Virginia Tech Ionospheric Scintillation Measurement Mission

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Abstract. The Virginia Tech Ionospheric Scintillation Measurement Mission (VTISMM) is a small spacecraft design, build, and fly project being funded by the Air Force Research Laboratory, the Defense Advanced Research Projects Agency, and NASA's Goddard Space Flight Center. The mission concept includes one 10 kg spacecraft that will fly in formation with two similar satellites being built by students at Utah State University and the University of Washington. The three satellites will fly in close proximity, using GPS receivers for position determination, microsensors for attitude determination, interlink communications for data transmission and relative position determination, microthrusters and differential drag for formation-keeping, and GlobalStar for telemetry, tracking, and commanding. The three satellites will share two ground stations to be located at Utah State and Virginia Tech. The VTISMM science mission focuses on collecting and analyzing GPS data to characterize ionospheric scintillation effects on the communications signals, and all three satellites will operate probes for collecting additional data about the ionosphere. The three-satellite formation is called the Ionosphere Observation Nanosatellite Formation (ION-F), and will be launched on a space shuttle via the Shuttle Hitchhiker Experiment Launch System (SHELS).

Introduction

In Summer 1998, the Air Force Research Laboratory (AFRL) announced the University Nanosatellite Program[22] as part of the TechSat21 Program[21]. The Virginia Tech Ionospheric Scintillation Measurement Mission[9] (VTISMM) is Virginia Tech's contribution to the Nanosat Program. Our original proposal was to build two nanosatellites for a simple formation-flying mission to make measurements of ionospheric scintillation effects. However, as the nanosats proposed by Utah State University (USU) and the University of Washington (UW) also make ionospheric measurements, we formed a team to develop a three-satellite formation called the Ionosphere Observation Nanosatellite Formation (ION-F). Consequently, the VTISMM design now comprises a single 10 kg satellite which will fly in formation with USUSat and UW's DawgStar[22].

The VTISMM system will be designed, built, and operated by undergraduate students in Aerospace, Computer, and Electrical Engineering, using existing and new facilities, and cooperating closely with our colleagues at Utah State University and the University of Washington. Undergraduates are participating in the project through capstone design courses and special project technical electives supervised by the principal investigators, and graduate students are integrating work on this project into their thesis research. The principal investigators have active research programs involving key aspects of the VTISMM concept, including flight dynamics, space system design, satellite communications, computer systems, power systems, and the effects of ionospheric irregularities on communications signals. These research projects are funded by the National Science Foundation, NASA, AFOSR, and industry. The VTISMM system is in the preliminary design phase, with a team of freshmen through M.S. candidates from aerospace, electrical, and computer engineering working towards a completed design in Fall 1999. This paper presents highlights of the preliminary design of the VTISMM spacecraft and ground station, as well as some aspects of its role in the larger ION-F mission.

Mission Concept

The VTISMM mission concept is illustrated in Fig. 1. The spacecraft, commonly called HokieSat, has a simple hexagonal bus design and incorporates a variety of technology demonstrations as described below. The spacecraft uses a GPS receiver both for orbit determination and for the primary science mission. In addition to an S-band transceiver system, a GlobalStar telephone is used for basic communications between the ground station and the spacecraft. An inter-satellite communications system is used for communications between HokieSat and the other two satellites in the ION-F formation.

The ION-F satellites will be launched on a shuttle mission in late 2001; we are assuming that this will be a supply mission to the International Space Station, so that the ION-F orbit will have a 51.6° inclination and an altitude of about 380 km.

HokieSat flies in a gravity-gradient stabilized orientation using a 10-meter tether configured so that the gravity and aerodynamic torques are balanced in the vertical attitude. The primary science mission is to collect the amplitude and phase of received GPS signals. These are saved in memory along with position information for later transmission to one of two ground stations to be located at Virginia Tech and Utah State University and shared by the ION-F satellites. Smaller amounts of data and telemetry can be transmitted to the Virginia Tech ground station through the GlobalStar constellation of communications satellites.

