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IDEASSat: The Ionosphere Dynamics Explorer and Attitude Subsystem Satellite

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ABSTRACT

CubeSats are becoming an increasingly important and viable platform for space physics observations, in addition to their longstanding role in education and technology demonstration. With proper mission formulation, design, and testing, CubeSats have the potential to extend the capability of observations from large satellite missions. The Ionosphere Dynamics Explorer and Attitude Subsystem Satellite (IDEASSat / INSPIRESat-2) is a 3U CubeSat mission funded in part by the Taiwan National Space Organization (NSPO) and executed by Taiwan National Central University (NCU) in conjunction with international partners as part of the International Satellite Program in Research and Education (INSPIRE) consortium. The science payload is the Compact Ionospheric Probe (CIP): an all in one in-situ plasma sensor combining retarding potential analyzer, ion trap, ion drift meter, and planar Langmuir probe modes in a time-sharing manner, providing measurements of ion density, temperature, composition, and drift velocity, as well as electron temperature. CIP traces its heritage to the Advanced Ionospheric Probe (AIP) launched and currently operational onboard the FORMOSAT-5 satellite since August 2017. With both spacecraft operational in high inclination Sun synchronous orbits following the expected IDEASSat launch in 2020, comprehensive in-situ measurements of ionospheric variability and irregularities can be obtained to understand their effects on radio communications and satellite navigation signals.

INTRODUCTION

The Earth's ionosphere is comprised of plasma formed from the photoionization of the tenuous neutral air of the mesosphere (~50 – 90 km altitude) and thermosphere (~90 - >500 km altitude). Mixed with the denser neutral gasses of the upper atmosphere, the structure, composition, and motion of ionospheric plasma is influenced both by the neutral atmosphere – including vertical coupling with the lower and middle atmosphere, as well as to driving geomagnetic and solar effects[1]. As such, the ionosphere forms part of the interface between the Earth's atmosphere and near-Earth space.

In addition to its role in the Earth system, the ionosphere has a direct effect on modern wireless communications and navigation technology, both terrestrial, and space borne. Ionospheric plasma will reflect radio waves with frequencies that are identical to the plasma frequency, determined by the plasma electron density. It has thus been well known since the early 20th Century that high frequency (HF, 3 – 30 MHz) radio signals launched obliquely can propagate extremely long distances, and are utilized extensively for civil broadcasting, as well as civil and military aviation, maritime, and other long-distance communications[2]. Ionospheric total electron content (TEC) along the line of sight between Global Navigation Satellite System (GNSS) satellites and receivers can also introduce a time delay to the measured pseudorange, thus contributing significantly to positioning error[3]. Finally, irregularities and gradients in ionospheric plasma such as equatorial plasma bubbles or sporadic E clouds can cause the rapid fluctuation of satellite communications or navigation signals. This phenomenon, known as scintillation, can cause severe signal fading and loss of lock, thus disrupting the use of such satellite systems[4]. Understanding the structure and variability of the ionosphere, as well as the distribution and driving mechanisms of the aforementioned phenomena is therefore of great importance for the continued use and design of such technologies.

Owing to the remoteness of the domains to be observed, as well as the need for global scale measurements, small satellites have long been of interest for their potential to address the observational needs of the aeronomy, space weather, and geospace communities. In the following, we introduce the science mission and spacecraft design of the Ionosphere Dynamics Explorer and Attitude Subsystem Satellite (IDEASSat). IDEASSat is a 3U CubeSat funded in part by the Taiwan National Space Organization (NSPO) as part of an effort to develop indigenous spacecraft design and operations capacity, as well as to encourage growth of the indigenous aerospace sector. The spacecraft is being developed by student teams at the Graduate Institute of Space Science at Taiwan National Central University (NCU) and forms the inaugural mission for the NCU Center for Astronautical Physics and Engineering (CAPE) supported by the Taiwan Ministry of Education.

IDEASSat is being developed utilizing experience gained by NCU students and faculty from participation in the International Satellite Program in Research and Education (INSPIRE) and utilizes customized designs from INSPIRESat-1 – the first spacecraft developed under this international consortium. In that sense, IDEASSat is considered to be INSPIRESat-2, the second satellite developed by the INSPIRE consortium[5].

Table 1: IDEASSat Science Traceability Matrix.

Science Objectives	Objectives / Measurement	Measurement Requirements (Capabilities)	Instrumentation	Instrument Requirements (Capabilities)	Data Processing Requirements (Capabilities)
Science: Ionosphere					
S1. Measure planetary scale waves and structures in the ionosphere and quantify their variability and contribution to ionospheric structure. S2. Measure the distribution, occurrence rate, and structure of ionospheric irregularities and Travelling Ionospheric Disturbances (TIDs). S3. Infer the electric fields driving horizontal plasma drift, and their relation to the ionospheric F region wind dynamo.	Ionospheric parameters in the F-region (400 – 600 km altitude). 20 km (100 km) horizontal sampling resolution. Latitude range exceeding +/- 30°. 400 - 600 km orbital plane in quadrature or parallel with DMSP / FORMOSAT-5. Likely 0930 – 1030LT. Observations for at least six months.	Horizontal resolution: At least 0.5x the horizontal scale of a typical plasma bubble. Orbit: Pointing knowledge Lifetime: 6 months	Compact Ionosphere Probe (CIP)	90° FOV. Power: < 5 W Pointing Accuracy: Ram pointing, < 0.5° Pointing Knowledge: < 0.1° Science Data Packet Size: 280 bytes / packet	Onboard Storage (1 month of data): > 5 GB Daily Downlink: 24.8 MB/day, 1 raw data packet every second, full mode cycle every 3 seconds (4.6 MB/day, if sampled as 1 raw data packet every 15 seconds).
Science - ADCS					
E1. To perform an operational test for components of the Taiwan Attitude Determination and Control Subsystem (ADCS).	Spacecraft attitude and angular velocities. Spacecraft position and time. Star tracker imagery.	Operation during eclipse. Campaign to be performed when scheduling and power requirements allow.	GPS BC XACT ADCS module	Image Size: 25 Mb	Attitude Determination Experiment: Daily data volume not to exceed 150 Mb/day

