INSPIRESAT-4 / ARCADE: A VLEO Mission for Atmospheric Temperature Measurements and Ionospheric Plasma Characterization

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Abstract

Most nano-satellite and small satellite missions are designed for 400 km or higher altitudes. This is because small satellites, with mass, volume and power constraints, have limited propulsion capabilities to counteract the high aerodynamic drag in lower altitudes. Thus little or no science data has been gathered in-situ in the altitude range of 200 to 300 km by small satellite missions. INSPIRESat-4 (IS4) Atmospheric Coupling and Dynamics Explorer (ARCADE) is a ring-deployed 27U spacecraft that aims to bridge this gap by achieving a sustained flight in the VLEO (Very Low Earth Orbit) region to make in-situ Ionospheric plasma measurements. This paper first describes the science motivation of the mission. INSPIRESat-4 carries three payloads which are AtmoLITE (a Spatial Heterodyne Interferometer for upper-atmosphere temperature measurements), CIP (Compact Ionospheric Probe) for in-situ plasma measurements and an RGB Imager for high resolution imagery from VLEO. In this paper, the mission design for the VLEO mission is described in detail including analysis conducted for orbital lifetime prediction, attitude maneuvers and power generation. The paper concludes with a brief overview of the various subsystems including Command & Data Handling (C&DH) system , Electrical Power System (EPS), Flight Software (FSW), Communication system and Attitude Determination and Control System (ADCS).

1 Introduction

The Atmospheric Coupling and Dynamics Explorer (ARCADE) small satellite mission is a Singapore-funded small satellite mission to explore the Earth's Mesosphere-lower-Thermosphere (MLT) region and for ground imaging of the tropical region from a Very Low Earth Orbit. INSPIRESat-4 (IS4) ARCADE, slated for launch in Q4 2020, is the fourth satellite in the International Satellite Program in Research and Education (INSPIRE) series of satellites. INSPIRE is a consortium of universities and research institutions across the world coming together to produce innovative space science missions. The INSPIRE program leverages on expertise from contributing universities to enable capacity building in satellite development and space science. INSPIRE also aims to train and develop future workforce in the space industry through heavy student involvement in projects. Science data generated from the INSPIRE satellites is open source and available in the public domain. IS4 is a collaboration between Nanyang Technological University in Singapore, University of Colorado at Boulder in the United States, Indian Institute of Space Science and Technology in India, National Central University in Taiwan and University of Wuppertal in Germany. INSPIRESat-4 carries a heterodyne interferometry-based limb imager for middle atmospheric temperature measurements. The obtained temperature profiles will be used to characterize the effect of gravity waves on mean flow and global circulation. IS4 also carries the Compact Ionospheric Probe (CIP), an in-situ plasma sensor suite with heritage on FORMOSAT-5, INSPIRESat-1 and IDEASSAT. IS4 will be launched by the Polar Satellite Launch Vehicle (PSLV) rocket from Indian Space Research Organization (ISRO) into a 535 km x 450 km initial orbit with 5^o inclination. The PSLV is a dedicated launch for 8 Singaporean satellites. The key novelty in IS4 mission is maintenance of VLEO altitude (300 km or under). After a 6 month initial science mission at deployed altitude, IS4 will decrease its orbit to 300 km through a combination of passive and active means. Thereafter, a 6-month science phase at VLEO will commence with the Xe-based Hall Effect thruster being used for active orbit maintenance. The thruster provides 0.6 mN thrust with total available impulse 2500-3000 Ns.

