_B = CK\_B + CK\_A$

}

3.8 Database Storage

This section describes how Requirement R8 is met by the implementation of a MySQL database.

The telemetry data flow for USU's ground station can be seen in Fig 3.28.

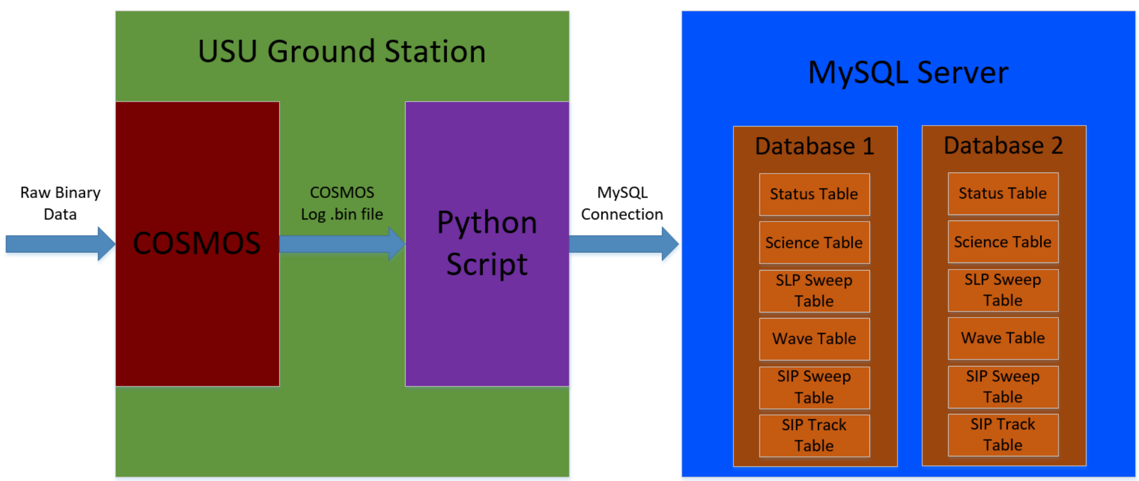


Fig. 3.28: Data Flow Diagram for Space Weather Probe Development

The diagram seen in Fig 3.28 shows how the data received from the operations ground station gets processed and stored for USU. The raw binary data flows into the USU Ground Station through a TCP/IP connection as raw binary data. This data is processed through

The indicators L0, L1, and L2 at the top of Fig 3.28 correspond to levels of telemetry.

Level 0 data (L0) is the raw data received. This L0 data is stored as in a raw binary format. This data can then be later streamed back through the ground station for processing. Level 0.5 data (not shown) corresponds to data that has been fully reassembled and timestamped. The goal of this data is to be ready to be combined with the ancillary data in order to give full context for each data point, and once it is combined, it is considered Level 1 data. The binary values from Level 0 will be reassembled and converted into the corresponding voltages and currents for the Level 1 data, corresponding to the requirements found in Table 2.2. Finally, the data will be processed from currents and voltages into the plasma parameters found in Table 2.1, corresponding to Level 2 data.

3.8.1 Telemetry Path

This section provides details and explanations for the choices made in the command and telemetry path for the SPORT mission.

The flight computer handles the storage and transfer of data to a ground station and the data is received at USU's ground station computer via a TCP/IP socket connection. This connection pipes the data into COSMOS, an open source software developed by Ball Aerospace for command and telemetry control. COSMOS records data to binary log files, which are then parsed using a Python script to convert and store the data in a local MySQL database. This can be seen in the diagram in Fig 3.29.