MISSION

Mission Definition

Reflecting the needs of the aeronomy community and the need for aerospace capacity building in Taiwan, the scientific objectives of the IDEASSat mission can be classified into the categories of a primary mission focused on ionospheric science, as well as a secondary mission concerning spacecraft attitude determination.

The Science Traceability Matrix of the IDEASSat mission is shown in Table 1. The first objective of the ionospheric science mission (S1) is to measure the planetary scale structures of the Earth's ionosphere, such as the well-known zonal variability in the equatorial ionization anomalies (EIAs) driven in part by the vertical propagation of nonmigrating atmospheric tides excited in the lower atmosphere[6]. This requires a latitude range spanning ±30° latitude, covering the EIA region where such effects are expected to be strongest. The structure and occurrence rates of smaller scale ionospheric irregularities such as scintillation causing equatorial plasma bubbles will also be measured (S2), again requiring measurements in the low latitude region[7]. As such equatorial plasma bubbles are a nighttime phenomenon, it is therefore crucial that measurements be made during eclipse. The small horizontal spatial scale of such phenomena also necessitates sampling rates for the science payload sufficient to resolve scales at least as small as 20 km. This roughly corresponds to a 3 second sampling cadence for low Earth orbit (LEO) velocities. Finally, the drift velocity of ionospheric plasma will also be measured to understand the directions and distribution of the driving electric fields (S3). Ionospheric parameter observations that will achieve this goal include ion and electron temperatures, ion drift velocity, ion density, and ion composition. These parameters are within the measurement capability of the Compact Ionospheric Probe (CIP) that will be described in the next section.

All three ionospheric science goals require a mission lifetime of at least 6 months to partially resolve seasonal ionospheric variation. The design lifetime for IDEASSat is one year. Compliance with orbital debris disposal requirements mandates deorbit within 25 years of the end of mission. Reentry analysis for a standard 3U CubeSat with deployable solar panels indicate that both of these requirements are attainable for circular orbits with altitudes between 400 – 600 km. We have therefore selected a 500 km Sun synchronous orbit (97.41° inclination) as our nominal orbit, with local time of ascending node near 10:00 local time, which is similar to that of FORMOSAT-5 at 720 km. The longest eclipse percentage for Sun synchronous orbits of various beta angles at 500 km altitude is less than 40%. Sun synchronous orbits are also attractive in that secondary payload launch opportunities are more readily available.

The secondary mission for IDEASSat involves the development of attitude determination capacity. Images from an onboard star camera will be acquired and transmitted to the ground for use in tests of image recognition and attitude determination algorithms. The derived attitude will then be compared to that of the TRL 9 onboard attitude determination and control subsystem (ADCS). It was initially envisioned that a star camera developed at NCU would be flown for this purpose. However, this plan was later abandoned due to the space constraints inherent to a 3U CubeSat. Data acquisition for this secondary mission will be performed using the star camera of the onboard XACT ADCS from Blue Canyon Technologies (BCT) when conditions and data volume constraints permit.

Payload: Compact Ionospheric Probe

The Compact Ionospheric Probe (CIP) is a payload uniquely suited to achieve the objectives of the IDEASSat ionospheric science mission. CIP is an all-in-one in-situ plasma sensor derived from the larger Advanced Ionospheric Probe (AIP) developed at NCU and launched aboard the FORMOSAT-5 satellite in August 2017[8]. AIP has been operational since September 2017 and is performing nominally with a duty cycle of approximately 33% in the low latitudes during eclipse.

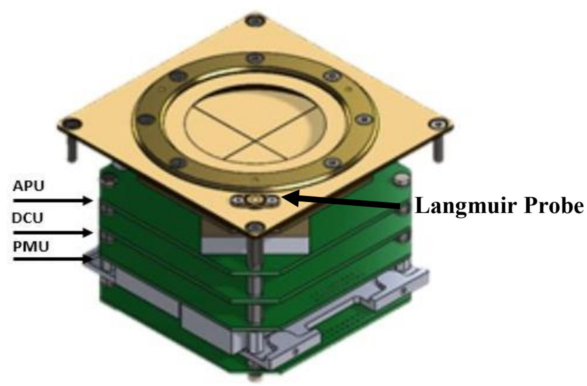

Figure 1: CIP mechanical structure.

Like AIP, CIP combines and switches between four operational modes, each providing a unique set of plasma measurements:

- Planar Langmuir Probe (PLP): electron temperature.
- Ion Trap (IT): Ion density.
- Retarding Potential Analyzer (RPA): Light / heavy ion mass ratio, ion temperature, ion velocity magnitude.
- Ion Drift Meter (IDM): Ion arrival angle.

Combining the ion velocity magnitude, ion arrival angle, and spacecraft velocity vector, the ion velocity vector can be derived. The raw data from each operational mode takes the form of current and voltage curves, which are formed into science data packets for each individual measurement.