2 Science & Payload

2.1 AtmoLITE payload

INSPIRESat-4 aims to quantify the impact of atmospheric gravity waves on variability of the ionosphere. Gravity waves are meso-scale waves that account for most of the vertical transport of energy and momentum from their sources in the atmosphere. Generating due to a variety of mechanisms in troposphere and middle atmosphere, their propagation and dissipation results in significant forcing of the large scale circulation and the thermal and constituent structures of the middle atmosphere [5]. Gravity waves are not considered in Earth climate models because the wave scales are generally smaller than the available model resolutions. Thus, em-

pirical data is key to developing an understanding of gravity wave interactions with the mean flow to develop a better understanding of global climatology. Gravity wave momentum flux and gravity wave drag can be derived from temperature profiles of the atmosphere [6]. IS4 accompolishes this by carrying AtmoLITE (Atmospheric Limb Interferometer for Temperature Exploration). AtmoLITE is a highly compact limb imager employing a monolithic spatial heterodyne interferometer for day- and night-time atmospheric temperature sounding. Atmospheric temperature profiles are obtained by limb-sounding O_2 A-band emissions at a wavelength 762 nm from LEO. AtmoLITE provides spatial and spectral information simultaneously- the dimension parallel to interferometer gratings provides vertical profile of the sounded atmosphere while the dimension perpendicular to the grating encodes the interferogram. This imposes a pointing requirement for IS4 since it is required that AtmoLITE optics be kept aligned with the horizon and the line-of-sight pointed at 110 km above the surface. AtmoLITE will measure daytime temperatures between 80-140 km altitude while nighttime measurements will be done between 85-100 km altitude. Nighttime measurements will also enable characterization of Atomic Oxygen in the upper atmosphere - the key parameter impacting the oxidative degradation for VLEO spacecraft.

2.2 CIP payload

The Compact Ionospheric Probe (CIP) is the successor to the Advanced Ionospheric Probe (AIP) aboard the FORMOSAT-5 satellite. Equipped with a sampling rate range of 1 - 1,028 Hz, the CIP is designed and fabricated to comprehensively measure pertinent ion and electron parameters to aid in the quantification and prediction of the ionospheric environment. The CIP is a plasma sensor suite consisting of Planar Langmuir probe, an Ion Trap, Ion Drift Meter, and a Retarding Potential Analyzer. CIP data would consist of ion temperature, density, composition, drift velocity, and electron temperature. CIP data will be used to study equatorial spread F and, equivalently, the Equatorial Plasma Bubbles (EPBs). In the local time sector after sunset, EPBs are essentially plasma depletions caused by nonlinear processes of the Rayleigh-Taylor instability. Each bubble scale size can span up to 5-6 orders of magnitude, with the largest scale augmenting to the order of many kilometers [9]. The smaller-scaled EPBs destructively degrade radio waves over a large range of frequencies due to diffraction [7]. This is particularly problematic for radio signals associated with Global Navigation Satellite Systems (GNSS) due to the fact that scintillation will introduce a time delay to the receiver-obtained pseudorange, thereby exacerbating positioning error [8]. CIP can be used for the observation and characterization of EPBs and thus its effects on radio communication and satellite navigation analysis. The CIP may also be employed for background ionospheric studies, specifically the ion parameter features in different local time sectors [2].

2.3 VLEO experiment

IS4 aims to demonstrate VLEO mission capability on a small satellite. Due to mass, volume and power constraints, small satellites tend to have limited propulsion options. Rapid deorbiting due to aerodynamic drag below 300 km altitude causes most of the small satellite missions to be at 400 km or higher altitudes. Also, little or no science data is gathered during the deorbiting phase due to inadequate pointing control. Currently, sounding rockets are the only chief instruments used for VLEO studies [3]. Thus, a gap exists in satellite observations below 300 km altitude. VLEO spacecraft is lucrative for Earth imaging due to the higher resolutions attainable. IS4 carries Xe-based Hall effect propulsion unit NPT-30 from ThrustMe to enable VLEO science mission. The RGB Imager carried by IS4 will offer a high-resolution imagery option from a small satellite platform in VLEO. The VLEO mission will enable in-situ measurement of ionospheric plasma parameters through CIP for a range of altitudes not typically covered by satellites. Another avenue pertaining to VLEO mission is the observation and analysis of Atomic Oxygen (O) flux and its inherent influences on spacecraft material. Atomic oxygen keenly reacts with spacecraft material leaving behind severe traces of erosion and degradation of spacecraft material properties. Hence, O data derived from AtmoLITE nighttime measurements will be invaluable for prediction models and other studies. Investigation of atomic oxygen effects will also help in development of protective coatings and hybrid materials to make spacecraft surfaces resistant to erosive effects [4]. Thus, IS4 will be a demonstration of low altitude orbit maintenance through electric propulsion that would enable in-situ ionospheric data collection and high-resolution earth observation from a smallsat platform.