Ground station operations for VTISMM will be nearly autonomous. Software being developed at Virginia Tech regularly obtains and processes GlobalStar and VTISSM two-line element sets to determine when effective GlobalStar communications can be accomplished. Similar routines will be used to determine when effective direct space-to-ground communications can be accomplished. During each communications period, VTISMM will retrieve this information from the Virginia Tech Ground Station, and then plan the next communications passes. Telemetry and

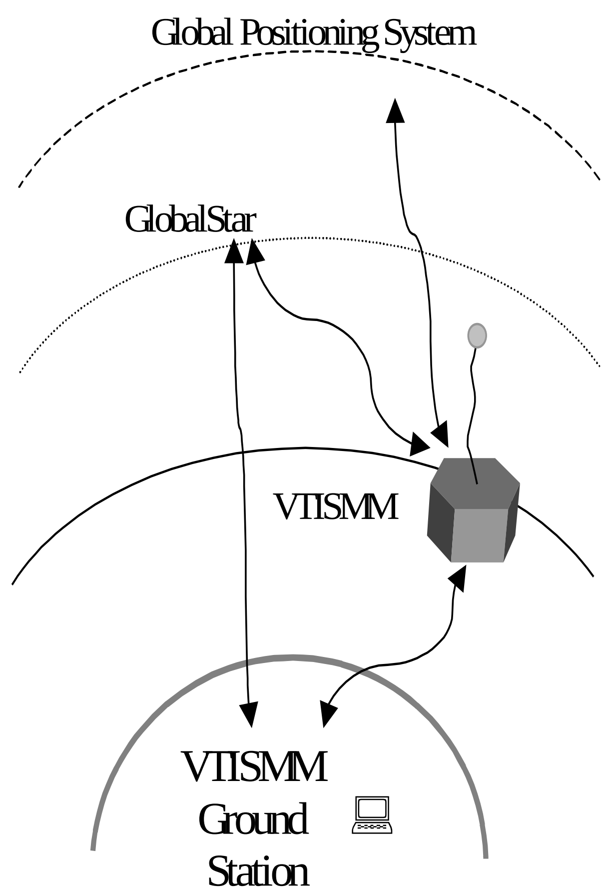

Figure 1. VTISSM Mission Concept

GPS data delivered to the Ground Station will be saved in an ASCII format suitable for publishing on the internet for access by other researchers and students. This concept will reduce operations costs, and allow validation of the operational procedures to be incorporated into student laboratory assignments.

Science Mission

The key scientific objective of this mission is to study the effect of ionospheric irregularities on GPS signals through the production of scintillations, a problem of current interest to the USAF. The equatorial and high latitude regions of the ionosphere produce significant scintillation activity in the L band. These scintillations are typically created by the production of instabilities in the ionospheric plasma. Low-Earth orbit satellites flying below the F-layer peak of the ionosphere have the potential to collect data on scintillation due to overhead irregularities, which would complement existing data on GPS occultations[24]. Investigation of these scintillations on GPS signals is important for several reasons. From a scientific standpoint, scintillation signatures may be used to infer important information about the production and evolution of ionospheric irregularities. Fundamental issues regarding radiowave propagation through the ionosphere under these conditions may also be addressed. A number of investigators are currently using GPS signals to study ionospheric irregularities[1, 2, 17]. From a practical standpoint, the effects of scintillations on the GPS navigation system itself may be investigated. The signal fading associated with scintillations introduces a real source of error that may compromise navigation with GPS.

Recently, progress has been made towards utilizing GPS receivers to study GPS signal amplitude scintillations[11, 23, 4]. In particular, the study at Cornell University[4] developed a novel modification of a commercial GPS receiver for amplitude scintillation measurements. The investigators at Virginia Tech have extensive experience in using these receivers in collaborations with Cornell University, and similar receivers are used in a new senior level Electrical Engineering course in GPS theory and design at Virginia Tech.

In addition to the ionospheric scintillation measurements, HokieSat will also include one of two instruments being developed for USUSat: the plasma impedance probe (PIP) or DC probe (DCP). These instruments measure the electron density in the ionospheric plasma. Each of the three ION-F satellites will carry a GPS receiver and one or both of these probes.

The primary scientific outcomes of this work from the student perspective are the development of spacecraft systems for collection of scintillation and electron density data, and the opportunity to analyze and contribute to understanding of the structure of the ionosphere.