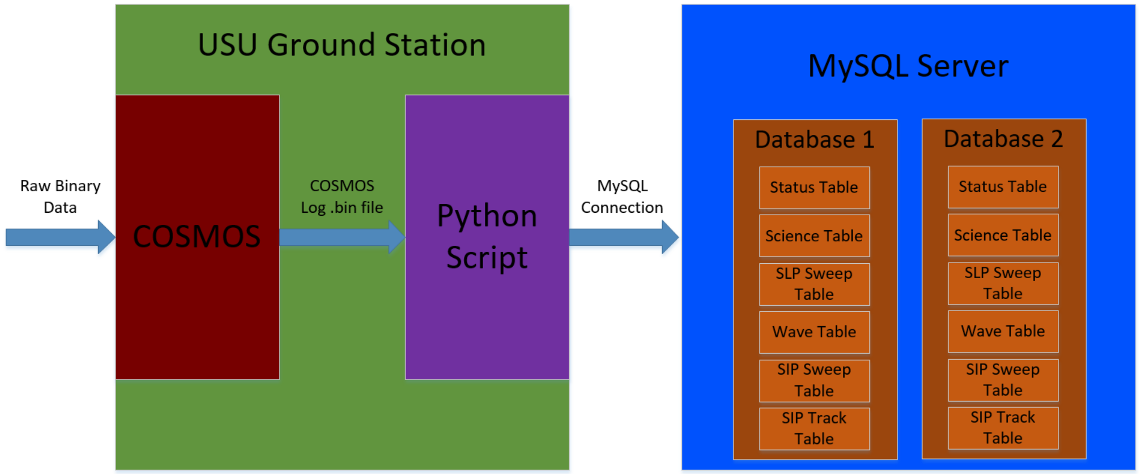


Fig. 3.29: Data Flow Diagram for Space Weather Probe Development

The MySQL server is setup so that each set of data is stored in a different database. Each database contains a table for each type of telemetry packet. This design is shown in Fig 3.29, where Database 1 and Database 2 represent different sets of data that have the same structure. As many databases will be created as needed to properly store and organize the data. A reference database has been created to index the various databases within USU's MySQL server.

3.9 Telemetry Summary

Figure 3.30 provides a convenient summary for all the telemetry data produced from the Space Weather Probes.

Packet Name	Header (Bytes)	Granule (Bytes)	Number of Granules	Checksum (Bytes)	Total Packet (Bytes)	Granule Rates (Hz)	Assembly period (ms)	Interpacket Delay (ms)	Period (ms)	Bits per Second
Status	10	94	1	2	106	100	10	119990	120000	7
Science	10	18	100	2	1812	100	1000	0	1000	14496
SLP Sweep	10	10	1052	2	10532	2000	526	119474	120000	702
SIP Sweep	10	10	512	2	5132	1000	512	119488	120000	342
SIP Track	10	4	100	2	412	100	1000	0	1000	3296
Wave	10	144	10	2	1452	10	1000	0	1000	11616

Fig. 3.30: Total Telemetry Description

The total maximum telemetry stream is 30,459 bits per second, which meets the requirements for the payload.

CHAPTER 4

Testing

4.1 Clock Calibration

Three clock schemes are used on board of the Space Weather Probes, so calibration is needed to align these clocks.

4.1.1 Clocks on Boot Up

Upon boot up, the System Clock is always reset to zero. This system clock then starts counting milliseconds and continues until it rolls over or is turned off. After the system is powered on, each successive GPS timestamp is received and stored and used for time stamping. The Real Time Clock has a backup power source, so it keeps time between resets. Thus any rollover or power cycle in the System Clock can be compared with the Real Time Clock for reference.

4.1.2 Calibration Process

The GPS clock, Real Time Clock, and System Clock are all different ways of tracking and time stamping data. Every clock listed will drift differently than the others, so the GPS is picked as the gold standard and the other clocks are measured in comparison to them. The method of calibration will be discussed and then the results of calibration shown.

For calibration, all three-clock values are read in and converted into millisecond. This is imported and graphed for reference as seen in Fig 4.1.