3 Mission Overview

3.1 Mission summary

The INSPIRESat-4/ ARCADE mission can be summarized in following phases:

1. Launch and Early Operation (LEOP) Phase - involving post-deployment checkout of satellite bus and the payloads
2. Normal Science Phase (NSP) - 6 months science mission at the deployed altitude
3. VLEO Science Phase (VSP) - 6 months science mission at VLEO inclusive of orbit lowering to 300 km
4. Mission Termination Phase (MTP) - decommissioning and deorbiting

4 Mission Design

This section details the simulation results that were used to derive the Concept of Operations for INSPIRESat-4.

4.1 Orbital lifetime prediction

INSPIRESat-4 is expected to be deployed in a 535km x 450 km orbit. After 6 months of science observations in this orbit, it is required to lower the orbit to 300 km altitude. The orbit lowering can be done passively (relying on drag) or actively (through retrograde thruster firing). Once at 300 km, prograde thruster operation must be used to prevent rapid decay of the orbit. Thus, it is desired to save as much thruster fuel

as possible for the orbit maintenance at VLEO and so the passive orbit lowering mode is preferred. A full orbit simulation was developed taking into account the different environmental disturbances and higher order gravitational perturbations. Figure 1 shows that due to drag alone the orbit can be lowered to approx. 330 km in about 1 year time. This corresponds to orbit lowering through purely passive means.

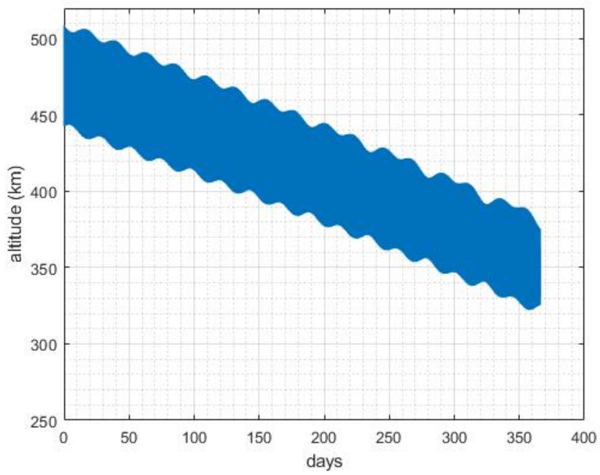

Figure 1: Simulation result showing orbit decay due to drag only with INSPIRESat-4 in nominal pointing

The effect of using thruster for orbit lowering in conjunction with drag-induced decay, viz. the hybrid approach, is also analyzed. Decay in orbit during the first 6 months of operation after deployment in 535 km x 450 km orbit is shown in figure 2. It is seen that the orbit altitude is lowered to sub-400km in 6 months due to drag alone with INSPIRESat-4 in nominal pointing. Subsequent operation of thruster can bring the orbit lower to 300 km in about 10 days of operation, as shown in figure 3. The 10 days of thruster firing will consume 20% of the total impulse available, leaving the remaining 80% for orbit maintenance at VLEO.

Further analysis is performed to evaluate if the available thruster capacity is sufficient for orbit maintenance at VLEO. It is calculated that approximately 6 months of orbit maintenance can be achieved with 80% out of 2500 Ns total impulse available. Thus, mission definition outlined in section 3.1 is deemed feasible.

