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A Preliminary Design for the INSPIRESat-1 Mission and Satellite Bus: Exploring the Middle and Upper Atmosphere with CubeSats

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ABSTRACT

Spanning an altitude range from 20 – 1000 km, the Earth's middle and upper atmosphere forms the interface between the Earth system and near Earth space. Driven by solar activity, geomagnetic storms, as well as waves and tides propagating upward from below, the winds and temperatures in this region have important implications both for the Low Earth Orbit space environment, as well as understanding vertical coupling processes in the atmosphere as a whole. However, existing satellite measurements of this region are limited both in spatial and temporal coverage. There is therefore a need for compact sounding payloads that may be deployed using small satellites satisfying the payload requirements.

As part of the International Satellite Program in Research and Education (INSPIRE), we present a preliminary design and analysis for INSPIRESat-1: a CubeSat mission carrying the Doppler Wind and Temperature Sounder (DWTS) instrument being co-developed by CU LASP, GATS and Brandywine Photonics. This design for INSPIRESat-1 was spearheaded by students from National Central University (NCU) in Taiwan, in collaboration with Taiwan's National Space Organization (NSPO). The final design for INSPIRESat-1 will be based upon this design, in conjunction with parallel designs from other universities participating in the INSPIRE consortium.

INTRODUCTION

International Satellite Program in Research and Education (INSPIRE)

Initiated by the University of Colorado (CU) Laboratory for Atmospheric and Space Physics (LASP) in 2015, the International Satellite Program in Research and Education (INSPIRE) is a multinational consortium of universities collaborating to develop a constellation of small satellites for cutting edge space and earth science research, a supporting global ground station network, as well as research and educational programs covering spacecraft design, space systems engineering, operations, and data analysis.

Preliminary design work for INSPIRESat-1, the first spacecraft in this project, was initiated in 2015. INSPIRESat is planned to be a 6U CubeSat carrying the Doppler Wind and Temperature Sounder (DWTS) instrument co-developed by LASP, GATS, and Brandywine Photonics, to measure the winds and temperatures of the middle and upper atmosphere. Current INSPIRE consortium participants involved in the mission and spacecraft design of INSPIRESat-1 include CU LASP, the Indian Institute of Space Science and Technology (IIST), and National Central University (NCU) in Taiwan.

Since late 2015, graduate and undergraduate students at the aforementioned institutions have been engaged in developing parallel mission concepts, systems definitions, and preliminary designs for INSPIRESat-1. Building on past experience in scientific payload design and aeronomy research, the INSPIRESat-1 student design team at NCU conducted a semester-long feasibility study during Winter 2015 with guidance from the Taiwan National Space Organization (NSPO). The objective of this study was to formulate the mission concept and subsystem requirements for INSPIRESat-1, in order to determine whether such requirements can be met using COTS (Commercial Off The Shelf) components. This feasibility study was then subjected to a Systems Definition Review (SDR).

The initial COTS-based SDR design was subsequently revised during Spring 2016, incorporating updated DWTS payload requirements, more advanced thermal and structural analysis, as well as the preliminary design of laboratory prototype subsystems. This work culminated in a Preliminary Design Review (PDR) in June 2016. The resulting mission concept, feasibility analysis, and preliminary design of INSPIRESat-1 are presented in this report.

The Middle and Upper Atmosphere

The Earth's middle and upper atmosphere is defined as consisting of the region spanning the stratosphere (~20 – 60 km), mesosphere (~60 – 90 km), thermosphere (~90 – 1000 km) [Holton and Alexander, 2000; Vincent, 2015]. Unlike the troposphere (~0 – 20 km), which is home to nearly all human activity, water vapor, and what is traditionally thought of as "weather", the middle and upper atmosphere are dry, with densities rapidly decreasing over an extremely large vertical range. The neutral atmosphere of this region has also been extremely difficult to study on a global scale in the past, with in-situ instruments limited by the horizontal and vertical range of their balloon or sounding rocket launch vehicles.

Despite this, the middle and upper atmosphere are known to play an important role in the Earth's atmospheric environment, climate, and weather, as well as having significant influences on atmospheric and space operations and technology. The structure and stability of the stratospheric polar vortex is known to play a large role in influencing tropospheric pressure gradients and the jet stream, manifesting in wintertime weather as the Arctic Oscillation [Thompson et al., 2000]. Incorporation of assimilated stratospheric observational data into weather forecast models has become recognized as being crucial in forecasting such weather phenomena [Baldwin et al., 2003; Sigmond et al., 2013]. On a climatological scale, photodissociation of stratospheric molecular oxygen by solar middle and far ultraviolet radiation is the formation mechanism for the ozone layer, whose variation is strongly influenced by temperature dependent chemical processes [Jackman et al., 2014], as well as transport by stratospheric winds such as the Brewer-Dobson Circulation [Holton and Alexander, 2000].

Further aloft between 90 – 1000 km, the thermosphere forms what is considered to be the outermost layer of the Earth's atmosphere, extending across altitudes covering much of Low Earth Orbit (LEO). Despite its high altitude, the thermosphere, as well as the ionosphere formed from photodissociation of thermospheric air by solar extreme ultraviolet radiation, have long been known to exert a significant influence on space operations and wireless communications technologies, while also serving as a key interface in the solar-terrestrial system [Mayr et al., 1978; Qian and Solomon, 2012; Kelly et al., 2014].