Other Mission Objectives

The University Nanosatellite Program provides an excellent opportunity to incorporate space-flight experiments into university research and education programs. The VTISMM mission complements the research programs of the PIs, while providing students and faculty with an orbiting laboratory environment and useful space-flight experience. Our mission objectives are organized into three categories: educational, technological, and scientific.

Educational Objectives

- To maximize student involvement in every aspect of the project
- To enhance the space design experience
- To improve other space-related courses through lessons learned in the project

Technological Objectives

- To demonstrate a significant capability in a nanosatellite "formation"
- To demonstrate GPS orbit determination
- To demonstrate attitude determination
- To demonstrate relative position determination
- To demonstrate low-power intersatellite communications
- To demonstrate low-cost spacecraft development
- To demonstrate TT&C using GlobalStar
- To demonstrate near-autonomous mission operations

Scientific Objectives

- To collect new data relevant to ionospheric scintillation of GPS signals
- To characterize the effects of ionospheric scintillation on GPS signals

Technology Demonstrations

One of the goals of the University Nanosatellite Program is to demonstrate the use of novel technologies on small, inexpensive spacecraft, and as described above, there are several technical objectives involved in this mission. In this section we describe several of the technologies being demonstrated by VTISMM.

GlobalStar for TT&C

The idea for using GlobalStar on HokieSat originated in a NASA study[16] on using commercial communications satellites for telemetry, tracking and commanding (TT&C) on NASA's LEO satellites. The report predicted that the GlobalStar constellation could be used to provide at least 5 minutes of 9600 baud connectivity per day for satellites with altitudes less than 600 km and inclinations between 28 and 52°. However, since HokieSat will likely be at 51.6° inclination, the access time is substantially better.

The GlobalStar constellation is a 48/8/1 Walker pattern[12], with 52° inclination and 1414 km altitude[8]. The orbital period is 113 minutes, which is only slightly greater than HokieSat's expected 92-minute period. Since the satellites are nearly in the same inclination, HokieSat has many opportunities to access GlobalStar, and many of these accesses are lengthy.

Using Satellite ToolKit[19], we have completed a detailed study of GlobalStar accessibility. Over a 10-day period, GlobalStar yields an average of 97 accesses per day over 5 minutes in duration. The average duration of these accesses is 13 minutes, and there is some overlap, so that continuous coverage is not possible; however, the longest pass is nearly 40 minutes. The maximum range-rate that GlobalStar encounters for fixed terrestrial users is slightly greater than 5 km/s, whereas for satellite users, this can be substantially greater. Introducing this limitation, the number of accesses decreases to 52 accesses per day, where each pass is 5 minutes or longer, and the average pass length is almost 19 minutes. This increase in average is due to the fact that the short passes are generally those that have the higher range-rates. Thus the range-rate limitation only rules out the least useful passes.

Based on this analysis, we will be able to use GlobalStar to transmit a significant amount of data to the ground station, and we will certainly be able to transmit telemetry information on a regular basis. Similarly the relatively lower data rate for commands will be easy to handle using GlobalStar access.

Gravity-Gradient Tether

Attitude control for smaller spacecraft is especially challenging, since the hardware normally used for attitude control is massive and power-hungry. For example, Ithaco's smallest momentum wheels are >3 kg in mass and require >20 W peak power. While smaller momentum wheels are likely to be developed in the near future, they are also likely to be expensive. Thus there is some interest in a simple, inexpensive attitude control system for small satellites. Our approach is to design a small tether to provide gravity-gradient stability.

In designing a tether for this application, we must account for both the gravity gradient torque and the aerodynamic torque. The gravity gradient torque for a given deflection away from nadir-pointing increases as the length of the tether increases, since the difference between the minor axis inertia and the largest moment of inertia increases. However, the tether and its tip mass also increase the aerodynamic drag, and the resulting torque tends to act in the opposite direction as the gravity gradient torque. These torques balance at an angle usually called the torque equilibrium angle (TEA). Using a tether made of 0.4mm diameter Spectra 1000, with a 0.25 kg tip mass of 1cm diameter, the TEA can be calculated and used to select the tether length. A sample calculation is illustrated in Fig. 2, where the desired length is slightly less than 9 meters.