The mechanical structure of CIP is shown in Figure 1. The Aperture and Meshes Module (AMM) contains the PLP electrodes, grids, collectors, and sensor pot, which are exposed to the plasma environment. There are three printed circuit boards behind AMM. These are the Analog Preprocessing Unit (APU), Digital Control Unit (DCU), and Power Management Unit (PMU).

The requirements and specifications of CIP are shown in Table 2. CIP is designed to be flown in the ram direction when operational. The pointing knowledge and control requirements are stringent, respectively 0.1° and 0.5°. CIP has a UART serial interface and returns science data packets of 280 bytes size for each individual measurement. CIP can perform measurements and return science data packets at a cadence of 1 Hz (Normal mode) or 8 Hz (Fast mode), with the latter allowing for spatial resolution of ionospheric structures on the order of 1 km (0.95 km for the nominal 500 km orbit). For 100% duty cycle, this results in a science data rate of 24.1 MB day^{-1} for Normal mode and 193.5 MB day^{-1} in Fast mode.

Table 2: CIP requirements and specifications.

Mass	0.6 kg
Volume	0.8U
Power	Peak: 5 W Nominal: 3.84 W
Data Interface	UART serial data bus in a Modbus-like protocol. RS-422 encoding with LVTTL logic levels
Data Rate (100% duty cycle)	Normal: 24.1 MB day^{-1} Fast: 193.5 MB day^{-1}
Pointing Knowledge	< 0.1°, all axes.
Pointing Control	Aperture facing ram direction < 0.5°, all axes.

The Ion Velocity Meter (IVM) aboard the six FORMOSAT-7/COSMIC-2 satellites, each with a mass of approximately 215 kg, utilizes the same operational principles as CIP. To elucidate the difference in spatial resolution between the two instruments, we note that the requirements for the IVM sampling rates are 1 Hz for ion density, temperature, in-track drift, and mass fraction, and 4 Hz for cross-track drift. For the Special Sensor for Ions and Electrons (SSIES) onboard Defense Meteorological Satellite Program (DMSP) satellites, the sampling rate ranges from 24 to 0.25 Hz, depending upon the measurement mode. CIP therefore offers to potential to complement and enhance the observational capacity of fine scale ionospheric structures and irregularities, while utilizing a 3U CubeSat platform.

From the above, it can be seen that key challenges for the spacecraft design using a 3U CubeSat platform include the tight pointing requirements and the large data volume that can be produced, especially if CIP is operated in Fast mode. Additionally, the limited volume of a 3U CubeSat is also a major constraint.

SPACECRAFT

System Level Description and Concept of Operation

Per the resources available from NSPO, as well as capacity building considerations as the first independently developed spacecraft at NCU, IDEASSat is a 3U CubeSat conforming to CubeSat design specifications and the P-POD deployer requirements.

The mechanical design of IDEASSat is shown in Figure 2. The spacecraft is a 3U CubeSat with one body mounted, and two deployable solar panels. A deployable UHF tape measure antenna is used for beaconing and command uplink, while an S-band patch antenna is used for higher bandwidth science data downlink. We define a coordinate system with the *x*-axis normal to the same face as the BCT XACT ADCS star tracker. The *z*-axis is normal to the face opposite the CIP aperture, which is also the anti-ram direction when CIP measurements are being made in Science mode. The *y*-axis points normal to the face of the spacecraft opposite that covered by the body mounted solar panels, such that the coordinate system is righthanded. We note that the number of solar cells on the body mounted panel are subject to change. Power estimates in this paper are based on a conservative worst-case scenario of five cells.

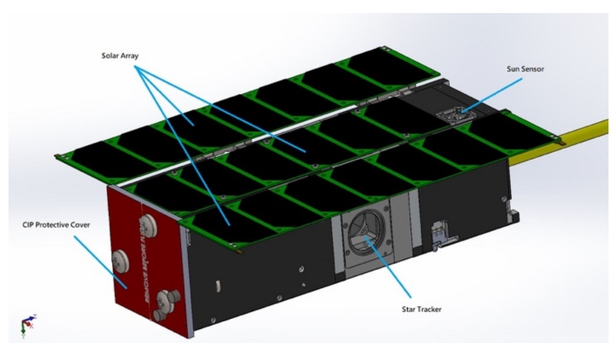

Figure 2: IDEASSat mechanical design. Note the Remove Before Flight cover over the CIP aperture.

The components used to satisfy the IDEASSat subsystem requirements are listed in Table 3, as well as the corresponding Technological Readiness Level

(TRL). IDEASSat includes both Commercial Off the Shelf (COTS) components, as well as components developed at NCU in collaboration with INSPIRE partner universities. In addition to IDEASSat, CIP is also the science payload aboard the 8 kg INSPIRESat-1. This has enabled the rapid development and customization of common subsystems and designs between the two projects.

Table 3: IDEASSat subsystem components.

Subsystem	Solution	TRL
ADCS	Blue Canyon Technologies XACT with GPS	9
COMM (UHF transceiver)	SpaceQuest TRX-U	9
COMM (UHF Antenna)	CU deployable monopole antenna	9
COMM (S-band transmitter)	CPUT STX-01-0017	9
EPS (Battery & Control PCBs)	Modified INSPIRESat-1 EPS	3
EPS (Solar Cells)	AzurSpace TJ Solar Cell Assembly 3G30A	9
CDH	Modified INSPIRESat-1 IIST CDH Board	5
	Emcraft SmartFusion2 System-on-Module	5
STR	Modified INSPIRESat-1 bus	3

The overall selection criterion for IDEASSat subsystems has been to develop specific subsystems in-house that were judged to be within the current capabilities available at NCU, while selecting high TRL COTS components for subsystems where NCU capacity is still being developed. EPS and CDH are arranged in a PC104 stack, whereas the other subsystems are interfaced by means of cabling and adaptor boards.