The neutral atmospheric density of the thermosphere produces satellite drag on spacecraft in Low Earth Orbit (LEO), forming one of the major orbital perturbations for operational spacecraft in this region [Brown, 2002; Qian and Solomon, 2012], and rendering orbits with altitudes less than 300 km unstable for missions longer than one year [Gorney, 1990]. Monitoring and forecasting of thermospheric drag conditions and variability have become crucial for LEO operations, using empirical models such as the Jaccia-Bowman (JB) series [Bowman et al., 2008], and more recently physics-based models such as the Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIE-GCM) [Richmond et al., 1992].

Photoionization of the neutral thermosphere by solar extreme ultraviolet radiation forms the plasma of the ionosphere, which acts to refract and reflect radio waves from terrestrial and satellite transmitters. Such ionospheric refraction acts to produce scintillation effects on satellite communications [Kelly et al., 2014], while also affecting the propagation of long range HF radio communications [Frissell et al., 2014].

Variability in both the thermosphere and ionosphere is strongly affected by the wind and temperature fields of the thermosphere and mesosphere, whose dynamics are dominated by both vertically propagating waves and tides excited from the lower atmosphere, as well as in-situ forced effects [Holton and Alexander, 2000; Vincent, 2015]. Such dynamical drivers of thermosphere and ionosphere variability can include the cumulative effects of composition changes driven by breaking atmospheric waves in the thermosphere [Qian and Solomon, 2012; Chang et al., 2014], modulation of the ionospheric wind dynamos tidal/planetary wave winds, and propagation of such waves and tides into the thermosphere from the mesosphere [Oberheide et al., 2015].

From the above, it is apparent that the need exists for global scale observations spanning the entire vertical domain of the middle and upper atmosphere. This observational need is complicated by the fact that the atmospheric tides driving middle and upper atmospheric dynamics have periods that are harmonics of a solar day and zonal wavelengths that are harmonics of the Earth's circumference. The tides can therefore be aliased with background zonal mean zonal winds and stationary planetary wave fields if proper longitude/local time sampling requirements are not satisfied. Unambiguous resolution of the global structure of these tides requires global scale sampling over 24 hours of solar local time in all longitude zones, ideally from pole to pole [Zhang et al., 2006]. Spacecraft in Sun-synchronous orbits, as well as low inclination orbits are therefore respectively unable to meet these local time and latitude sampling requirements. Furthermore, these two sampling requirements are mutually contradictory, as the high inclination orbits required for broad latitudinal sampling possess a slower local time precession rate due to nodal regression [Vallado, 1997]. For example, the 74.1° degree inclination, 625 km circular orbit occupied by the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) spacecraft requires 60 days of observations to satisfy the sampling requirements necessary to resolve the tides, severely limiting the resolution of sub-seasonal scale variability.

Current satellites also operate under the observational limitations of current wind and temperature sounding payloads, which can only resolve one of the two variables, over an altitude range much smaller than the entire span of the stratosphere, mesosphere, and thermosphere [Gordley and Marshall, 2011]. Ideally, these sampling and instrumentation limitations could be overcome through the deployment of a constellation of small satellites carrying a sounding payload capable of simultaneously resolving winds and temperatures throughout this entire vertical domain. Addressing this need forms the scientific objective of our proposed INSPIRESat-1 mission, utilizing the Doppler Wind and Temperature Sounder (DWTS) as payload.

Doppler Wind and Temperature Sounder

DWTS is a radiometer payload concept developed and patented by the U.S. aerospace firm GATS [Gordley and Marshall, 2011; Gordley et al., 2013], which addresses the aforementioned observational needs. DWTS is capable of providing continuous daytime and nighttime measurements of winds and temperatures across a vertical range of 25 – 200 km.

As described in depth by Gordley and Marshall [2011], DWTS functions by limb scan measurements of Doppler shifted NO and CO_2 emissions from the Earth's middle and upper atmosphere. The process requires an IR camera using a Focal Plane Array (FPA) detector pointed in the cross-track direction, which measures the radiances from the aforementioned emissions after passing through a gas cell filter. The Doppler shift and width of the observed NO emission lines, from single along-track points, can be used to infer atmospheric winds and temperatures, respectively.

For the purposes of this operational test, a single channel DWTS payload measuring NO emissions at 5.3μm has been developed. This single channel payload will be capable of resolving winds and temperatures from 30 – 50 km and 85 – 200+ km altitude. The major payload subsystems include the IR camera (with integrated cryocooler), optics (including gas cell), cooler and heater for cell temperature control, and processor for data aggregation and compression. The instrument will have operational, standby, safehold, and off modes. The volume of DWTS alone is 29 x 10 x 9 cm, approximately corresponding to that of a 3U CubeSat. Power and data storage requirements will be satisfied by the satellite bus [Gordley et al., 2013]. Figure 1 shows a conceptual design of DWTS mounted inside the 6U spacecraft bus of INSPIRESat-1. The DWTS aperture points out of the top panel (20 cm x 10 cm) of the spacecraft, which must therefore be oriented in the cross-track direction.

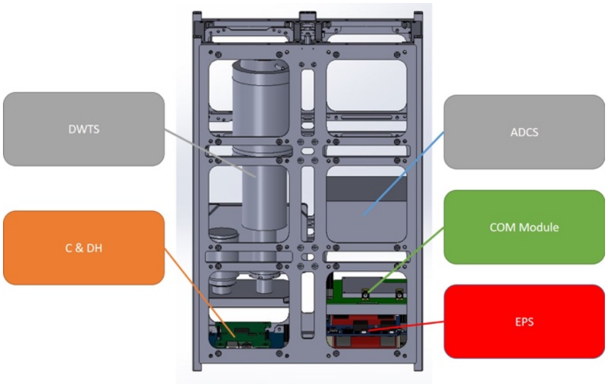

Figure 1: Conceptual design of INSPIRESat-1 bus, illustrating orientation of DWTS. Solar panels not shown.