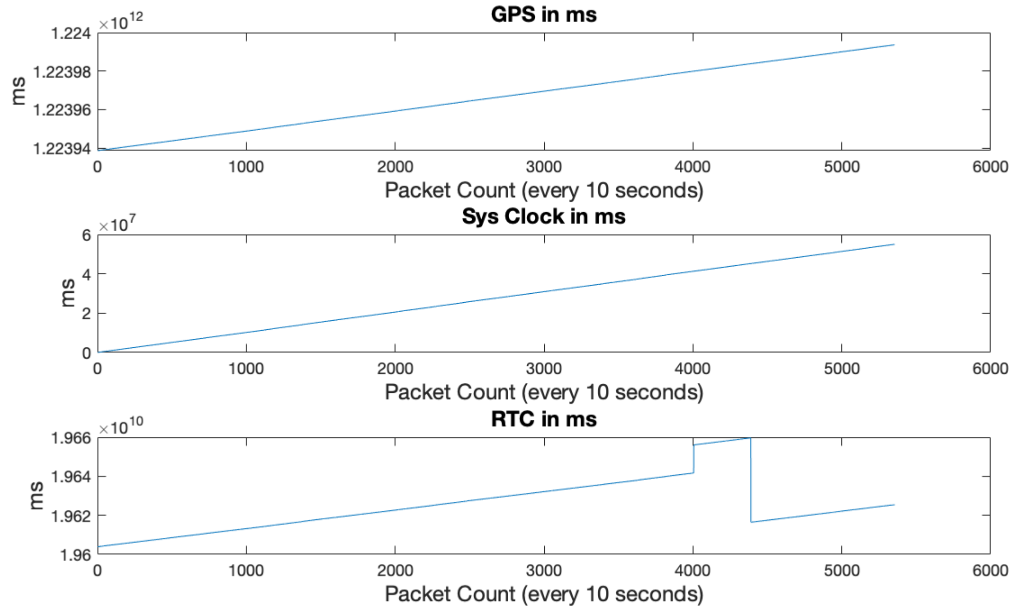


Fig. 4.1: Plots of all Clocks

In Fig 4.1 the GPS is first plotted, followed by the System Clock and the Real Time Clock. The time frame for the x-axis is approximately 14.7 hours for reference. The Real Time Clock was read in unreliably during this early calibration process, and this can be seen in the sudden jump both up and down in the graph.

Next in the calibration process, all clock schemes are set so that each starts at zero milliseconds and ticks up from there. This can be seen in Fig 4.2. The main difference is the y-axis intercept is now at the origin.

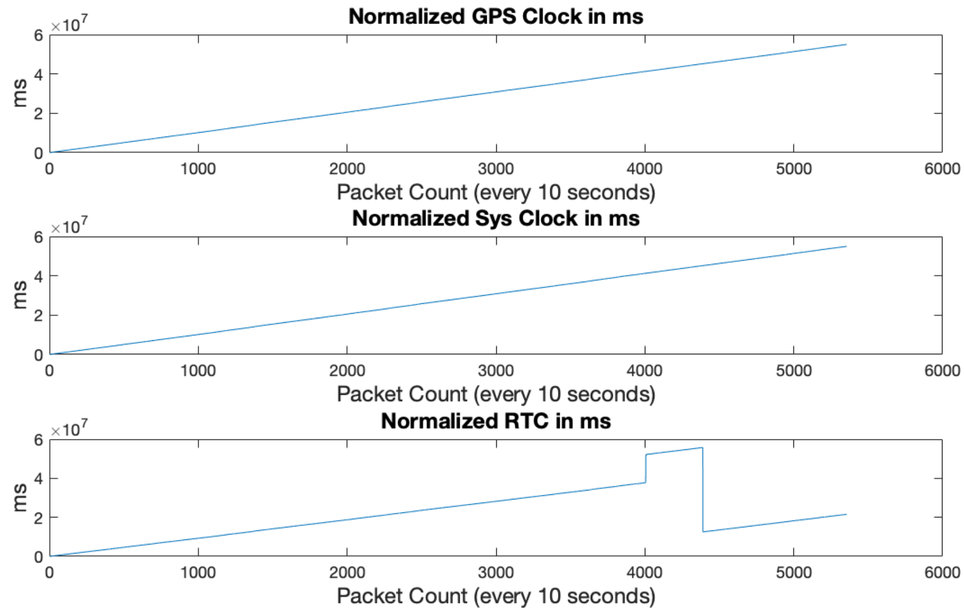


Fig. 4.2: Plots of all Clocks Starting at Zero

Finally, the values of the System Clock and the Real Time Clock have the GPS time subtracted from the other two. These can then be graphed with the x-axis be the GPS time and drift can be seen from how the System Clock and Real Time Clock differ from the x-axis. This can be seen in Fig 4.3.