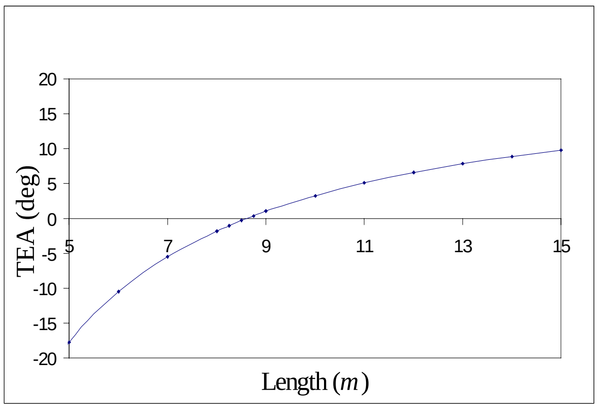

Figure 2. Torque Equilibrium Attitude

The desirable TEA is of course 0°, and it is possible to design the tether appropriately in the ideal case. However, it is impossible to know all system parameters exactly, especially the aerodynamic properties. Current efforts are directed towards determining the sensitivity of the design performance to uncertainty.

Deployment of the tether represents another design challenge. Deployment of long tethers generally uses a complicated arrangement of motors and pulleys[6] which would be too massive for a small satellite. Our design involves coiling the tether onto a conical spool, and holding it in place with a compressed soft spring and damper connected to the tip mass. Deployment will involve releasing the tip mass, with the spring supplying the deployment energy, and the damper eventually eliminating the oscillations in the spring. This approach has the disadvantage that the tether will not be retrievable should a problem occur; however, its simplicity is attractive for this nanosat mission. Another concern with use of a short tether is the "pigtail" effect where the tether remains coiled after deployment[5]. The principal impact of this effect is that it drives the minimum length of the tether for which residual coiling will not occur. We are currently evaluating various tether materials for appropriateness in this application.

The spacecraft will also include a small digital camera for imaging the tether during deployment and during the eclipse exit period of the orbit. This will provide useful data on the flexible dynamics of tether systems, including the deployment dynamics and the results of sudden thermal excitation.

Formation Flying

The University Nanosatellite Program is part of the TechSat21 Program, which focuses on the application of formation flying to a space-based radar system. Formation flying is a simple concept that has grown in interest in the past few years. While the concept is simple, many issues ranging from metrology to control algorithms complicate its implementation. The ION-F mission will demonstrate a modest level of formation of three spacecraft using dissimilar control mechanisms.

Initially, the three satellites will be deployed from the Shuttle Hitchhiker Experiment Launch System (SHELS) as a stack. Current plans are for HokieSat to be on the "bottom," DawgStar to be in the middle, and USUSat to be on the "top." After deployment of the stack, a checkout will occur of the subsystems, including GPS calibration, attitude determination, and possibly communications. After initial checkout and relative calibration, the satellites will separate. The satellites will deploy into a close formation, and the individual spacecraft performance will be characterized.

The first formation flying experiment will be to attempt to achieve a leader-follower formation. Using UW/Primex Micro-Pulsed Plasma Thrusters (μPPT's), possibly VT/Primex HAN-based Monopropellant Thrusters, and the differential drag capability of USUSat, three-satellite formation-keeping will be accomplished.

More complex formations will be attempted, such as side-by-side (same altitude but different inclination) and same ground track (NASA Goddard's "ideal" formation). The operations will include maneuvering into a new formation, and subsequent formation-keeping.

Complex three-satellite formations will be attempted. Two examples include 1) maneuvering three satellites in a leader-follower formation to three satellites with the same ground track; and 2) a rotating formation about an equidistant point.

HAN-Based Propulsion

Initially, the VT nanosat proposal did not include any propulsion capability. However, after the formation of the ION-F team, we are considering including a propulsion capability. Based on material presented at an AFRL Workshop[3], and on material provided by NASA[18], we are evaluating the use of a HAN-based propulsion system[7,15]. This is a relatively new concept using environmentally friendly monopropellants based on blends of hydroxylammonium nitrate (HAN). At present, we have identified basic propulsion system requirements, and are working with Primex Aerospace Company to determine the feasibility[14] of implementing a HAN-based system into the HokieSat design.