Data transmitted to the satellite bus every 2 seconds includes the FPA data records, as well as camera and heater settings sampled and returned with each record. The thermal data can be used to calibrate and remove detector effects provided the temperatures drift smoothly, thereby imposing thermal stability requirements. The Doppler shift operational principle of DWTS, as well as the accuracy of the derived along-track wind vector and limb tangent point altitude impose a cross-track pointing requirement for the camera field of view (FOV), as well as stringent attitude knowledge, control, and stability requirements. The requirements of this single channel DWTS are summarized in Table 1.

Table 1: DWTS Requirements and specifications

DWTS Requirements & Specifications	
Mass	4 kg
Volume	29 x 10 x 9 cm
Power	Standby and Operational: 7 W Safehold: 1 W Off: 0 W
Pointing Knowledge	±0.5 arcmin, all axes
Pointing Stability	< 6 arcsec/sec
Attitude Control	±1°, all axes
Field of View	Sun must not appear in field of view. Oriented cross-track.
Spacecraft Velocity Knowledge	±1 m/s
Data Rate	Downlink 200 Mbits/day
Thermal Stability	FPA: ±0.1 K/minute Gas Cell: ±1 K/minute
Thermal Requirement	Anti-Sunward Side: -10 - 0°C

INSPIRESAT-1 MISSION CONCEPT

DWTS offers the potential to greatly expand our observational capabilities of the middle and upper atmosphere, which will dramatically benefit atmospheric science research, as well as operational atmospheric and space weather monitoring. Prior to inclusion on a large scale, long duration mission, it is preferable that DWTS be operationally tested aboard a smaller scale mission. This forms the mission objectives for INSPIRESat-1, which include:

- Demonstrate the ability of DWTS to measure winds and temperatures from 30 – 200 km.
- Demonstrate that error due to stray light effects can be rendered negligible using both optical and digital means, including calibration from lunar scans [Gordley and Marshall, 2011].

This mission will serve to develop instrument heritage and validate operational data processing procedures, increasing the DWTS Technology Readiness Level (TRL) from TRL 3 to TRL 9. Data acquisition and validation over all four seasons would be ideal, but it is not required for the main objective of testing instrument performance and data analysis. However, the following additional objective can be achieved with just a three-month period of operation [D. Fritts, private communication]:

- Unambiguously resolve atmospheric tides and planetary waves with zonal wavenumbers from 1 – 4, from 60°S to 60°N.

INSPIRESAT-1 SYSTEMS DEFINITION, FEASIBILITY, AND PRELIMINARY DESIGN

The results of the SDR and PDR level analysis and design based upon the aforementioned mission concept are presented by subsystem in the following sections. We focus on defining the necessary subsystem requirements, and illustrating their feasibility through supporting analysis, as well as identification of whether such requirements can be met using COTS components.

Orbit and Navigation (ORB/NAV)

The orbit selection for INSPIRESat-1 is driven primarily by a few key requirements including lifetime, instrument resolution, and local time sampling.

Constraints on orbital altitude and eccentricity are imposed by the requirement for a mission lifetime greater than 3 months, as well as that for consistent 3 km vertical x 10 km horizontal resolution of 2 second aggregated data from the DWTS FPA sensor. Orbital decay simulations were performed using the NASA Debris Assessment Software (DAS, http://orbitaldebris.jsc.nasa.gov/mitigate/das.html) to establish mission lifetimes for INSPIRESat-1 following the expected August 2018 launch. As will be shown in subsequent subsystems analysis, the spacecraft is expected to be a 6U CubeSat with a total mass of 8 kg. DAS simulation results indicate an expected lifetime of 1.199 years for such a CubeSat with a 20 cm x 30 cm cross section in a 350 km orbit. The expected lifetime increases dramatically with altitude, with a 650 km orbit projected by DAS to have a lifetime of 37.7 years. For the purposes of this feasibility study, we consider an 800 km orbit.

As mentioned previously, the orbit inclination is constrained by the opposing needs for latitude coverage as well the need to achieve 24 hours solar local time coverage within the operational lifetime for unambiguous resolution of atmospheric tides. Figure 2 shows the period of time required for a 350 km circular orbit to precess through 24 hours of solar local time due to nodal regression [Vallado, 1997], corresponding to a 180° precession of the orbital plane with respect to the Sun vector. Based upon this analysis, we have selected a 65° inclination angle for the INSPIRESat-1 orbit, which will achieve 24 hours solar local time coverage in approximately 45.18 days. This will be sufficient to resolve tidal amplitudes and phases within the 3-month minimum mission lifetime.

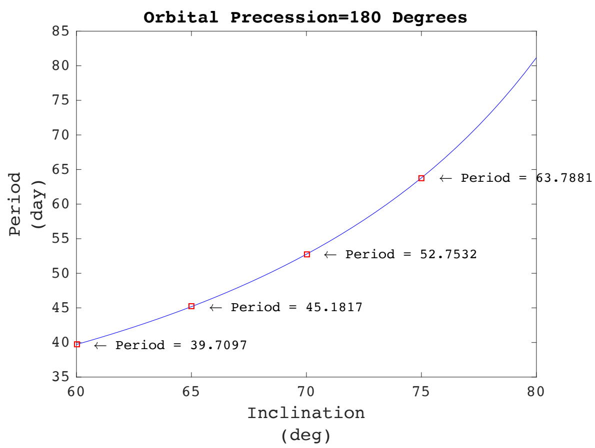

Figure 2: Period required for 24 hours of local time coverage for 350 km orbit as a function of inclination.

