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Regional Ionosphere Mapping and Autonomous Uplink (RIMAU) Satellite Constellation for Space Weather monitoring and nowcasting over Singapore

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ABSTRACT

The Regional Ionosphere Mapping and Autonomous Uplink (RIMAU) mission is a constellation of six CubeSats in an equatorial orbit, making Radio Occultation (RO) measurements of the atmosphere and in-situ Ionospheric measurements to characterize the ionosphere over equatorial South-East Asia in near real time. RIMAU builds on the success of the VELOX-CI mission developed and operated at the Satellite Research Centre (SaRC) at Nanyang Technological University, which carried a commercial-off-the-shelf GPS receiver and have been operating successfully since December 2015. RIMAU will carry GPS receivers for RO and an Ionospheric payload, the Compact Ionosphere Probe (CIP) developed by National Central University of Taiwan, consisting of a planar Langmuir probe, retarding potential analyser and Ion trap/drift meter. RIMAU-1 is scheduled to be in operation by 2021 with the full constellation scheduled for flight by 2023. A secondary objective of RIMAU is to provide a Low Earth Orbiting nanosatellite platform for communication with remote sensors in the region. RIMAU-1 will demonstrate communication with remote water sensors monitoring water pollutants and uplink from ground based GPS sensors to adjust the sampling rate for the Ionospheric probe during periods of high scintillation. Understanding the occurrence and impact of Ionospheric irregularities is critically needed for equatorial countries like Singapore. In this paper, we present a novel idea to combine ground based and space based Ionospheric observations to monitor in near-real time the Ionosphere over the Singapore region to characterize Ionospheric disturbances and their impact on communication and navigation systems. The main data products from these measurements will be vertical profiles of the Total Electron Content (TEC) in the ionosphere, atmospheric temperature and humidity profiles in the troposphere. RIMAU TEC measurements will be combined with ground based TEC measurements from ~ 60 GPS receivers in the SE Asia region, operated by the Earth Observatory of Singapore to produce 3D maps of the Ionosphere.

INTRODUCTION

Ionospheric irregularities at low (equatorial) latitudes or "bubbles" can cause amplitude fades and phase distortions (a communications operator would say the signal has been "scintillated") of radio signals propagating between a satellite and Earth and thus have a detrimental impact on communications and navigation. Therefore, understanding the occurrence and impact of Ionospheric irregularities is critically needed for equatorial countries like Singapore. Figure 1 illustrates the effects of scintillation (left panel) on communication and navigation signals and the mechanism of scintillation (right panel) from Ionospheric anomalies. Forecasting Ionospheric plasma bubbles and their day-to-day variability is one of the long-standing frontier challenges in space physics. In this paper, we present a novel idea to combine ground based and space based Ionospheric observations to monitor for the first time ever in near-real time, the Ionosphere over the Singapore region.

The importance of Ionospheric irregularities at low latitudes has been appreciated for decades from the phenomenon known as spread-*F*, in which reflected radio signals are severely scattered The occurrence rate of irregularities can be strongly controlled by the geomagnetic conditions through Space Weather events and also be related to the perturbations from the neutral atmosphere. "*Plasma Bubbles*" of low-density plasma percolate through the higher density above. The steep gradients on the edges of the bubbles can cause the spurious radar echoes as well as amplitude fades and phase distortions of radio signals propagating between a satellite and Earth[1]. Ionospheric irregularities at low latitudes or "bubbles" can thus have a detrimental impact on communications and navigation. The irregularities can extend over hundreds of kilometres in altitude and many degrees of longitude, and have an adverse effect on ground-to-satellite and satellite-to-ground communication and navigation signals. For military application, one important study[2] demonstrated that the large-scale Ionospheric disturbances could potentially cause an outage on the UHF Satellite Communication used by U.S. Army during 4 March 2002 in Afghanistan war. An urgent message that was sent to the rescue team was never received. The communication outage turned the rescue mission into a 17-hour firefight and cost seven lives.