IDEASSat is designed to transition between four operating modes. The operational state of the individual subsystems in different modes are shown in Table 4.

Table 4: IDEASSat Operational Modes.

	Phoenix	Safe	Charging	Science
EPS	ON	ON	ON	ON
ADCS	OFF	ON	ON	ON
CDH	ON	ON	ON	ON
UHF (Tx)	BEACON	BEACON	BEACON	BEACON
UHF (Rx)	ON	ON	ON	ON
S-Band (Tx)	OFF	OFF	AS REQ.	AS REQ.
CIP	OFF	OFF	OFF	ON

The nominal operation of IDEASSat is to transition to Science mode during eclipse and Charging mode when in sunlight. CIP is powered on during Science mode and will be able to observe nighttime plasma irregularities. The spacecraft attitude will be such that the CIP aperture on the *-z* face will be pointed in the ram direction. In Charging mode, CIP is powered down, while the spacecraft attitude is adjusted such that the body mounted and deployed solar panels on the *-y* face are oriented towards the Sun to maximize power generation. Science data will be downlinked via S-band when passing over S-band ground stations participating in the INSPIRE consortium, including in Boulder, Colorado, as well as S-band stations being installed at NCU in Taiwan and the Indian Institute of Space Science and Technology (IIST) in India. Command uplink via UHF will occur when passing over NCU, while regular beaconing of housekeeping data at a set beaconing rate will occur continuously.

Safe and Phoenix modes are power saving modes intended to allow the spacecraft batteries to recover to a higher state of charge in the event of higher discharge levels. It is possible that such high discharge situations could occur due to battery discharge during pre-deployment storage, or due to anomalously high levels of power consumption post-deployment. Safe mode is a reduced power consumption case of Charging mode. During Safe mode, S-band data downlinks will cease, and the spacecraft will not transition to Science mode during eclipse. As in Charging mode, the spacecraft will orient to maximize sunlight exposure for the solar panels during Sunlight. For extreme cases of high battery discharge, the spacecraft will enter Phoenix mode. In this situation, power requirements are further reduced by powering off the ADCS. The tradeoff of reduced power consumption in this case is the loss of Sun-pointing capability to maximize power generation, the effect of which must be modelled extensively to ensure that the spacecraft will be capable of recovering from Phoenix mode.

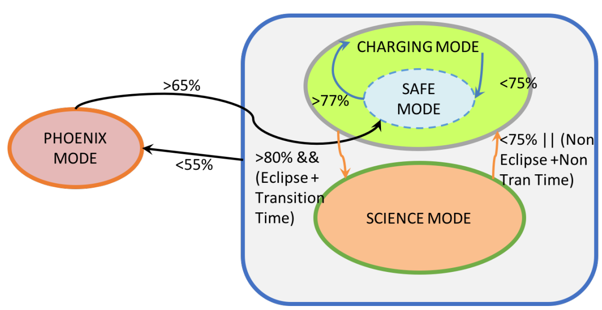

Figure 3: IDEASSat mode transition conditions.

The conditions and pathways for operational mode transitions are illustrated in Figure 3. Mode transitions are based on a combination of battery charge level and lighting state. The spacecraft will transition to Science mode in eclipse only if the battery is at 80% charge level when crossing the terminator. If the battery charge level falls below 75% at any point in Science mode, the spacecraft will immediately halt CIP observations and transition to Safe mode. Further reductions in battery charge level to values below 75% will result in Safe mode, while charge levels less than 55% will result in Phoenix mode. The threshold battery charge levels for mode transitions are designed as parameter tables in flight software that may be reconfigured as necessary.

IDEASSat is designed to be deployed from P-POD or compatible CubeSat deployers. Per CubeSat specifications, the spacecraft will be powered off while inside the P-POD through the deployment switches located at the base of the deployment rails. Following deployment, IDEASSat will remain inert for 30 minutes, after which the spacecraft will check the status of flags indicating the state of the deployable solar panels and UHF tape measure antenna. The deployable devices are restrained through use of nylon fishing wire (burn wire) tied around resistors, with deployment accomplished by passing a current through the resistor to melt the burn wire. If the deployment flags indicate negative deployment, the flight software will activate the burn wires simultaneously, which was demonstrated to be effective by the Miniature X-ray Solar Spectrometer (MinXSS) CubeSat mission in 2016[9]. The flight software will continuously activate the burn wires periodically, until the deployment flags are reset by uplinked command. Since uplink and beaconing will not be possible until the UHF antenna is deployed, this ensures that deployment attempts continue until successful. Housekeeping data indicating solar panel voltage levels can be analyzed to determine whether solar panel deployment has been successful.

Electrical Power Subsystem (EPS)

The IDEASSat EPS is comprised of one body mounted and two deployable solar panels, as well as a power controller board, and a battery module. The primary requirement driving the design of the EPS is the need to remain power positive in all operational modes, while also complying with the limited size and volume of a 3U CubeSat.

For power generation, the IDEASSat solar panels include two deployable solar panels with seven AzurSpace 3G30A solar cells. The body mounted solar panel includes five AzurSpace 3G30A solar cells,in order to accommodate the ADCS Sun sensor and GPS antenna. In full Sun, the solar panels are capable of generating 23.11 W of power. The solar panel design is a modification of that utilized aboard MinXSS[10].