Orbit determination and data association needs require continuous measurement of spacecraft position and velocity. This necessitates the inclusion of a GPS navigation subsystem. We have identified four COTS options satisfying our requirements. The SkyFox Labs pqNAV-L1/FM, Surrey SGR-05U, and SSBV GPS Receiver all accommodate GPS L1 C/A signals, while the GPSRM 1 GPS Receiver Module accommodates GPS L1/L2/L2C and GLONASS L1/L2 signals. For the purposes of the later power analysis, we have selected the specifications of the GPSRM as it has the highest power requirements of the four COTS options.

Attitude Determination and Control (ADCS)

The operational principle and specifications (Table 1) of DWTS, as well as the needs for the operational demonstration imposes several requirements on the ADCS subsystem. Based on these needs, we have defined the ADCS requirements as follows:

- The ADCS shall ensure that the DWTS field of view is in the cross track direction away from the Sun.
- The 30 cm x 10 cm side of the spacecraft shall be pointed at nadir.
- The ADCS shall be a three-axis stabilized type.
- The ADCS shall perform periodic yaw maneuvers to avoid DWTS pointing to the sun.
- The ADCS shall have attitude knowledge of ±0.5 arcminutes, ±0.5 arcminutes and ±1.0 degree for the yaw, roll and pitch angles, respectively.
- The ADCS shall have an attitude control of ±1 degree in all axes.
- The ADCS shall ensure that the spacecraft has an angular drift of <6.0 arcsecs/sec for all axes.

We have identified COTS ADCS modules satisfying the above requirements. Our first choice is the XACT Capability module from Blue Canyon Tech. It has 1 star tracker, 1 sun-sensor, 1 IMU, 3 reaction wheels, 1 magnetometer and 3 torque rods. It has ±0.003 degree pointing accuracy for 2 axes and ±0.007 degree pointing accuracy for the third axis. Another module we are considering is the FleXcore Control Capability also from Blue Canyon Tech. It has 2 star trackers, 1 sun sensor, 1 IMU, 4 reaction wheels and 3 torque rods. Its pointing accuracy is at ±0.002 degrees on all 3 axes and the 2 trackers. Table 2 shows a summary of basic specifications.

Table 2: COTS ADCS Module specifications.

COTS ADCS Module Specifications		
Module	FleXcore Control Capability	XACT Capability (Star Tracker)
Instruments	2 star trackers, 1 sun sensor, 1 IMU, 4 reaction wheels, 1 magnetometer and 3 torque rods	1 star tracker, 1 sun-sensor, 1 IMU, 3 reaction wheels, 1 magnetometer and 3 torque rods.
Pointing Accuracy	±0.002° (1-sigma), 3 axes, 2 trackers	±0.003° (1-sigma) for 2 axes ±0.007° (1-sigma) for 3rd axis
Lifetime	3 Years (LEO)	3 Years (LEO)
Mass	0.85 kg	0.85 kg
Volume	0.5 U	0.5 U
Electronics Voltage	5 V	5 V
Reaction Wheel Voltage	28 V	12 V
Data Interface	RS-422	RS-422
Maximum Power	-	2.83 W

The XACT Capability is already priced at almost US$140,000. As the FleXcore Control Capability has more instruments and higher accuracy, we expect it to be more expensive. Also, XACT has previous flight heritage, as it has already been used on a previous CubeSat, MinXSS. In fact, XACT is used in a complete spacecraft bus that Blue Canyon also offers, the XB1 6U Bus. Both modules have integrated on-board processing of attitude determination using Kalman filter algorithms. Hence, no additional processing will be needed from other satellite bus subsystems. Attitude control algorithms are also incorporated into the module.

Electrical Power Subsystem (EPS)

The EPS will supply and distribute power to every sub-system in the spacecraft for at least 3 months, supporting power requirements for average and peak electrical load. Preliminary analysis using COTS components, as well as the DWTS power requirements were used to estimate the INSPIRESat-1 power budget. In the case where multiple COTS options were available for a given subsystem, the power budget estimate was computed using the component with the highest power requirements. The resulting power budget is shown in Table 3. The total power requirement is estimated to be 17.133 W. An additional power margin of 0.8566 W was defined as 5% of the aforementioned power requirement.

Table 3: INSPIRESat-1 Power Budget

INSPIRESat-1 Power Budget		
Subsystem	Power Requirement	Notes
DWTS	7 W	Operational & Standby modes
NAV	1.3 W	GPSRM
EPS	-	
CDH	0.003 W	CubeSat Kit Motherboard
COM	6 W	Astrodev Helium (Transmit mode)
ADCS	2.83 W	XACT
Total	17.133 W	
Margin	0.8566	5% required power consumption.

From this preliminary power budget, a preliminary definition for each operational mode for the spacecraft has also been specified. This is given in Table 4. The launch mode begins from the time the satellite is integrated into the deployment mechanism and ends when the satellite's antenna is deployed successfully. The nominal mode is the mode wherein the satellite operates under normal condition thus all sub-systems are on. The nominal mode will have the maximum power consumption of 17.133 W. The safe mode is utilized when a sub-system has any unusual condition. Only the navigation and communication sub-systems (in beacon mode) are turned on. This will require 1.503 W of power. The downlink mode is utilized when the satellite connects with the ground-station to receive command and to transmit housekeeping and science data. This will require 4.333 – 10.133 W. The desaturation mode is utilized when the satellite needs to desaturate its control moment gyros. This will require approximately 10.133 W with variations depending on the ADCS.