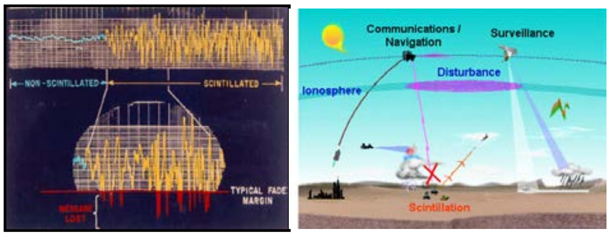

Figure 1: left: non-scintillated and scintillated signal. Right: Satellite signal scintillation mechanism.

The Regional Ionosphere Mapping and Autonomous Uplink (RIMAU) mission is a constellation of six 12U CubeSats in an equatorial orbit, making Radio Occultation measurements of the atmosphere and in-situ Ionospheric measurements to provide an understanding of the finer scale Ionospheric structure. The outcomes from this project is expected to be: (1) Vertical profiles of the Total Electron Content (TEC) in the ionosphere, and atmospheric temperature and humidity profiles in the troposphere. (2) RIMAU TEC measurements will be combined with the extensive already existing ground based TEC measurements to produce near-continuous regional 3D maps of the Ionosphere over the SE Asia region. (3) RIMAU will demonstrate the capability to autonomously communicate with remote GPS sensors on the ground to adjust the sampling rate for the Ionospheric probe during periods of high scintillation. By demonstrating continuous autonomous communication with remote sensors, RIMAU will provide a satellite communication network for any compatible autonomous sensor and demonstrate this with monitoring of sensors for water pollution.

MISSION

Proposed Approach

The state of the Ionosphere can be monitored by observations of the TEC measured from ground based GPS receivers which make use of Global Navigation Satellite Systems (GNSS) signals. Figure 2 shows TEC plot made from ground based and spaced RO measurements compiled by MIT Haystack laboratory. It can be seen from this figure that while the TEC measurements over Europe, North America and Japan are reasonably good, the Eastern hemisphere and Africa have large measurement gaps.

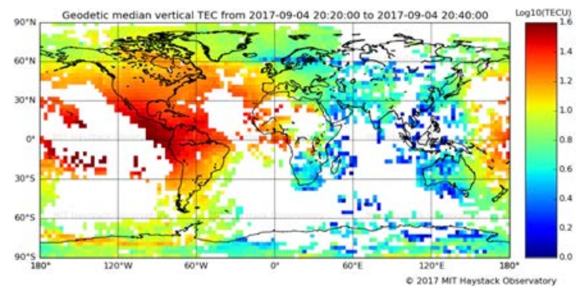

Figure 2: Global TEC maps available from ground based and space based observations compiled by MIT haystack laboratory for 04 September 2017

Figure 3 left panel shows the GPS receivers on the Earth Observatory of Singapore Sumatra GPS Array (SuGAr) network used for monitoring earthquakes and Tsunamis in the SE Asia region. GPS TEC data is also available from receivers in Singapore, Malaysia and Indonesia as part of the International GNSS service (IGS) network. Another data source for GPS TEC is from the SINGA (Sensing and Integrated Navigation with GNSS Augmentation) project which supports deployment of ground-based multi-GNSS receivers in Singapore. Together these represent one of the highest density of GPS receiver stations globally.

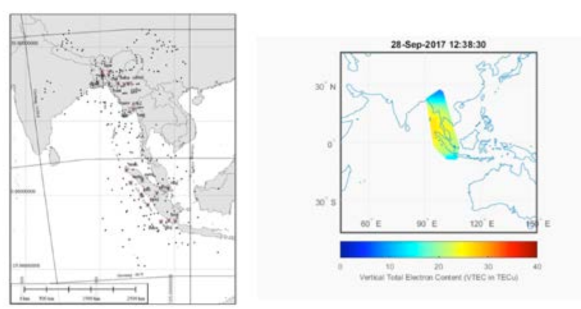

Figure 3: left panel: The dots indicate the GPS receivers available from the EOS SuGAr network. Right panel: A TEC plot generated from the EOS network for September 28 2017.