The power budget of IDEASSat over one orbit in the nominal Science and Charging modes is shown in Table 5. The power budget accounts for duty cycling of various subsystems, including the eclipse only duty cycle of CIP, the sunlight duty cycle of the solar panels oriented to full Sun in Charging mode, as well as UHF and S-band transmissions while passing over INSPIRE ground stations at NCU. IIST, and CU. The eclipse percentage assumed here is a worst case of 40%. We have additionally included a 30% reserve power on top of current estimated requirements to account for possible future increases in power requirements.

Table 5: Nominal power budget in Science and Charging modes.

Subsystem	Nominal Power (W)	Duty Cycle (%)	Avg. Nominal Power (W)
EPS	1.78	100.00	1.78
ADCS	4.12	100.00	4.12
CDH	0.91	100.00	0.91
UHF (Tx)	7.00	1.67	0.12
UHF (Rx)	0.20	100.00	0.20
S-Band (Tx)	4.60	0.86	0.04
S-Band (Stand by)	0.61	99.14	0.60
CIP	3.465	40.00	1.39
		Total	9.16
		30% reserve	2.75
Solar Panels	23.11	60.00	13.86
		Margin (%)	51.41

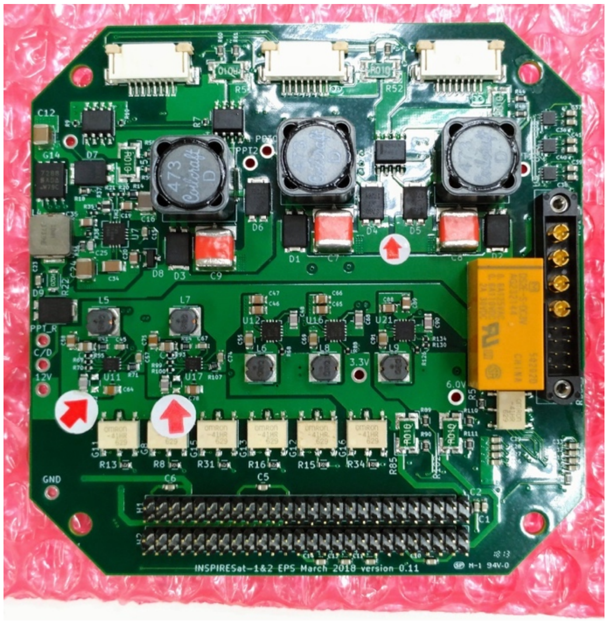

Figure 4: EPS controller board.

With a 40% duty cycle for CIP under these nominal power requirements, the spacecraft is still power positive with a margin of 51.41%. We note that the duty cycle for AIP aboard FORMOSAT-5 is approximately 33%, due to scheduling and slewing constraints.

The self-developed EPS power controller board (Figure 4) includes ICs to handle DC/DC conversion for the power rails to the individual subsystems, deployment and kill switch circuits for pre-deployment and deployment power cutoff needs, maximum power point tracking, as well as thermistors and I2C voltage sensors to monitor component temperatures, and a PC104 external interface. The power control board has been subject to debugging by iteration, where prototypes were subjected to a battery of validation tests to ensure compliance and identify necessary revisions. This has led to several lessons learned, including the identification of anomalous voltage drops due to a defective lot of solid state relays used as power rail switches.

A separate battery module includes four cylindrical Sanyo 18650A lithium ion batteries, which have extensive prior flight heritage. The battery module also includes charging regulators, temperature sensors, as well as a battery heater. This accounts for the fact that the batteries have the tightest temperature constraints aboard the entire spacecraft.

Attitude Determination and Control Subsystem (ADCS)

CIP has extremely stringent attitude knowledge and control requirements. Attitude knowledge must be to within 0.1°, while attitude control must be to within 0.5°. These requirements will be satisfied using the COTS XACT high precision ADCS module produced by Blue Canyon Technologies. The pointing accuracy stated on the XACT datasheet is ±0.003° for two axes and ±0.007° for the third axis, which are compliant with CIP requirements. The first on-orbit test of the XACT was aboard the MinXSS CubeSat mission, where it was observed to have a pointing accuracy of 0.0042°, 0.0117°, and 0.006°, and successfully detumbled the spacecraft following Nanoracks deployment from the International Space Station (ISS) in 145 seconds[11]. We note that these values correspond to the first generation of the XACT. A third-generation model will be used for IDEASSat.

As configured for IDEASSat, the XACT ADCS will contain three reaction wheels and three torque rods for actuation. Sensors include a star tracker, an externally mounted pyramid Sun sensor, magnetometer, and an internal inertial measurement unit. The XACT is interfaced with a NovAtel OEM719 GPS receiver, which is utilized autonomously by the XACT to provide spacecraft ephemeris which can be saved as housekeeping data or used to initialize onboard orbit propagators for navigation purposes in the event of loss of GPS signal.

The XACT initially boots into a Sun pointing safe mode, where the Sun sensor is utilized to search for the Sun, and maximize the sunlight falling on the face of the spacecraft upon which the Sun sensor is mounted. As such, the Sun sensor on IDEASSat is located on the *-y* face, which corresponds to the orientation of the three solar panels following successful panel deployment. To accommodate the Sun sensor, as well as a GPS patch antenna, the body mounted solar panel will only contain five or six cells. The ADCS will be off in spacecraft Phoenix mode and powered on in spacecraft Safe mode. The positioning of the Sun sensor ensures that the solar panels will be exposed to maximum Sun following the transition to Safe mode.