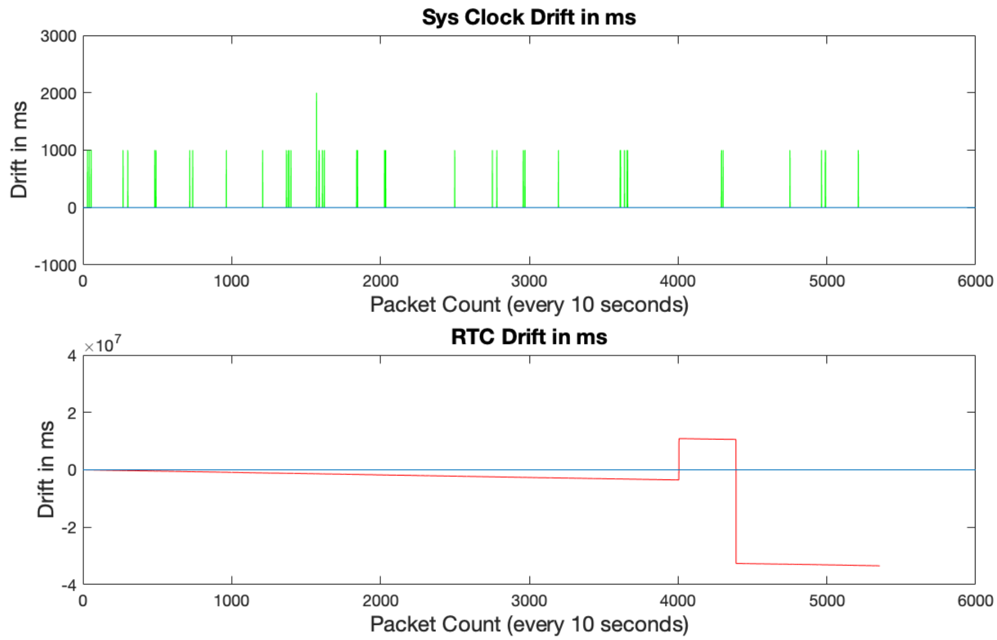


Fig. 4.3: Plots of Calibrated Clocks

Note in Fig 4.3 that the System Clock deviates from the GPS clock in 1000 millisecond spikes at times. The clock does drift slowly, but these spikes do not permanently affect the System Clock's reliability. This is thought to be a slight delay in the system when the System Clock value is retrieved.

The Real Time Clock data was incorrectly interpreted in this first calibration graph. This accounts for the significant spikes in the deviation from the real GPS data. These interpretations were post-processing issues that were addressed after this calibration session.

4.1.3 Final Calibration

Once all these issues were addressed, the most recent clock calibration results can be seen in Fig 4.4.