Other Subsystems

Attitude Determination and Control

The HokieSat attitude determination system uses a suite of sun sensors currently being designed at Virginia Tech, and one or more horizon sensors from EDO Barnes. Specific components have not yet been selected, but the Barnes Model 13-470 Earth sensor is typical. This device weighs less than 4 oz, uses 60 mW of power and provides about 1.15° accuracy. The sun sensors use one of several photodiodes that are currently under evaluation.

Structure

The HokieSat structural configuration is compatible with the USUSat and DawgStar configurations. The 3 satellites are all hexagonal, with a diameter of 18". The heights vary, and HokieSat will be approximately 12" high. The 3-satellite stack will be configured with HokieSat on the bottom, so it will require a stiffer structure than the other two satellites. Furthermore, the stack must meet launch load requirements, so that a detailed structural analysis of the stack must be completed before the individual structural designs can be finalized. However, the basic structural configuration is fixed.

All 8 structural panels (top, bottom, and 6 sides) will be fabricated of aluminum isogrid, and will be connected with screw fasteners. All 8 panels will be covered externally with multi-layer insulation (MLI) fabricated at Virginia Tech of mylar and β cloth. The actual thickness of the MLI depends on the final design of the propulsion subsystem.

Communications

The HokieSat design includes four distinct communications systems. As already described, a GlobalStar user terminal will be modified so that HokieSat can directly transmit telemetry and data to the ground station. This is a 9600 baud full-duplex system, so that commands can also be sent to HokieSat using GlobalStar. The uplink system will operate at about 400 MHz, and the downlink system will operate in the S-Band (2.2–2.4 GHz). The fourth communications system is the inter-satellite system. At the present time, we are expecting to use a system being developed by the Applied Physics Laboratory under contract with NASA. This system will also include a GPS receiver[20], which will be used for orbit determination, relative position determination, and the amplitude and frequency measurements needed for the scintillation study.

Computer

The flight processor will be the 3.3V Sharp LH77790A microcontroller version of the ARM family of processors. This 32-bit processor has low power consumption (<200 mW), and many useful features. It includes 3 UARTs and 24 user-definable I/O pins, has a large user base, and has been verified to work properly in several space products such as the MITEL GP2000 GPS receiver. The system includes 12MB of low power Flash memory and 2MB of SRAM for temporary data buffering. A Xilinx XC4010XL FPGA will facilitate communications with 5V parts, and contains the custom PCM downlink serializer. The real-time kernel will be the μCOS-II operating system, which is free but will require porting to the selected processor. The computer interfaces are described in Table 1 and Fig. 3.

Power

The power subsystem will be typical of small satellites, including body-mounted solar panels, NiCd batteries, and a simple power management system. At the time of writing, we are awaiting information from AFRL regarding the donation of high-efficiency solar cells. Detailed design of the power subsystem is delayed until the decision regarding these cells has been made.

Camera

The HokieSat camera will be on the "top" of the satellite and will be used to take sequences of photographs of the tether during periods of expected interesting tether motion, such as during deployment and during exit from eclipse. The camera we will use is the FUGA15d by IMEC. This is a 512×512 pixel addressable single chip imager with a logarithmic intensity response. Its dimensions are 4.2×3.8 cm, it is radiation tolerant up to 100kRad and has flown on space missions in the past.

Conclusions

The Virginia Tech Ionospheric Scintillation Measurement Mission is a novel, student-centered, small spacecraft project. By itself, it will demonstrate the use of GlobalStar for low data rate communications and the use of a short tether for gravity gradient stabilization. Through collaboration with Utah State University and the University of Washington on the Ionosphere Observation Nanosatellite Formation, it will also be a part of a truly unique space system demonstration involving coordinated science measurements and formation flying.

Acknowledgements

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Table 1. HokieSat Computer Interfaces

Subsystem	Interface	Controlling Device	Details
Globalstar	RS-232	Processor	9600 baud
GPS	RS-232	Processor	9600 baud
Camera	I2C	FPGA	
Tether Stepper Motor	PWM	Processor	PWM Output
Elevation/Attitude Sensor	3 Analog Inputs	MAX 186 ADC	0-5V per channel
Communication – Crosslink	RS232	Processor	4 Discrete I/O
Communication – PCM	Custom Serial Output	FPGA	4 Discrete I/O
Power Control	8 inputs	FPGA	On/Off
	8 outputs		OverCurrent
Thermal/Strain/Health	8-channel, 12-bit ADC	MAX 186 ADC	
DC Probe	1 Analog Input	MAX 186 ADC	12 bit value
Battery Monitor	1 Bidirectional I/O	Processor	DS2437
Thrusters	8 External I/O	FPGA	
Real-Time Clock	3 I/O	GPS card	For event scheduling.