Table 4: INSPIRESat-1 operational modes and power requirements.

INSPIRESat-1 Operational Modes		
Mode	Power Requirement	Active Subsystems
Launch	0.003 W	EPS, CDH
Nominal	17.133 W	EPS, CDH, DWTS, NAV, COM, ADCS
Safe	1.503	EPS, CDH, NAV, COM
Downlink	4.333 – 10.133 W	EPS, CDH, NAV, COM, ADCS
Desaturation	10.133 W	EPS, CDH, NAV, COM, ADCS
Slew	10.133 W	EPS, CDH, NAV, COM, ADCS

Preliminary analysis using the Satellite Power Analysis Tool (SPAT, https://sourceforge.net/projects/spat-sat/) was done to determine the approximate eclipse period. For INSPIRESAT-1, the preliminary set altitude is 800 km with an eccentricity of 0 and an inclination of 60°. The eclipse period is around 1.9758 to 35.0728 minutes. The variation of the eclipse period is shown in Figure 3.

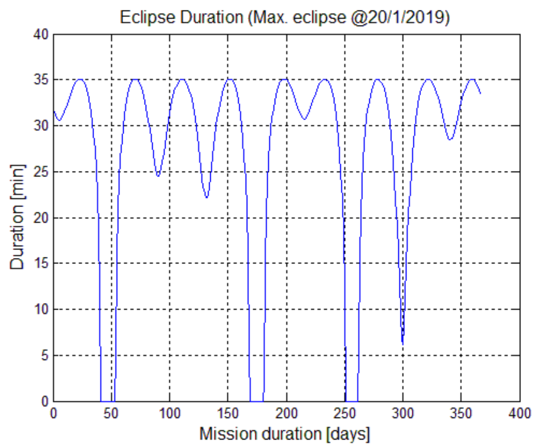

Figure 3: Eclipse duration for INSPIRESat-1 calculated using SPAT.

The solar-panel power requirement was calculated using the following equation from Brown [2002]:

$$P_{sa} = \frac{P_n T_n}{X_{a-b} X_{b-l} T_d} + \frac{P_d}{X_{a-l}} \quad (1)$$

In this equation, $X_{a-b} = n1 * n2 * n3 * nC * n4 * nB$ is the Solar Array to Battery Efficiency, $X_{b-l} = n5 * n6$ is the Battery to Loads Efficiency, $X_{a-l} = n1 * n2$ is the Solar Array to Loads Efficiency, P_n is the eclipse period power consumption, P_d is the day time power consumption, T_n is the eclipse period and T_d is the day time period.

Assuming a 30% power loss efficiency, INSPIRESAT-1 will have a solar panel power requirement of 25.1709 W to 43.1479 W. Hence, we set as a requirement that the solar panels shall provide 44 W.

The required battery capacity is calculated using the equation:

$$E_{req} = \frac{P_n T_n}{X_{b-l} DOD} \quad (2)$$

Using the same values in the calculation of solar panel requirements along with an assumed 70% efficiency and 80% Depth of Discharge (DOD) for the battery, the INSPIRESat-1 mission will have a battery capacity requirement of 17.8809 Wh. Hence, we set as a requirement that the batteries shall have a required capacity of at least 20 Wh. The required voltages that will be provided by the EPS power interfaces to the other subsystems will be 3.3 V, 5 V, and 12 V.

Using the aforementioned estimates to define the solar panel power requirement and battery capacity, we have identified COTS EPS options for both the solar panels, as well as the EPS module itself, which will provide switching, voltage control, voltage and battery temperature monitoring, as well as overvolt, undervolt, and overcurrent protection.

For a preliminary estimate of the number of solar panels needed, the GOMSpace NanoPower P110 Series solar panel (http://gomspace.com/?p=products-p110) is used. It has an effective area of 60.36 cm^2, 30% efficiency and can provide up to 2.3 W. Thus, to achieve 44 W with this solar panel, assuming full Sun at 90° β angle, approximately 20 panels corresponding to 1207.2 cm^2 are needed. This area alone can be satisfied with 2 deployable solar panels mounted on the two 20 cm x 30 cm and 30 cm x 10 cm sides of the 6U spacecraft, as well as the 20 cm x 10 cm side opposite the DWTS aperture (Figure 4).

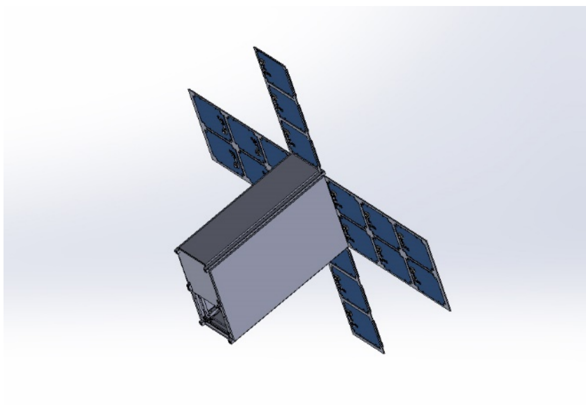

Figure 4: Conceptual illustration of INSPIRESat-1 deployable solar panels.

Other COTS panels were found but they were already set as a fully assembled single-side 3U panel. Clyde Space has a 3U solar panel on a 7S1P configuration rated at US$6400. It can provide 7W at Beginning of Life (BOL). Pumpkin Space has a 3U solar panel on an 8S1P configuration, which can provide 8W at End of Life (EOL). From these fully assembled single-side 3U panels, the power provided by one solar cell is approximately 1 W which indicates that the worst-case estimated number of solar panels is 45 cells. Nevertheless, our required solar panel power is satisfied by available COTS options, showing that the INSPIRESat-1 power requirements are feasible.