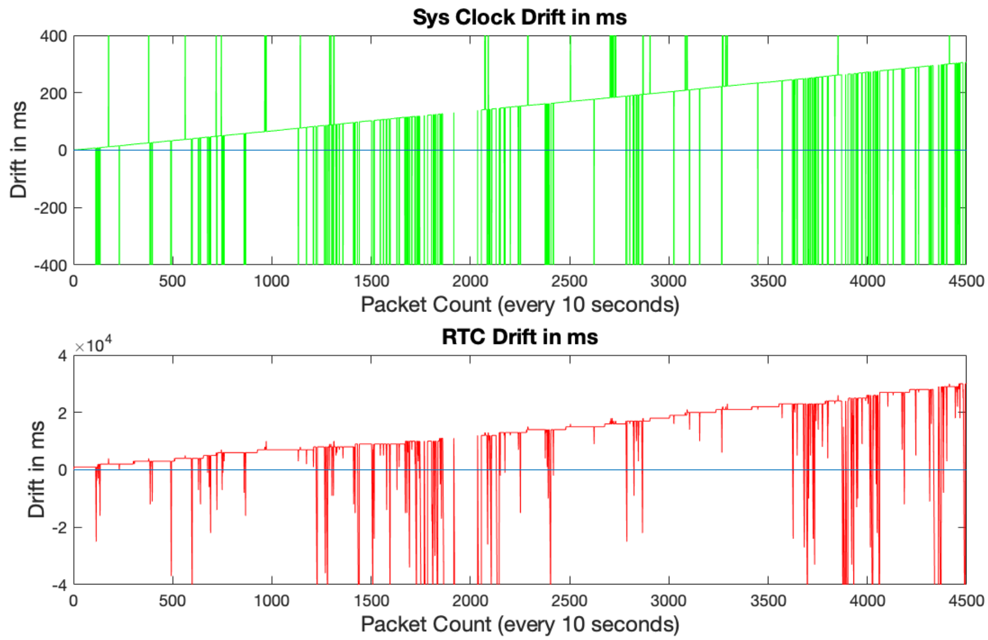


Fig. 4.4: Plots of Calibrated Clocks

Note that the scale on the System Clock y-axis is much smaller in Fig 4.4 than Fig 4.3. This newest calibration shows the clock drifting over the course of 12.5 hours of running. Both clocks show an increased number of spikes low because these plots are of how much the clocks deviate from the GPS time received. These spikes out the bottom of the plots represent a GPS packet that was not received or was not correct. The Space Weather Probes sends the most recent correlated time stamping every status packet, which is ten seconds in this calibration. When a GPS packet was not received within the 10-second time window, the next System and Real Time Clock values were sent with an old GPS value.

The drift of the System Clock is six parts per million, which translates to the 300 millisecond drift over the course of 12.5 hours as seen in the graph. The Real Time Clock shows a 66 parts per million drift, which translates to the 3000 millisecond drift over that same 12.5-hour period. It can also be noted that the System Clock has a linear drift where the Real Time Clock has a semi-linear drift. For the purposes of this application, both clock drifts are acceptable and useful. The System Clock linear drift presents an easy calibration for remapping the System Clock values to GPS time, and the Real Time Clock drifts significantly more, but is ultimately a failsafe for when the System Clock rolls over or when the instruments are shut down.

4.2 Telemetry Flow

The flow of data into and after COSMOS has gone through many iterations, and the process and decisions will be discussed here.

4.2.1 Ground Station Decisions

The SPI connection from the Space Weather Probes to the Flight Computer was well established in early design decisions. The organizations from Brazil receive the data and will get it to the ground in a usable form. From there, the scheme shown in Fig 4.5 has been developed to develop, test, and run the full payload.

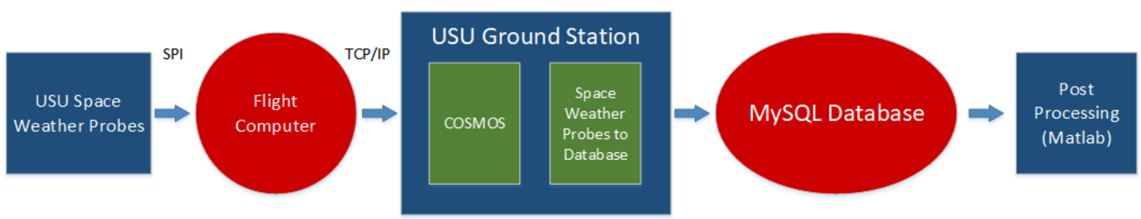


Fig. 4.5: Telemetry Flow in Detail

The decision to use a TCP/IP connection to USU's ground station was made for early convenience and development. This was chosen so that the flight computer and USU ground station only required an internet connection. This also allowed a relatively simple flight computer emulator to be created to bridge the SPI and TCP/IP connection gap for development. A Raspberry Pi was used to run a python script developed to connect GPIO pins to the Space Weather Probes and to be a preliminary test point. This emulator reads packets out of the Space Weather Probes when ready and can calculate the checksums to verify packet integrity from the payload. The development board was left producing telemetry packets for more than 50 hours early on and produced hundreds of thousands of packets without detecting a bad checksum.

The decision to use COSMOS was made quickly because it is versatile, and industry standard, and was used in SPORT's legacy missions. COSMOS allows for packet definitions so that single fields can be identified, graphed, and manipulated in real time. These capabilities were invaluable for testing of development of almost every aspect of the payload. A custom COSMOS interface was developed by another student to unpack super-commutated data for graphing purposes, as well as re-joining fields broken up over multiple 16-bit words. COSMOS also provides the ability to replay data through the system if needed.

Several GUI's were developed to make COSMOS a more intuitive experience for future operators. Those who do not understand the complexities of the command or telemetry data can use buttons and see visual representations of data for intuitive control. An example of this can be seen in Fig 4.6.