4.2 Attitude Maneuvers & ADCS sizing

AtmoLITE has a stringent Line-of-Sight pointing requirement due to orientation of the interferometer gratings capturing spatial and spectral information simultaneously. CIP operation occurs in eclipse and the instrument requires ram-pointing. Orbit maintenance using thruster application requires that the thrust axis be tangential to the orbit.

Evaluation of ADCS momentum and torque requirements was done by first characterizing the disturbance environment. Spacecraft disturbance torques were simulated. Atmospheric

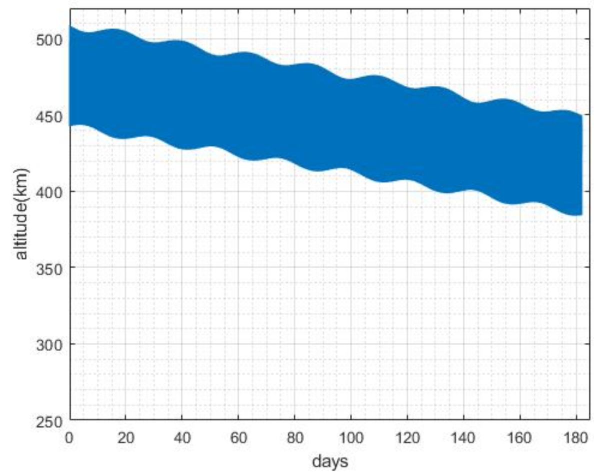

Figure 2: Simulation result showing orbit decay due to drag in first 6 months of ARCADE mission

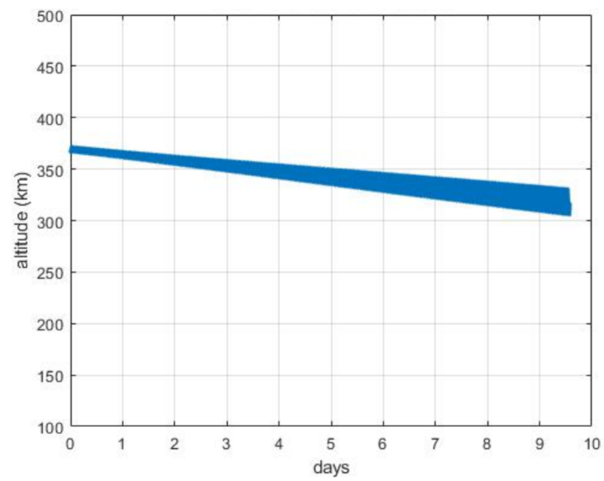

Figure 3: Simulation result showing orbit decay due to 10 days of thruster operation after first 6 months of ARCADE mission

	Requirements	IS4 capability
Pointing knowledge	0.5 arcmin	0.3 arcmin
Pointing accuracy	1 arcmin	0.4 arcmin

Table 1: ADCS requirements and capabilities in IS4

density from a scale height model was used to compute aerodynamic disturbance, International Geomagnetic Reference Model (IGRF-12) was used to model the geomagnetic field for magnetic disturbance simulation. Figure 4 shows the disturbance torque magnitudes in deployed altitude and figure 5 shows the torque contributions at VLEO. Integration of disturbance torque profiles at VLEO shows that the reaction wheels for XACT-50 will saturate in 2 orbits without any momentum dumping.

A detumbling analysis was performed to check for magnetorquer moment adequacy in stabilizing the spacecraft post