Following the acquisition of valid attitude, time, and ephemeris, XACT will transition to Fine Reference Point mode, which will allow much more precise pointing. This will be the ADCS mode required for nominal operation of the spacecraft, allowing for CIP to be pointed in the ram direction in Science mode, and for the solar panels to be rapidly oriented to face the Sun in Charging mode.

Communications Subsystem (COMM)

The COMM requirements for IDEASSat will be satisfied using UHF transmissions for command uplink and beaconing of housekeeping and tracking data. The large science data volume will be downlinked using an S band transmitter aboard the spacecraft. The two frequencies are complementary as S-band has a much higher bandwidth compared to UHF but has fewer ground stations. Conversely, there are a large number of UHF ground stations operating in the 430 – 440 MHz amateur radio band, which maximizes coverage for tracking purposes.

IDEASSat will use the COTS SpaceQuest TRX-U UHF transceiver operating with a baud rate of 9600 bps, which ensures compatibility with most COTS amateur radio transceivers. The TRX-U supports four preset uplink/downlink channel combinations, which will be submitted in our IARU (International Amateur Radio Union) frequency coordination application and can transmit with power of 1 to 5 Watts. In this case, we will utilize half duplex communications. Packetizing of the data to be transmitted will be handled by CDH, while the TRX-U will handle modulation and demodulation.

IDEASSat COMM extensively utilizes designs that were flight proven aboard MinXSS and shares several characteristics with that of INSPIRESat-1. The UHF modulation will be GMSK, which is consistent with that utilized by MinXSS and is compatible with existing hardware. The TRX-U will be interfaced with a deployable tape measure quarter wave monopole antenna based upon that utilized by MinXSS[9]. The antenna deployment module is mounted just inside the +*z* face of the spacecraft and is secured in a closed position using the previously described burn wire mechanism. Laboratory tests with a network analyzer have shown that the length and standing wave ratio (SWR) of the antenna is heavily dependent upon the size, material, and interface of the antenna module to the ground plane. As such, the length of the quarter wave monopole antenna may not be exactly one quarter of the wavelength and must be determined through testing in the final flight configuration.

Nominal INSPIRE ground stations that will be used for IDEASSat operations include UHF transceivers at NCU, CU, and IIST. S-band ground stations are also in the process of being installed at all three locations. The UHF ground stations all share a similar setup, consisting of Yagi UHF antennas mounted atop an antenna rotator, interfaced with low noise amplifiers (LNAs) and a PC, utilizing a terminal node connector (TNC) for demodulation. This is shown in the case of the NCU UHF/CHF ground station shown in Figure 5. In the case of the NCU ground station, antenna control and Doppler correction are handled using the commercially available Ham Radio Deluxe software suite.

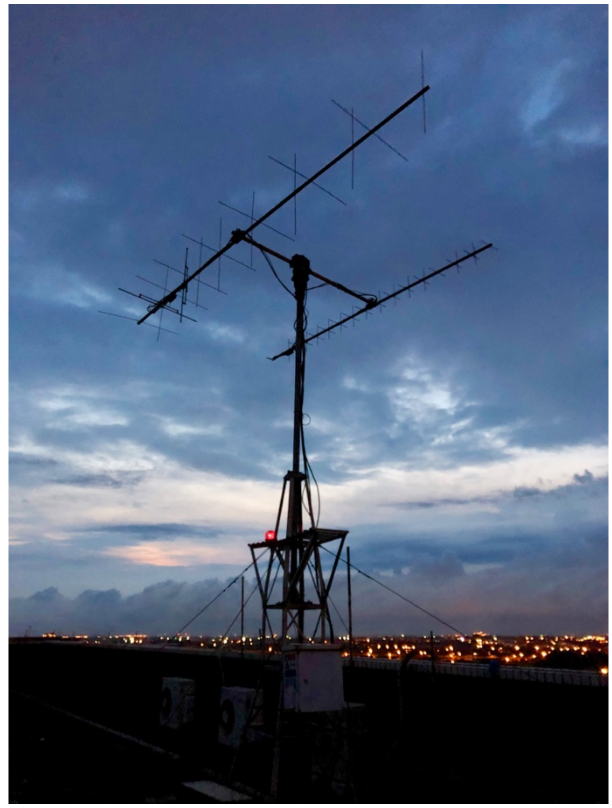

Figure 5: UHF/VHF ground station at NCU.

Table 6: UHF downlink link budget at NCU.

PARAMETER	**Downlink**		**UNITS**
System Parameters	MAX	MIN	
Frequency	0.437	0.437	GHz
Data Rate	9600	9600	bps (Hz)
Data Parameters			
Bit Error Rate Req.	1E-5	1E-5	[-]
Data Coding Scheme	GMSK/GFSK	GMSK/GFSK	
Required Bit Energy to Noise Ratio	9.6	9.6	dB
Carrier to Noise Ratio Density	49.42	49.42	dB-Hz
Required Design Margin	3.00	3.00	dB
Minimum Pr/No	**52.42**	**52.42**	**dB-Hz**
Propagation Parameters:			
Space Loss	-149.83	-149.83	dB
Atmospheric Attenuation (clear air)	-0.1	-0.1	dB
Polarization Loss	-3.0	-3.0	dB

Transmitter Parameters:			
RF Transmit Power	2	1.5	W
RF Transmitter Power	3.01	1.76	dBW
Effective Isotropic Radiated Power	3.76	2.51	dBW
Link Budget:			
Propagation Losses	-152.93	-152.93	dB
Receive System Gain	30.92	30.92	dB
Received Power	-118.25	-119.50	dBW
Receiver Sensitivity	-152.00	-152.00	dBW
Power Margin	33.75	32.50	dBW
System Noise Power	-199.09	-199.09	dBW/Hz
Carrier to Noise Ratio Density	80.84	79.59	dB-Hz
Minimum Pr/No	52.42	52.42	dB-Hz
Link Margin	**28.42**	**27.17**	**dB**