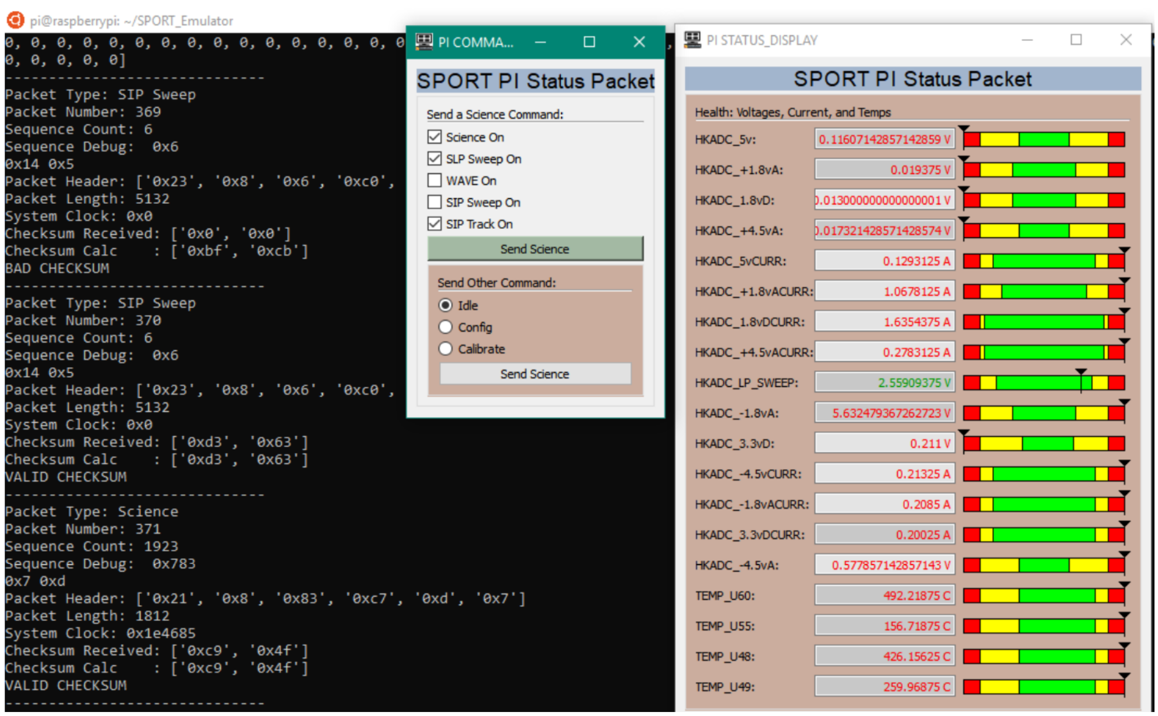


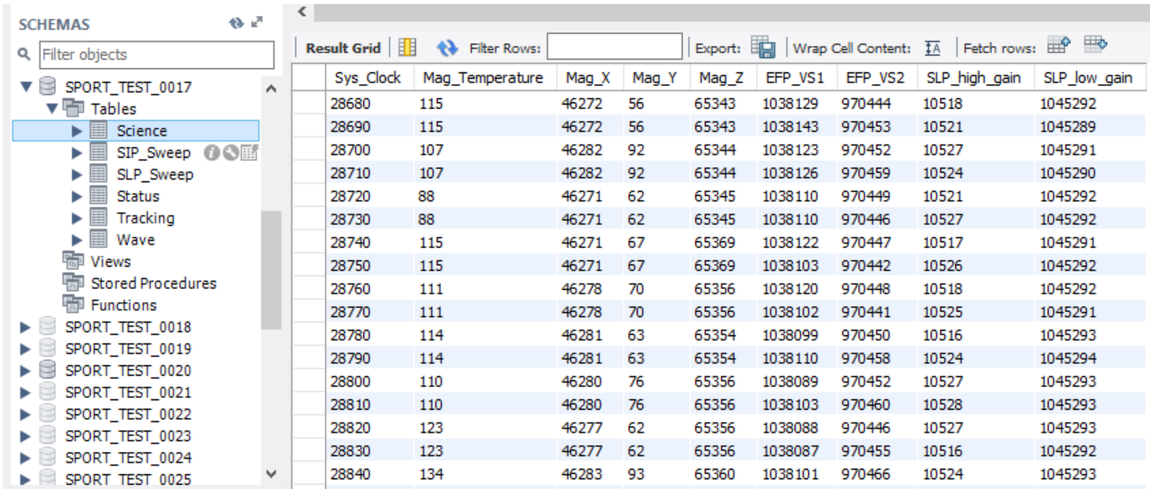
Fig. 4.6: Custom COSMOS GUIs

4.2.2 Database Decision

In choosing the specifics of the database, many options were available. The most convenient seemed to be a cloud database option such as Amazon or Google. This would be accessible from a wide variety of locations and would be backed up without any concern for hardware maintenance.

This cloud database option was pursued with Google but it was not a valid option. Connection with this database was not an issue, but the input data rate was limited. Most packets are produced once a second by the Space Weather Probes but would take many seconds to be uploaded to the database. This was tested on a local database first to ensure the method of pushing data was not the issue. Upon further inspection, there were limited operations per second with the Google Cloud option, and this was determined to be the choke point. This was a deal-breaker because any data storage must be as faster than the data production to ensure no bottlenecks. More capabilities could be purchased for a higher price, but this was not a worthwhile expenditure for this project.

The Center for Space Engineering owns and operates a local database computer in the office space, and this option had no issues uploading data in a timely manner. This is less convenient from the perspective of maintenance, but it did meet the performance criteria. Care will be taken to maintain and backup the data as the project moves forward, but these were acceptable tradeoffs to having full control of the data. A screenshot of this database can be seen in Fig 4.7.



Sys_Clock	Mag_Temperature	Mag_X	Mag_Y	Mag_Z	EFP_VS1	EFP_VS2	SLP_high_gain	SLP_low_gain
28680	115	46272	56	65343	1038129	970444	10518	1045292
28690	115	46272	56	65343	1038143	970453	10521	1045289
28700	107	46282	92	65344	1038123	970452	10527	1045291
28710	107	46282	92	65344	1038126	970459	10524	1045290
28720	88	46271	62	65345	1038110	970449	10521	1045292
28730	88	46271	62	65345	1038110	970446	10527	1045292
28740	115	46271	67	65369	1038122	970447	10517	1045291
28750	115	46271	67	65369	1038103	970442	10526	1045292