However, the cross-track pointing requirements of DWTS do impose an important constraint on the solar panel design and orientation with respect to the spacecraft β angle. As shown in Figure 5, DWTS will normally be pointing anti-sunward in the cross-track direction. The deployable solar panels will therefore receive full Sun when $\beta = 90°$, and no sunlight at $\beta = 0°$.

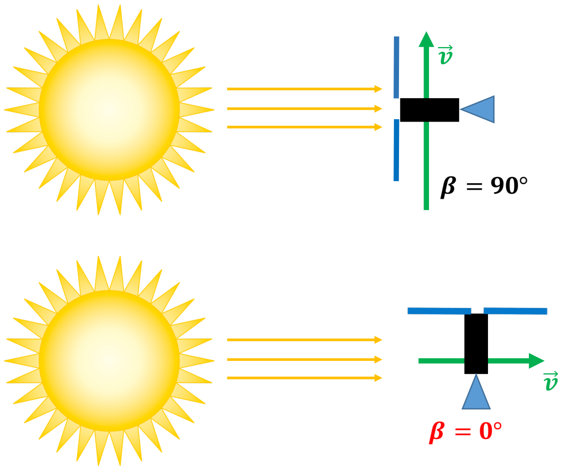

Figure 5: Orientation of fixed solar panels (blue lines) with respect to Sun vector (orange arrows), DWTS FOV (blue triangle), and velocity vector (green) at β=90° and β=0°.

This problem may be addressed using steerable solar arrays. COTS steerable solar arrays, in tandem with the requisite Sun sensors and attitude control are available. One such COTS solution is available with the Blue Canyon XB1 spacecraft bus, which also includes the previously considered XACT Capability ADCS subsystem. Another option is the use of deployable solar arrays that are fixed in orthogonal directions. This option comes at the cost of increased mass and cost. A third option involves the use of the deployable solar arrays shown in Figure 4, with the addition of a periodic charging mode. When in such an operational mode, the payload would be deactivated, and the spacecraft attitude adjusted to maximize solar exposure. This option would come at the cost of reduced observation time, while also introducing new complexities to mission operations.

The 20 Wh battery capacity requirement is satisfied by several COTS battery packs. Clyde Space has 20 Wh, 30 Wh and 40 Wh stand-alone battery packs priced at US\$2850, US\$3850 and US\$4850, respectively. These modules utilize the I2C interface. GOMSpace has a 38.9 Wh battery pack (price not provided). All of these COTS options satisfy our required battery capacity, while conforming to the PC104 form factor.

The COTS options for the EPS power distribution module are the P31us by GOMSpace, the 3rd Generation FlexU EPS by Clyde Space and the XEPS by Blue Canyon Tech. All of these options have built-in voltage and current protection, I2C or SPI interface and conform to the PC104 form factor. However, P31us only has 3 input channels that only attain 30 W, while only providing 3.3 V and 5 V voltage. On the other hand, FlexU can support high-power CubeSats from 3U to 12U with deployable solar panels as well as provide for 3.3 V, 5 V and 12 V voltages. XEPS has an accompanying battery pack that can provide 2.6 Ah (approximately 20 Wh) to 5.2 Ah (approximately 40 Wh). XEPS can also provide for 3.3 V, 5 V and 12 V voltages while providing up to 60 W of power with 6 power feeds.

In addition to the following COTS options for the EPS subsystem, NCU students are also designing and fabricating a laboratory prototype EPS module that will form the basis for future spacecraft needs, while also working to build student design and fabrication capacity. This design utilizes non-space-grade solar panels, battery packs and a self-assembled power distribution module. This allows us to test whether our EPS design can meet the required power consumption in a safe manner.

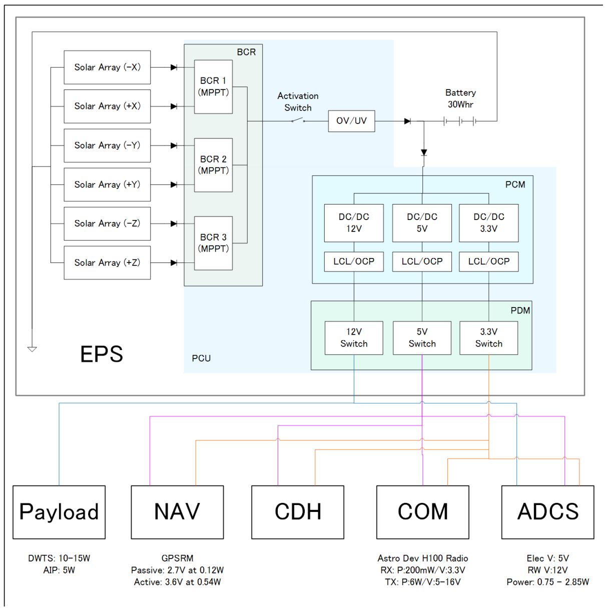

Figure 6: Power interface diagram for NCU EPS prototype.

Figure 6 shows the power interface diagram for this prototype EPS design. The figure shows that a preliminary estimate of 6 solar panels is connected to a battery charging regulator (BCR) that utilizes a maximum power point tracker (MPPT). This Direct Current/Direct Current (DC/DC) conversion steps the higher solar panel voltage down to the charging voltage of the battery. Additional over voltage and under voltage protection is then situated between the BCR and the battery as well as the power conditioning module. The power from both the battery and the solar panel undergoes another DC/DC conversion into the recommended 3.3 V, 5 V and 12 V voltages. The power here is further conditioned by a Latching Current Limiter (LCL)/Over Current Protector (OCP). Then, it is distributed to the rest of the sub-system via the power distribution module that comprises of 3.3 V, 5 V and 12 V switches.