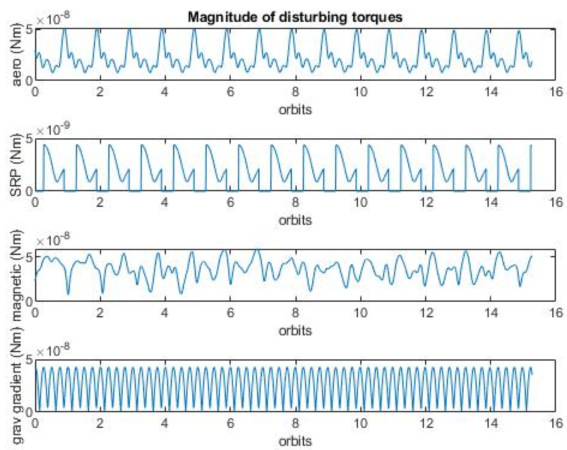

Figure 4: Magnitude of disturbance torques at 535 km x 450 km deployed altitude

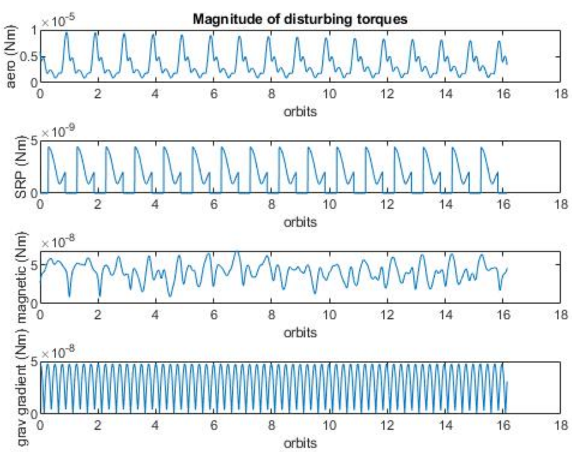

Figure 5: Magnitude of disturbance torques at 300 km VLEO

launch vehicle separation. A worse-case tip-off rate of [20,20,0] deg/s upon separation was assumed. Figure 6 shows that detumbling operation with magnetorquer moment of 0.2 Am^2 takes less than 1.5 days for stabilization using B-dot control.

Calculations for spacecraft agility show that IS4 can perform a 90 degree slew about either body axis within 20 s.

It is concluded that XACT-50 from Blue Canyon Technologies provides sufficient torque and momentum capacity to maintain attitude control within the requirements.

5 Satellite Overview

A brief overview of the various subsystems is presented in this section. Being the fourth mission in the INSPIRE series most of the subsystems will derive heritage from the previous missions. Table 2 summarizes some of the key parameters of the various subsystems of InspireSat-4.

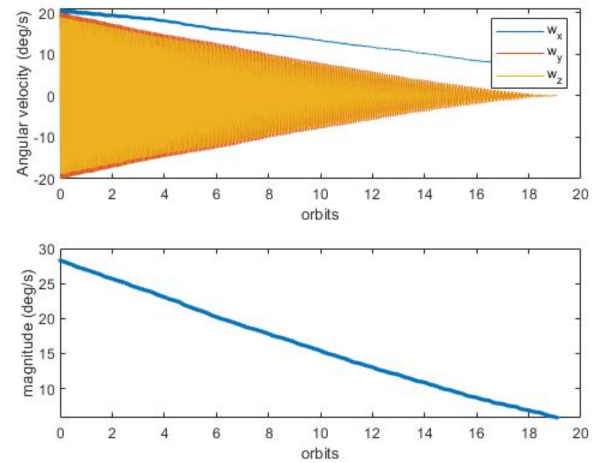

Figure 6: Simulated detumbling of IS4 using magnetorquers

Dimensions (L x W x H)	Stowed: 30 x 30 x 22.4 cm^3 Deployed: 85.6 x 49.8 x 30.4 cm^3
Mass	∼25 Kg
ADCS	BCT XACT50 - 1 x Star camera, 2 x FSS, 3 x Torque rods, 1 x 3-axis Magnetometer, 3 x Reaction Wheels, 1 x GPS
EPS	3 deployable, 1 body mounted solar panels, 85 W power generated 2s2p Li-ion battery configuration, 13.6 Ah @ 7.2 V
C&DH	Microsemi SoC FPGA , 2 - 128Gb SD Cards
TT&C	9600 bps UHF 2GPSK TMTC 1 Mbps S-band QPSK Transmitter
Payloads	AtmoLITE Limb Sounder RGB Imager Compact Ionospheric Probe
Launch Adapter	IBL-230 for PSLV

Table 2: Summary of INSPIRESat - 4 Subsystems

5.1 Command and Data Handling System (C&DH)

The C&DH board is custom built, using the low power COTS (commercial-off-the shelf) component, Microsemi SmartFusion2 SoC (System on Chip) FPGA. The SoC houses an ARM Cortex-M3 Processor along with programmable logic elements . The C&DH is responsible for interfacing with the various subsystems which includes sending commands as well as collecting science and housekeeping data. Figure 7 shows the electrical interfaces of the C&DH with the other subsystems. The C&DH also provides the platform to run the flight software which will be discussed subsequently.