28760	111	46278	70	65356	1038120	970448	10518	1045292
28770	111	46278	70	65356	1038102	970441	10525	1045291
28780	114	46281	63	65354	1038099	970450	10516	1045293
28790	114	46281	63	65354	1038110	970458	10524	1045294
28800	110	46280	76	65356	1038089	970452	10527	1045293
28810	110	46280	76	65356	1038103	970460	10528	1045293
28820	123	46277	62	65356	1038088	970446	10527	1045293
28830	123	46277	62	65356	1038087	970455	10516	1045292
28840	134	46283	93	65360	1038101	970466	10524	1045293

Fig. 4.7: Data Storage in MySQL Database

Note that science packet data seen in Fig 4.7 no longer is tied to the original telemetry packet it was received in, but now is only timestamped with the System Clock value of when the data was taken. Each granule of data is tied to System Clock to ease analysis of the data.

4.2.3 Major Tests

The Magnetometer was tested early, but was only tested to the extent that data was seen exiting the device. Some time later the part appears to have been damaged as it stopped producing useful data. So there is no current magnetometer data set for reference.

A flatsat was held for SPORT at Goddard Space Flight Center in Maryland on November of 2018. This provided an opportunity for the engineering models of the flight computer and payloads to interface and be tested.

In anticipation of this test, the Space Weather Instruments had implemented the full telemetry capabilities expected in the payload so that the maximum data rate could be shown and tested. All telemetry packets were produced and passed through the flight computer emulator to the ground station and then the database without any bottlenecks. This test provided confidence to the maximum bandwidth was achievable.

Testing occurred at GSFC to show the USU payload could successfully interface with the Brazilian flight computer model, and could send command and receive telemetry as expected.

CHAPTER 5

Conclusion

5.1 Successes

In this thesis, the design and development of an integrated, low-power instrument controller is discussed in detail. It is considered a mature and developed design that meets the requirements for this mission.