Battery, temperature, voltage and current sensors will be strategically positioned in the EPS and then connected to a micro-controller unit. These sensors will monitor the over-all condition of the EPS by initiating appropriate responses as well as informing the Command and Data Handling (CDH) subsystem. The EPS microcontroller will initiate over current and over voltage protective measures to reduce reaction time. Exact circuit design is still in progress.

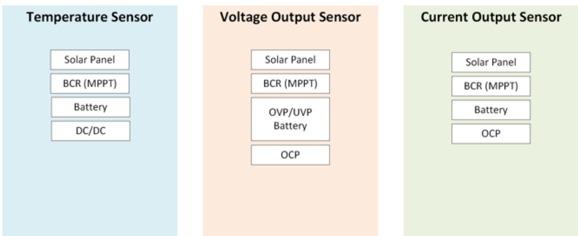

Figure 7: NCU EPS prototype data interface diagram.

The data interface diagram for this EPS is given in Figure 7. The figure shows that the temperature sensor will monitor the temperature of the solar panels, BCR, battery and DC/DC converters. The voltage and current sensors will monitor the voltage and currents of the solar panel, BCR, battery and the OCP.

For this design, the ZIPPY Flightmax 3000 mAh 3S1P 20C battery is utilized, which has a capacity of 3000 mAh, voltage of 11.1 V and 20 C constant / 30 C burst discharge. Commercially available ICs and sensors are also utilized for the BCR (BQ24650RVAT), over and under volt protection (BQ76920), DC-DC conversion (LM2576-3.3, LM2576-5, and MC3306A-Q1), LCL (TPS2553-1), PDM (CD4052 and CD4053), current and voltage sensor (INA226), and temperature (TMP121).

Command and Data Handling (CDH)

The CDH subsystem will be responsible for the control of all spacecraft subsystems, primary by interfacing with the controllers embedded in DWTS, as well as the NAV, ADCS, EPS, and COM subsystems. The CDH subsystem will also provide the data storage necessary for DWTS data, as well as housekeeping data from EPS and NAV.

For the purposes of this analysis, we have selected the CubeSatKit motherboard, as well as the dsPIC33 pluggable processor module. The key factor motivating the selection of this CDH subsystem is its extensive flight heritage, as well as an SD Card memory interface supporting > 2 GB of storage.

Structures (STR)

As mentioned previously, the dimensions of DWTS, as well as the estimated power requirements may be satisfied using a 6U CubeSat bus (Figure 1). Based on our preliminary COTS components, the INSPIRESat-1 mass budget is shown in Table 5.

Table 5: Estimate of INSPIRESat-1 mass budget.

INSPIRESat-1 Mass Budget		
Subsystem	Mass	Notes
DWTS	4 kg	-
NAV	0.012 kg	pqNAV-L1/FM
EPS	0.2 kg 0.6 kg	Power supply GOMspace solar panels
CDH	0.088 kg	CubeSat Kit Motherboard
COM	0.078 kg	Astrodev Helium (no antenna)
ADCS	0.85 kg	XACT Capability
TCS	-	TBD
Total Estimate	5.828 kg	
Margin	2.172 kg	Based on 8 kg total mass requirement.

Our preliminary estimate of the spacecraft mass is based upon the masses of identified COTS components. We note that the preceding estimate does not consider the mass of thermal control (TCS) components, as well as the spacecraft chassis, antenna, and connectors. Based on the customer issued mass requirement of 8 kg, future work will determine whether the aforementioned components can be designed to fit in the remaining 2.172 kg of mass margin.

Thermal Control (TCS)

Preliminary estimates for the INSPIRESat-1 thermal environment were performed for the spacecraft shown in Figure 4. Based on radiative equilibrium, the worst case hot temperature was estimated with the deployed solar panels exposed to full Sun, while the worst case cold temperature was estimated for the spacecraft in eclipse. The temperature range for the spacecraft was thus estimated to be -69.4°C – 50.1°C for a circular 600 km orbit, and -72.2°C – 48.8°C for a circular 800 km orbit.

The results of this preliminary estimate were then compared to the operational and survival temperature ranges of the selected COTS components, in order to identify components requiring additional thermal control. The results are shown in Table 6.

Table 6: Thermal risk analysis for INSPIRESat-1.

INSPIRESat-1 Thermal Risk Analysis		
Components	Operational	Survival
EPS	-40 ~ 85°C	-50 ~ 90°C
Batteries	5 ~ 20°C	0 ~ 25°C
Solar Panels	-150 ~ 110°C	-200 ~ 130°C
DWTS	-30 ~ 20°C	-15 ~ 55°C
GPS	-40 ~ 85°C	-55 ~ 95°C
ADCS	-10 ~ 40°C	-15 ~ 45°C
Motherboard	-40 ~ 85°C	-45 ~ 90°C
Antennas	-100 ~ 100°C	-105 ~ 105°C

Comparing the results of the thermal risk analysis to the estimated -72.2°C – 48.8°C temperature range of the 800 km orbit, it can be seen that with the exception of the solar panels and antennas, all of the examined components face exposure to a thermal environment that exceeds their operational temperature ranges. In particular, the batteries, DWTS, and reaction wheels all face both hot and cold temperatures that exceed their operational requirements.