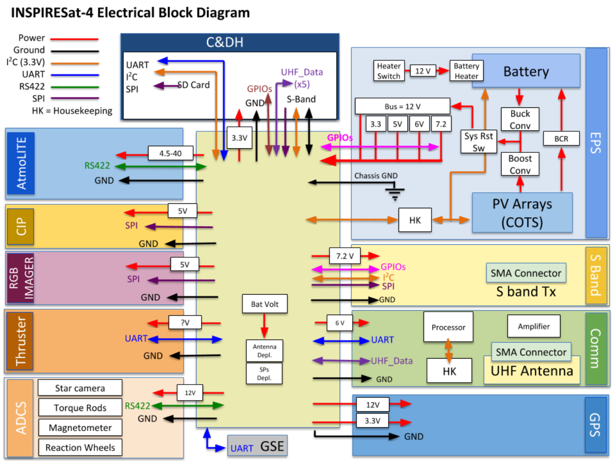

Figure 7: Electrical Block Diagram

5.2 Electrical Power System (EPS)

Considering the high power requirements of the mission, the EPS consists of two batteries, a primary battery and a dedicated battery for the thruster. The EPS and C&DH boards for this mission will be modified versions of the boards developed for INSPIRESat-1, shown in figure 8.

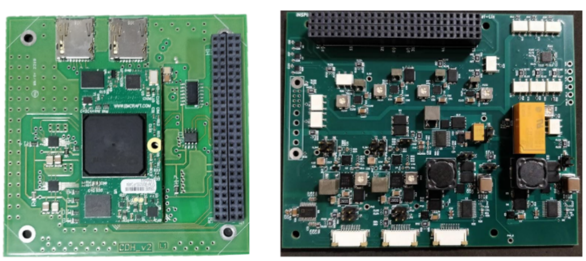

Figure 8: CDH and EPS boards developed for INSPIRESat-1

The primary battery, for the satellite bus, consists of 4 SAFT Li-ion MPS 176065 cells in a 2s2p configuration yielding a capacity of 98 Wh at 7.2 V. The primary battery is sized to provide adequate margin such that the depth of discharge during eclipse with all the subsystems running is under 30%. The secondary battery consists of 2 x 2s2p packs with a capacity of 196 Wh at 14.4 V. Calculations show that the secondary battery capacity is adequate for thruster operation with 30% duty cycling. The batteries are charged with 4 solar panels: 3 deployable and 1 body-mounted, each with 21 Azurespace 3G30A triple junction cells. Thus, about 85 W power is generated during sun-pointed charging mode.

5.3 Flight Software

Considering the complexity of the mission, the operation of the satellite has been divided into two phases, namely Science operation and Thruster operation. These phases are further divided into modes, between which the satellite transitions depending on the SOC (State of Charge) of the battery.

Science Operation

The phoenix mode is for critically low SOC levels. In this mode, only the critical subsystems are ON (even the ADCS is off) so that the satellite can quickly transition to the safe mode. Then when the satellite reaches the safe mode, Sun pointing is enabled to further increase SOC by charging the batteries using the solar panels.

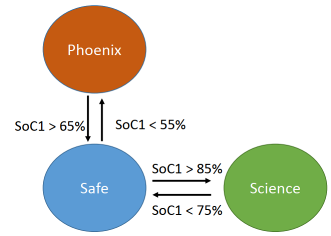

Figure 9: Modes in Science Phase (SoC1 refers to the State of Charge of the primary battery)

When the SOC crosses 85%, the satellite reaches the Science mode, where the ADCS actively orients the satellite to conduct different science measurements. These include ram pointing in eclipse for CIP, Line-of-Sight pointing for atmoLITE and Earth Pointing for the RGB Imager in VLEO.