The science and housekeeping telemetry is outlined for each type of instrument mode, and packet. The state, calibration, and configuration commands are outlined to properly control the Space Weather Probes. The time stamping scheme and CCSDS packet protocol are presented and their implementation is discussed. Finally, the storage of the telemetry is outlined, where the data will be ready for analysis and interpretation.

5.2 Suggested Improvements for Future Telemetry Schemes

5.2.1 Word Size

Early on in the SPORT project, a 16-bit word size was picked. This made sense because many data fields were exactly two bytes long. Ultimately, it would have been better to pick an 8-bit word size.

Not all of the data fields were an even 16 bits, so that meant in post processing data had to be stitched back together. This data stitching was difficult at times but once completed it did not have to be looked at again. Communicating data fields that were spread out over 16-bit words with the correct endianness proved more difficult than it was probably worth. Anytime spent debugging the telemetry scheme or communicating the telemetry to others resulted in confusing trouble shooting every time. This confusion was especially apparent in 32-bit data fields that were sent little endian with a 16-bit word system that required two sets of reorienting data to be easily read out.

5.2.2 VHDL Development and Revision Control

The students who worked on the firmware for SPORT learned most of digital design while working on this project. As such, some choices were made to expedite development rather than to make an informed project decision. Libero's SmartDesign tool helped the firmware development and visualization but was ultimately a poor choice in the end. This graphical interface would auto generate VHDL code to connect the files written by the SPORT team. This resulted in inconsistent and confusing bugs that had to be addressed multiple times during development.

Using this SmartDesign also limited revision control to include the entire project's folders and files because the auto generated code had hidden dependents that needed to be included. This resulted in difficult and painful updates to the ground station computer from development computers. Had the firmware been created exclusively in VHDL, version control pushes and pulls, and change tracking would have been far easier and resulted in more available time for development.

5.2.3 Telemetry Visualization

COSMOS was chosen early in the design phase of this project as the ground station software, but little attention was given to the visualization of data during calibration and testing. There were ways to work around the lack of flexibility in this software, but more time should be spent in future projects to understand the needs and limits of feedback in testing. This issue was addressed when a custom interface was made to the COSMOS software, but understanding and addressing this issue earlier was possible and could have informed design decisions.

5.2.4 Telemetry Stream Development

Emphasis in this project was given to producing understandable and deliverable data. This emphasis is understandable as it directly ties to the requirements of the project. This emphasis however, led to attempts to implement entire chains of data processing before verifying the data produced from ADC's and other sources. This method is understandable and worked in many cases but caused uncertainty in debugging inconsistent data streams. In future projects more attention should be focused on incremental progress that would ease troubleshooting as systems became more complex.

5.3 Summary

The phenomena of plasma bubbles have a significant impact on society by disrupting communications that pass through the ionosphere during their occurrences. The scientific community does not have a method to predict their specific occurrences, but this would have great value to society. SPORT is a project that will help scientists better understand what gives rise to radio scintillations caused by bubbles and may help us understand how to predict where and when they will occur.

In order to achieve the requirements for USU's payload, a command, control, and telemetry was implemented to adequately gather and send the data coming from the USU space weather probes. This scheme relied on several previous missions for heritage and this thesis suggests future improvements.

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APPENDICES

APPENDIX A

DVD Contents

The DVD attached to this thesis contains the following materials:

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/
├─ Documents
│  ├─ Command and Telemetry Dictionaries
│  ├─ Interface Control Document (ICD)
│  ├─ Presentations
│  │  └─ Various PowerPoint Presentations for Brazil
│  ├─ Python Scripts
│  │  └─ The scripts to take COSMOS bin files into MySQL Database
│  ├─ Sweeping Impedance Probe
│  │  └─ The PowerPoint and resources detailing the decisions made for the SIP
│  └─ Sweeping Langmuir Probe
│     └─ The PowerPoint and resources detailing the decisions made for the SLP
├─ Matlab
│  ├─ Scripts to do various data processing for Science and Status data
│  └─ .csv files containing the data for the Clock Calibration plots
└─ Thesis
   ├─ Thesis resources in the form of PowerPoints presented at PDR and CDR
   ├─ Thesis proposal material
   └─ LateX Directory
      └─ All LateX and image files for the thesis
```