This TEC data can be used to make high resolution TEC maps of the SE Asia Region as seen in the right panel of Figure 3.

Vertical profiles of TEC measurements will be provided by dual frequency radio occultation GPS receivers on board RIMAU satellites in equatorial orbits. Combining RO TEC measurements with the high resolution ground based TEC measurements will help to produce 3D mapping of the ionosphere regionally as illustrated in Figure 4. Six evenly spaced satellites will provide near real time coverage of the region and help to provide near-continuous 3D mapping of the ionosphere.

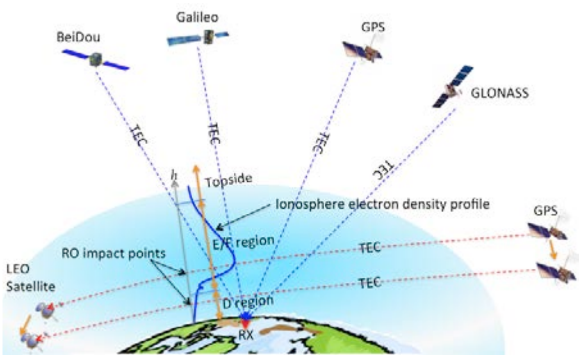

Figure 4: Illustration of a ground-based GNSS receiver and a LEO satellite measuring TEC from GNSS satellite over a common volume.

A Space based platform for continuous access to remote autonomous sensors.

The revisit time of a single satellite over a specific geographical location in an equatorial orbit is approximately 90 minutes. Each pass can last for approximately 15 minutes. A constellation 6 evenly spaced satellites can thus provide near continuous coverage over the Singapore region. The RIMAU constellation can provide a continuous efficient system for data relay. Such an equatorial constellation can prove to be a low cost alternative to using expensive bandwidth from geostationary satellites. RIMAU mission aims to conceptualize and prototype the ground and space segment for this space based data relay system. RIMAU will carry a duplex UHF radio and S-Band transmitter. Ground segment development will include prototyping low power UHF transmit system for beaconing and communication with RIMAU. The telemetry will consist of sensor health information and other parameters deemed of critical importance. It is also proposed to demonstrate satellite commanding of the remote sensor operations.

We will demonstrate the autonomous uplink in two ways:

1) The RIMAU constellation shall provide continuous low data rate access to remote GPS stations of the Earth Observatory of Singapore (EOS) and provide scientists with constant monitoring of key parameters and instrument health status. Figure 5 shows the locations of the Sumatra GPS Array (SuGAr). These GPS sensors will pass information the satellites whenever the ionosphere is scintillated. This will in turn let the satellites collect data from the in-situ ionosphere probe at a high frequency to monitor the finer scale structure of the ionosphere.

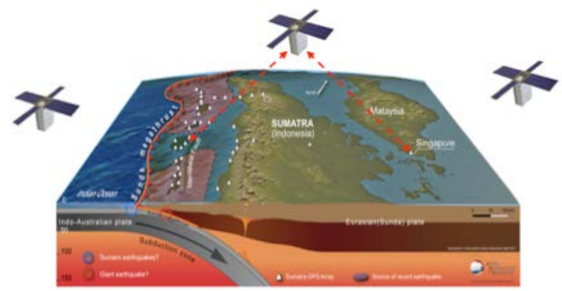

Figure 5: Illustration of RIMAU constellation for continuous monitoring and control of remote sensors not accessible by terrestrial networks in the Singapore regional neighbourhood.