These components will require additional thermal control measures, pending further analysis using thermal modeling software and radiation parameters computed using the NASA Thermal Radiation Analyzer System (TRASYS). Given the power constraints of INSPIRESat-1, such thermal control measures will likely be passive components such as radiators or multilayer insulation (MLI). The exception to this is the cryocooler already included as part of DWTS [Gordley et al., 2013].

Communications (COM)

The COM subsystem of INSPIRESat-1 builds on past heritage of academic and amateur radio CubeSats utilizing UHF/VHF amateur radio bands for telemetry purposes. The use of amateur radio frequencies is attractive given its relatively low cost in terms of spacecraft and ground station components, as well as the availability of collaboration with the international amateur radio community for beacon data reception.

For the purposes of INSPIRESat-1, we estimate a daily data rate requirement of 225 Mbits / day, which includes both DWTS and housekeeping data. Downlink of DWTS data will be performed when the spacecraft is within the line of sight of UHF/VHF ground stations located at institutions participating in the INSPIRE consortium, including NCU in Taiwan, IIST in India, and CU in the USA. Building on the heritage of CSSWE and MinXSS, the chosen digital signal modulation is FSK/GMSK. Frequency Modulation is also chosen because the transmitter can be operated at maximum power and highest power efficiency, and can operate at a lower signal-to-noise ratio than AM systems.

The expected overpass time for these ground stations was calculated assuming an 800 km altitude at 60° inclination using STK. The resulting estimate is shown in Table 7.

Table 7: INSPIRESat-1 overpass time estimated for participating ground stations.

INSPIRESat-1 Overpass Time	
Ground Station	Combined Duration
Taiwan	4438.011 secs/day
India	3873.101 secs/day
Singapore	3690.463 secs/day
Colorado, USA	5791.129 secs/day
Total	296.54 mins/day

Combining the link budget estimate with the 225 Mbits / day data rate requirement, the radio module used aboard INSPIRESat-1 must achieve at minimum, a data transfer rate of 12.646 kbits / sec. A COTS VHF/UHF radio module satisfying this requirement is the Astrodev Helium 100 VHF/UHF radio, which has a 38.4 kbits / sec data rate utilizing FSK/GMSK modulation. The Helium 100 is also attractive given its flight heritage aboard MinXSS. COTS deployable antenna systems are also available for UHF/VHF CubeSat radios. Further analysis will be performed to determine whether such a deployable antenna will be purchased COTS, or developed internally, drawing from the heritage of deployable tape measure antennas utilized on past CubeSat missions, including CSSWE and MinXSS.

The link budget was calculated to determine the expected downlink signal power at the receiving ground stations. The steps in this calculation are shown in Figure 8, quantifying gains and losses stemming from the spacecraft radio, transmission (Tx) cable, Tx antenna, free space and atmospheric path loss, receiving (Rx) antenna gain, amplifier gain, and Rx cable loss.

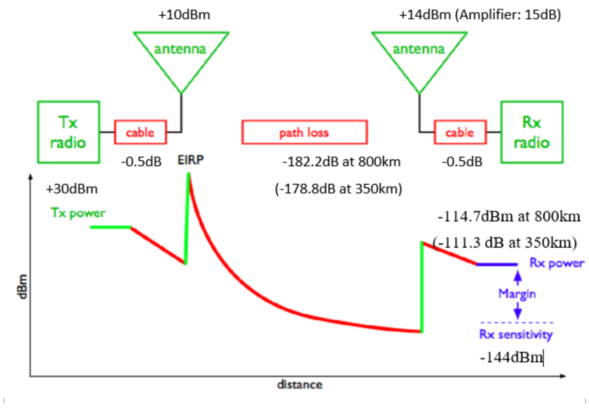

Figure 8: Diagram illustrating link budget for INSPIRESat-1.

The free space loss in the link budget calculation was performed using horizontal ranges corresponding to 0° elevation of an 800 km (worst case) and 350 km orbit, while line losses were assumed to be -0.5 dB [Wertz and Larson, 1999]. Tx antenna gain was assumed to be 10 dBm, based on COTS antenna models. The Tx power of the Astrodev Helium 100 is 30 dBm. The parameters of the ground station components were based upon the NCU ground station, which utilizes a HyGain 218sat antenna with 14 dBm gain, and 15 dB amplifiers.

The ground station receiver used is an ICOM IC-9100 transceiver, which has a sensitivity of -144 dBm. This is sufficient to receive the worst case predicted power of -114.7 dBm at 800 km horizontal range, as well as the -111.3 dBm at 350 km horizontal range.

From the above, we have determined that the Astrodev Helium 100 transceiver, combined with our existing UHF/VHF ground station, is sufficient to meet both data rate and link budget requirements of INSPIRESat-1.

CONCLUSIONS

In the above, we have presented a feasibility study for the INSPIRESat-1 mission intended to demonstrate and operationally test the DWTS radiometer, which will greatly advance satellite observations and monitoring of the Earth's middle and upper atmosphere. Our feasibility study shows that the subsystem requirements of an 800 km low Earth orbit (LEO) mission can generally be met using COTS CubeSat components, utilized with a 6U CubeSat bus. Key challenges identified include satisfying the spacecraft power requirements, while also satisfying the DWTS operational pointing requirements. Achieving proper thermal control to ensure that all components are within their operational temperature range using only passive thermal control mechanisms will also require further detailed modelling and analysis.

This collaborative spacecraft design project has allowed students and researchers at the NCU to engage in capacity building, expanding NCU's expertise from space science research and payload design to spacecraft design and mission operations support. These new capabilities will form a symbiotic relationship with existing abilities in space science research, space environmental monitoring, and forecasting. Observational capability, as well as an understanding of operational space weather needs will be greatly enhanced.

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