Thruster Operation

The NPT-30 thruster from ThrustMe is operated during the VLEO part of the mission. Here two modes are used, namely Thruster Charge and Thruster Eclipse. In Thruster Charge mode the dedicated battery for the thruster is charged in sunlight. During eclipse, the satellite goes into the Thruster Eclipse mode and carries out science measurements in the VLEO region. These modes ensure that the thruster is operated only when the SOC of the thruster battery is sufficiently above a safe threshold.

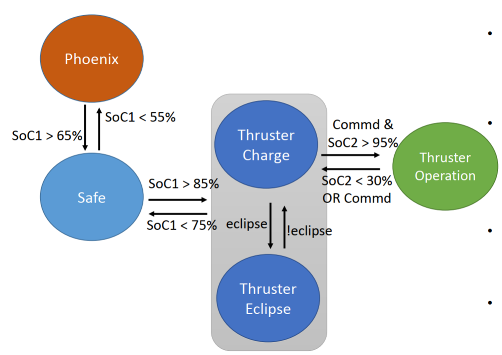

Figure 10: Modes in the Thruster Phase (SoC2 refers to the State of Charge of the Thruster battery)

Figure 11 shows a summary of the ON/OFF status of each subsystem in the various modes. The C&DH, EPS and the

UHF Receiver being critical subsystems are always ON. The payloads (CIP, atmoLITE, RGB Imager) are switched in Science mode as well as during eclipse in the VLEO region.

Subsystem	Emergency Modes		Nominal Modes			
	Phoenix	Safe	Science	Thruster		
				Charge	Eclipse	Operation
C&DH	ON	ON	ON	ON	ON	ON
EPS	ON	ON	ON	ON	ON	ON
ADCS	OFF	Coarse Sun	ON	ON	ON	ON
CIP-Payload	OFF	OFF	ON	OFF	ON	OFF
AtmoLITE	OFF	OFF	ON	OFF	ON	OFF
GECKO	OFF	OFF	ON	OFF	ON	OFF
UHF Rx	ON	ON	ON	ON	ON	ON
UHF Tx	Beacon	Beacon	ON	ON	ON	ON
S-band Tx	OFF	OFF	ON	OFF	ON	OFF
Thruster	OFF	OFF	OFF	OFF	OFF	ON
Battery Heater	As Required	As Required	As Required	As Required	As Required	As Required

Figure 11: ON/OFF Status of Subsystems

INSPIRESat Operating System (ISOS)

In addition to executing the mode transitions, the flight software performs various tasks, these include satellite monitoring, critical support and recovery, data transmission and other mission tasks. In order to execute these tasks efficiently the ISOS is a real-time operating system that is built in-house. ISOS follows interrupt-driven timing and scheduling, to perform periodic and non-periodic tasks. Figure 12 gives a block diagram representation of ISOS.

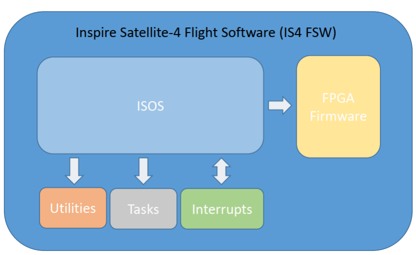

Figure 12: ISOS - InspireSat Operating System

ISOS is the main component of the Flight Software, acting as a master over the FPGA fabric. The interaction between ISOS and the FPGA fabric, allows multiple tasks to be executed in a non-blocking fashion. ISOS also implements task scheduling by executing higher priority tasks first and removing unresponsive tasks.