2) The RIMAU constellation will collect data from sensors monitoring water quality. The water sensors utilizes optical fibre based approach using a tapered optical fibre (TOF) with sub-wavelength tapered radius for straightforward sensing and real-time monitoring of water pollutants.

RIMAU constellation will thus provide a space platform for effective constant communication with such remote sensors.

Payload 1: GPS Radio Occultation Payload

Most GPS RO missions, like SAC-C, TerrSAR-X,GRACE, COSMIC, adopt the BlackJack series receivers developed by NASA’s Jet Propulsion Laboratory (JPL)[3]. The VELOX-CI satellite developed at the Satellite Research Centre at NTU flew a Commercial off-the-shelf (COTs) receiver for RO measurements from LEO. COTS receivers have the advantage of low cost and short development cycle.

VELOX-CI carries three receivers, and their orientation is illustrated in Figure 6. The antenna field of view is 120°. The receiver B is mounted zenith direction for precise orbit determination purpose, while receiver A and C are mounted at forward-velocity and after-velocity directions to receive more signals from the occultation events. All the antenna are passive, which means low energy consumption can be achieved. The total power of the GPS payload subsystem is less than 7.8W when all the receivers and micro controllers are switched on.

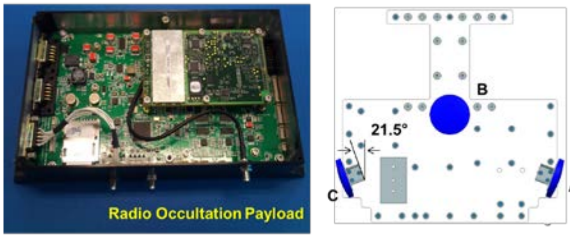

Figure 6: VELOX-CI and the GPS payload subsystem and orientation of GPS receiver.

The data logging rate of the RO receiver is able to log at 100Hz. However, due to the system limitation, the maximum logging rate is restricted to 50Hz when logging data from 2 channels at the same time. In the actual experiment, we normally use 1~20Hz logging rate for the radio occultation experiments on receiver A and receiver C. Receiver B logs at 0.1~1 Hz frequency for precise orbit determination. When 20Hz logging is enabled, the VELOX-CI bus can support up to 5 data logging channels at the same time.

Due to the high dynamics of the LEO orbit, the COTs receiver requires some prior knowledge of the channel and Doppler frequencies in order to fix the initial position. The VELOX-CI mission design software is able to calculate the Doppler shift and manually assign the channel with the user command. The channel allocation and Doppler shift for each channel are pre-determined from the orbit and attitude information. The TLE orbit propagation using SGP4 model is implemented in the mission planning software. With the help of the Doppler shift pre-knowledge, the COTs receivers in VELOX-CI is able to achieve the time to first fix (TTFF) in the range of 40~80 seconds in most cases.

Payload 2: Compact Ionosphere Probe

The Compact Ionospheric Probe (CIP) is an all-in-one in-situ plasma sensor derived from the larger Advanced Ionosphere Probe (AIP) developed at NCU and launched aboard the FORMOSAT-5 satellite in August 2017[4]. Like AIP, CIP combines and switches between four operational modes, each providing a unique set of plasma measurements.

These operational modes and the corresponding measurements are:

- Planar Langmuir Probe (PLP): electron temperature.

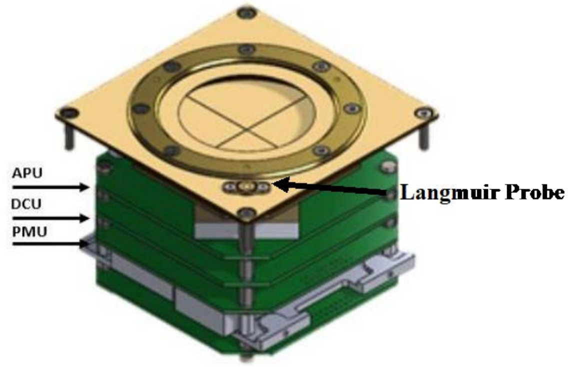

Figure 7: CIP mechanical structure.