The UHF link budget for nominal IDEASSat downlink at NCU has been calculated and is shown in Table 6 for both maximum and minimum transmitter power. The link budget assumes a worst case of 10° minimum elevation angle, and including losses due to free space, polarization, atmospheric, residential, and receiver noise. Despite these factors, IDEASSat COMM is still link positive in both cases with the received signal to noise ratio (Pr/No) exceeding the minimum required to maintain a bit error rate (BER) of 1E-5. UHF uplink is similarly link positive (not shown).

To determine the data volume that can be downlinked, the access times between IDEASSat and the three ground stations at NCU, CU, and IIST have been calculated over the year of 2021. We only consider access times longer than 5 minutes in duration, to account for the time required for handshaking.

Table 7: Ground station access times and data volume for 2021.

Ground Station	Mean duration per access (min)	Total access time (min)	Total data volume (MB)		Mean daily data volume (MB)	
			UHF	S-band	UHF	S-band
CU	6.67	5828.75	419.67	87431.2	1.10	229.17
NCU	5.66	2483.57	178.82	37253.6	0.47	97.92
IIST	6.61	4322.06	311.19	64830.9	0.81	168.0

The resulting mean duration per access, as well as total access time over 2021 are shown in Table 7. It can be seen that on average, each pass over a ground station has a duration on the order of 6 minutes. The total access time is highest over CU, which is a midlatitude station, owing to the high inclination of the 500 km Sun synchronous orbit. Although NCU and IIST are both located in the low latitudes, the access time over NCU is shorter due to the higher minimum elevation angle of 15°, versus 10°. This is considered to be a conservative estimate, pending more rigorous testing for the NCU UHF ground station.

We again note that the science data rate for CIP is 24.1 MB day^{-1} for Normal mode and 193.5 MB day^{-1} in Fast mode at 100% duty cycle. Applying the 9600 bps UHF baudrate, it is apparent from the estimated UHF total and mean daily data volumes shown in Table 6 that UHF alone is insufficient for downlinking the science data produced by CIP, even with the aforementioned 40% duty cycle. Constraining downlink to UHF also negates the high sampling frequency of Fast mode, which is one of the key scientific advantages of CIP.

As such, IDEASSat will utilize the Cape Peninsula University of Technology (CPUT) STX high bandwidth S-band transmitter for science data downlink. Operating on the amateur band between 2.4 – 2.45 GHz with output power from 24 – 30 dBm and QPSK modulation, the STX is capable of data transmission rates of up to 2 Mbps. The CPUT STX will be connected to a nadir pointing S-band patch antenna located on the +*y* face of IDEASSat. The S-band total and mean daily data volumes shown in Table 6 clearly show that the STX provides more than sufficient data downlink volume to satisfy the CIP data downlink requirements in Fast mode when utilized either with the mid-latitude CU S-band ground station only, or by combining S-band receivers to be installed at the low latitude NCU and IIST ground stations.

IDEASSat is being licensed as a space station by the Taiwan National Communications Commission (NCC) and will be one of the first space stations licensed in Taiwan. Licensing will also be sought in the United States and India in order to allow for command uplink at the CU and IIST ground stations. In this process, assistance from the amateur radio community in Taiwan and the Chinese Taipei Amateur Radio League (CTARL) has been invaluable. Acceptance tests of the TRX-U have been conducted using a PC serial terminal across a USB / TTL interface.

Command and Data Handling (CDH)

As in the case of EPS, IDEASSat utilizes a self-developed CDH subsystem adapted from the IIST-led CDH design of INSPIRESat-1. The CDH is comprised of a COTS Emcraft SmartFusion2 System-on-Module (M2S-FG484 SOM), which includes a System On Chip (SOC) containing a microprocessor embedded in an FPGA. The original manufacturer's baseboard for the SOM has been replaced by a "flight card", which provides the interfaces to the spacecraft subsystems. The IDEASSat flight card has been modified from that of INSPIRESat-1 (Figure 6) to account for variations in pin mapping and interfaces but retains a PC104 connector.

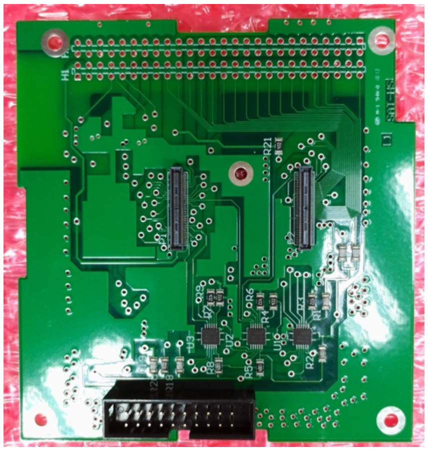

Figure 6: Flight card for INSPIREsat-1 to be customized for IDEASSat.

CDH is responsible for execution of flight software, polling sensors and subsystems for housekeeping data, issuing commands to the various subsystems, as well as storing and retrieving data returned from other subsystems on a space grade SD card. Considering the requirement that CDH shall be capable of storing three months of science and housekeeping data, this requires an SD card with a capacity of 18 GB or larger assuming a 100% duty cycle in CIP Fast mode. In practice, the actual volume used will likely be smaller since the CIP duty cycle will be 40% or less in nominal operation. In this case, the requirement can be satisfied using 8 GB of SD card storage. CDH will be capable of replaying stored data on command, in the event there is a backlog in data to be downlinked.