5.4 Communication System

The role of the communication subsystem is to provide enough data downlink capabilities, so as that the large amount of science data produced by the instruments con be completely. Figure 13 summarizes the subsystem along with the various data rates. The UHF transceiver uses a tape measure antenna, whereas the S-Band Transmitter uses a patch antenna.

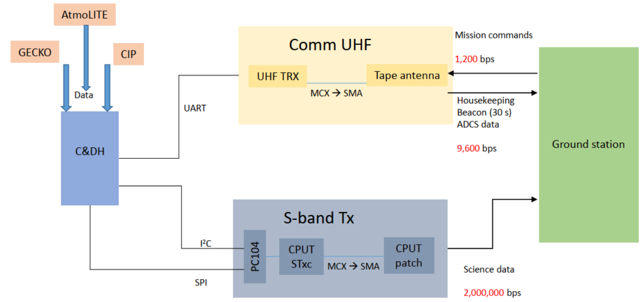

Figure 13: Block diagram representation of the Communication Subsystem

The link budget analysis for UHF transceiver considering various losses was carried out and a margin of 22.9 dB and 6.7 dB was obtained for Uplink and Dowlink respectively. A similar analysis for the SBand transmitter results in a link margin of 13.4 dB. Access time analysis was carried out for the SBand & UHF groundstation at NTU as well as the UHF groundstation at IIST. Average data download per orbit is obtained to be 1.44 MB and 168.5 MB for UHF and S-band respectively. This ensures a comfortable margin on the data downlink capabilities over the data generated per orbit for the mission.

5.5 Structures/Thermal

INSPIRESat-4 is a 27U satellite with stowed dimensions 30 cm x 30 cm x 30 cm. The satellite will be ring deployed from the PSLV rocket. The different operating modes (discussed under Flight Software) of the satellite require different pointing configurations. Varying pointing configurations result in different sun body angle and hence, different levels of thermal loads. Thermal analysis was performed to ensure that all subsystems are kept within acceptable temperature limits throughout the mission. AtmoLITE detector has a cold finger attached to it that especially needs to be held at a low temperature. Temperature requirements for the 3 payloads are listed in table 3.

	Requirements
AtmoLITE	-30 to 0°C
CIP	-20 to 60°C
RGB Imager	10 to 30°C

Table 3: Operating temperature ranges of IS4 payloads

The structural configuration considers the field-of-view (FOV) of the instruments. AtmoLITE, startracker of XACT-50 ADCS unit and the RGB imager are optical instruments that need unobstructed FOV. The satellite subsystems are laid out such that the S-band patch antenna and the RGB imager are typically nadir pointed while the solar arrays are sun-pointed. AtmoLITE looks towards Earth northern hemisphere with a cant of about 30 deg for observation of atmosphere at 110 km altitude. This layout minimizes the amount of maneuvering required in ARCADE mission.

Figure 14: CAD rendering of INSPIRESat-4. The PSLV deployer ring IBL 230 is visible on the top surface.

5.6 Attitude Determination and Control System

The ADCS requirements and sizing were considered in the mission design section previously. XACT-50 (figure 15) from Blue Canyon Technologies is chosen as the ADCS unit for INSPIRESat-4. XACT has a successful flight heritage and XACT-50 reaction wheels with 0.050 Nms momentum capacity was deemed sufficient for ARCADE mission [1].

Figure 15: XACT-50 ADCS unit from Blue Canyon Technologies

6 Conclusion

INSPIRESat-4 is a 27U satellite with VLEO capability to make in-situ ionospheric plasma measurements. INSPIRESat-4 will use the CIP payload to explore the tropical equatorial ionosphere at low altitudes to understand equatorial plasma anomalies. AtmoLITE payload on the satellite will study tropical gravity waves generated by convective storms and tropical storms and their influence in coupling the lower and upper atmosphere. The mission is currently being built with subsystem prototyping underway. Preliminary Design Review (PDR) of INSPIRESat-4 was completed in March, 2019 and Critical Design Review (CDR) is scheduled for November, 2019.

7 Acknowledgements

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