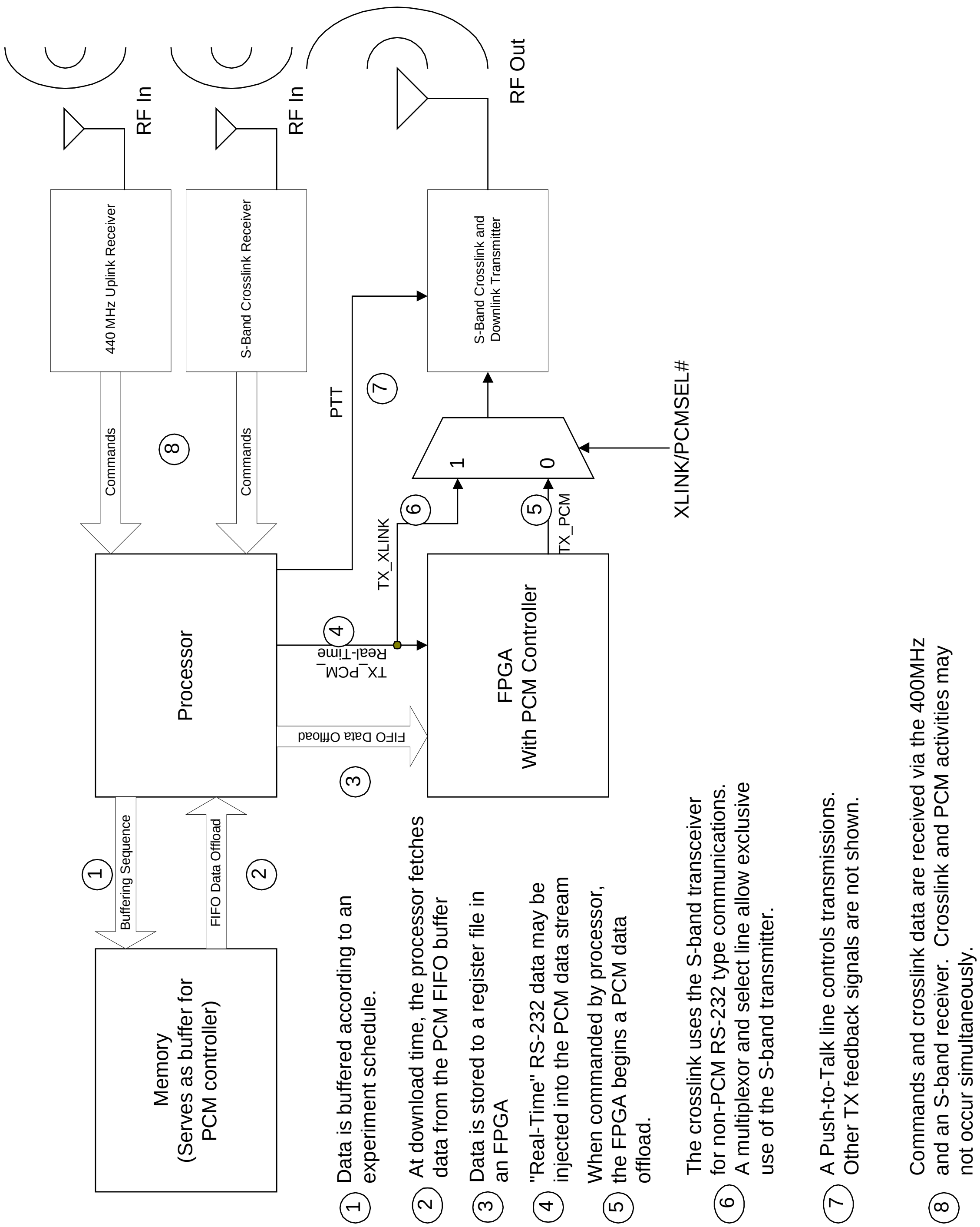

Figure 3. HokieSat Communications Block Diagram