Structures (STR) & Thermal Control (TCS)

As shown previously in Figure 2, IDEASSat utilizes a 3U CubeSat platform with deployable solar panels and UHF tape measure antenna. Starting from the *-z* face of the spacecraft and proceeding along the *+z* direction, the component placement inside the spacecraft can be roughly divided into four sections:

- CIP: The CIP sensor head (AMM), along with the CIP processing, control, and power card stack (APU, DCU, and PMU).
- PC104 stack: This section contains a stack of PC104 subsystem boards, including CDH, the S-band CPUT transmitter, and EPS, ending with the battery module. The batteries are thermally isolated from the rest of the spacecraft.
- ADCS: The BCT XACT ADCS module and NovAtel OEM719 GPS receiver.
- UHF COMM: The final segment terminating in the *+z* face of the spacecraft includes the SpaceQuest TRX-U transceiver, and the deployable UHF tape measure antenna module. The TRX-U is in thermal contact with the spacecraft chassis to facilitate heat dissipation produced when transmitting.

The mass budget of IDEASSat is shown in Table 8. At the time of writing, the total mass of IDEASSat is estimated to be 3.57 kg. Considering the 3.99 kg mass limit for a 3U CubeSat according to CubeSat Design Specifications, this corresponds to a margin of 0.42 kg. We note however that the aforementioned estimate does not yet include the mass of cabling and harnesses, both of which can add substantial amounts of mass. Work is continuing to finalize the mechanical design for IDEASSat, as well as to reduce the volume and mass of required cabling and harnesses. Along with the aforementioned power generation constraints, the mass and volume limitations of a 3U CubeSat are indeed proving to be another challenge that must be overcome.

Table 8: IDEASSat mass budget.

Subsystem	**Mass (kg)**
CIP	0.60
ADCS	0.91
COMM	0.21
C&DH	0.09
Structure	0.96
Power	0.10
Battery	0.19
Solar Arrays	0.51
Total	**3.57**
Mass Limit	**3.99**
Margin	**0.42**

Work is ongoing to perform stress analysis on the IDEASSat mechanical structure, as well as to simulate the assembly process using 3D printed component models. Component level thermal analysis will also be performed using SINDA and SolidWorks simulations and meshing.

LESSONS LEARNED

IDEASSat is the first small satellite project undertaken and managed independently by the team at NCU. Over the course of this project and INSPIRESat-1, several lessons have been learned that have been invaluable for spacecraft design capacity building. A few of these lessons learned have been compiled and are shared below:

- The footprint / package size of ICs and other electrical components on data sheets can be incorrect. Always double check with calipers before finalizing PCB designs.
- The size of and connection to the ground plane can have a very large impact on the SWR of a monopole antenna. Always test in flight configuration when determining antenna length using a network analyzer.
- Different manufacturing lots of the same component can have different characteristics. Never exclude the possibility that PCB components ordered may be defective or damaged during the manufacturing process.
- If designing a new subsystem from scratch, expect multiple revisions and iterations. Budget accordingly and formulate a standard test procedure to speed development.
- Plan and write down test procedures and required equipment before beginning the test. Expect unexpected issues to appear during testing which can increase the expected time to finish the test by an order of magnitude or more.
- Maintaining a friendly working relationship with the local amateur radio community is a big boost for both COMM development, as well as student interest and training in RF subsystems. Conversely, the amateur radio community is strongly affected by space weather, which can lead to mutually beneficial relationships.
- Ground station maintenance and operation is a never-ending task that can require having on-site teams on standby at all times.
- Expect export licensing and procurement procedures to add one to three months of additional processing time / delays to the spacecraft development process.
- Things that are intuitive to people working on one subsystem may be completely foreign to those working on another subsystem. Never make assumptions, and always ensure good communication between subsystem teams.
- Collaboration, technical and cultural exchange with international partners is invaluable for capacity building.

CONCLUSIONS

We have described the need, mission objectives, and design of IDEASSat / INSPIRESat-2, a 3U CubeSat designed provide in-situ measurements of the ionosphere using the Compact Ionosphere Probe. IDEASSat observations will be valuable for quantifying ionospheric variability, as well as structures on planetary scales and smaller scales on the order of 1 km, which can affect GNSS and terrestrial HF radio propagation and scintillation.

IDEASSat successfully passed Preliminary Design Review (PDR) in December 2017. Critical Design Review (CDR) is scheduled for late July 2018, System Integration Review in April 2019, and flight model delivery in December 2019.

Our results indicate that despite the power, mass, volume, and data volume constraints of a 3U CubeSat in LEO, IDEASSat will be capable of operating and downlinking data acquired from CIP with 8 Hz sampling and a duty cycle of 40%. We note that this sampling rate and additional coverage complements that of similar in-situ payloads carried aboard much larger satellites such as FORMOSAT-7 / COSMIC-2 and DMSP. Furthermore, the 40% CIP duty cycle possible aboard IDEASSat exceeds the 33% duty cycle of AIP aboard FORMOSAT-5, albeit with a lower sampling rate. These results show that CubeSats have the potential to provide in-situ ionospheric observations with spatial coverage and sampling that is competitive with larger satellites. CubeSats such as IDEASSat will therefore be able to augment and expand the coverage of these large satellite missions, enhancing capabilities for studying ionospheric variation, and potentially providing new data sets for assimilation into ionospheric space weather models.

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