- 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. 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 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. The sampling rate of observations from normal to fast will be changed based on the S4 scintillation index observed from the ground based GPS stations.

SPACECRAFT

System Level Description and Concept of Operation

The Satellite Research Center (SaRC) at the School of Electrical and Electronic Engineering at Nanyang Technological University has significant expertise in building cubesats ranging from 1U to 6U and microsatellites weighing upto 150 kg. For the RIMAU mission, we will use the expertise at SaRC to build a spacecraft bus based on heritage from the INSPIRESat-1 custom INSPIRE spacecraft bus which fits on the ISRO PSLV ring separation system termed IWL-150. For the pathfinder RIMAU mission, the launch vehicle is expected to be the ISRO Polar Satellite Launch Vehicle. The microsatellite structure will have dimensions of 30 cm x 20cm x 20cm (~ 12 U spacecraft) with a ring adapter as shown in Figure 8.

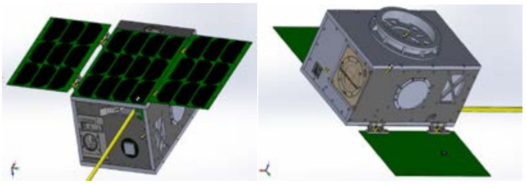

Figure 8: INSPIRE 12U spacecraft bus with ISRO IWL-150 Deployer.

Attitude Determination and Control System (ADCS)

The ADCS which includes reaction wheels, magnetorquers and star tracker for precision pointing requirements of up to 6 arc-seconds in three axis features will require the purchase of the COTS XACT ADCS system from Blue Canyon Technologies . Built-in flexible commanding in the XACT allows for multiple pointing reference frames: Inertial, LVLH, Earth-Fixed, Solar. Precise 3-axis control is provided by low jitter reaction wheels, torque rods and integrated control algorithms. The XACT ADCS system was successfully demonstrated on board the MinXSS cubesat.

Electrical Power Systems (EPS)

The Electrical Power System (EPS) board provides spacecraft electrical power control and distribution. Functionality is included for solar array input power with peak power tracking, on board or external battery, charge control, voltage regulation and distribution, and data acquisition Solar Arrays: SaRC will develop space qualified deployable arrays on the side of the spacecraft as shown in figure 8 to produce 42W at 80°C (BOL) when deployed. There is adequate margin for operating all RIMAU subsystems.

RF Communication

The RIMAU mission will use the COTS SpaceQuest TRX-U UHF transceiver and ClydeSpace CPUT S-Band transmitter. The spacecraft will be commanded (uplink) over UHF and data will be downlinked in S-Band. The ground station at SaRC has a high-gain cross-yagi antennas UHF/VHF ground station as well as a 6.1m S/X band ground station. To meet the 500 Mbytes/day data requirement, we make use of the 6 m dish at SaRC, expected to provide 3 Mbps using the flight proven CPUT S-Band transmitter which will provide a healthy link margin.

Table 1: RIMAU 1 subsystem components.

Subsystem	Solution	TRL
ADCS	Blue Canyon Technologies XACT with GPS	9
COMM (UHF transceiver)	SpaceQuest TRX-U	9
COMM (UHF Antenna)	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 CDH Board	5
	Emcraft SmartFusion2 System-on-Module	5
STR	Modified INSPIRESat-1 bus	3
Payload 1	COTS GPS receiver	9
Payload 2	CIP	7

CONCLUSIONS

The outcomes from the RIMAU mission will be a space weather 'now-cast' system for the SE Asia region, which has both civilian and defence applications to minimize impacts to a number of critical applications, such as point positioning and real-time kinematics (i.e., the location of moving vehicles), which are particularly relevant to the aviation and maritime industry and the emerging autonomous vehicle industry.

Acknowledgments

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