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Overview of Project SPATIUM – Space Precision Atomic-clock TIming Utility Mission

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ABSTRACT

The ionosphere contains large amounts of ionized plasma which is affecting the propagation of radio waves. The perturbation in ionospheric plasma significantly influences modern infrastructures that rely on radio and satellite communication. Hence, it is essential to develop a reliable platform for ionospheric plasma density monitoring. The Space Precision Atomic-clock TIming Utility Mission (SPATIUM) presents a new approach for ionospheric plasma mapping using a constellation of nanosatellites equipped with a high precision timing reference, double Langmuir probe and UHF inter-satellite ranging payloads. SPATIUM mission utilizes the breakthrough chip-scale atomic clock to generate highly stable and accurate clock signal for each satellite in order to determine the phase-shift in satellite signal. The ionosphere total electron content could be derived from ranging signals among satellites along the inter-satellite path. The pathfinder satellite, SPATIUM-I, was developed and successfully released from International Space Station on 6 October 2018. The main objective of this 2U CubeSat is to validate the clocking performance of a commercial off-the-shelf chip-scale atomic clock and demonstrate other key enabling technologies in orbit. The satellite is working well since deployment and the analysis of the captured satellite data is on-going.

INTRODUCTION

The ionosphere, located in Earth's atmosphere around 50 km to 1000 km altitude, results from the highly energetic part of the electromagnetic and ultraviolet spectrum of solar radiation. The ionosphere contains large amounts of ionized plasma and its density profile is constantly fluctuating under the impact of solar activity, neutral winds, geomagnetic storm, earth electric field and ion recombination. The perturbations of ionospheric plasma density give crucial information on space weather and atmospheric events[1].

In addition, the irregularities in the ionospheric plasma density greatly influence modern infrastructures that rely on wireless connectivity, navigation and radio communication. Ionospheric plasma along the line of sight between Global Navigation Satellite System (GNSS) satellites and GNSS receivers induces a time delay to the satellite signal, causes significant error in the measured pseudorange and positioning. On the other hand, irregularities and perturbations in ionospheric plasma density such as plasma bubbles, geomagnetic storm and sporadic E clouds cause fluctuation in satellite communication or navigation signals[2-3]. Therefore, it is essential to develop a reliable platform for monitoring the ionospheric plasma profile in order to gain an in-depth understanding of the morphology and dynamics of the ionosphere.

At current stage, we utilize various numerical simulations to study and predict the ionosphere plasma patterns. Some commonly used simulation models such as Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy (GAIA) from National Institute of Information and Communications Technology (NICT) in Japan and coupled Whole Atmosphere Model - Ionosphere Plasmasphere Electrodynamics (WAM-IPE) from National Oceanic and Atmospheric Administration (NOAA) in USA. There are many scientific instruments have been developed for studying of ionosphere such as ionosondes, incoherent scatter radar, HF Doppler and GPS radio occultation[4]. Since the advent of the space era, there have been numerous satellite missions that have contributed signicantly to the ionosphere monitoring such as Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER)[5], Dynamic Ionosphere CubeSat Experiment (DICE)[6], and FORMOSAT-3/COSMIC[7].

In the last two decades, small satellite technologies have attracted intense attention and advanced from educational research to a great variety of applications such as earth observation, communication, navigation, meteorology and others emerging applications. In addition, the ongoing technology evolution, miniaturization of cost-effective components and the possibility of launching of large quantity of CubeSats with single rocket launch have inevitably created potentially new mission architectures consisting of large constellations of CubeSats. In this contribution, we introduce a nanosatellite constellation mission for reliable and highly precise monitoring of ionospheric plasma density. The Space Precision Atomic-clock TIming Utility Mission (SPATIUM) program is a joint collaboration between Nanyang Technological University, Singapore and Kyushu Institute of Technology, Japan. The pathfinder satellite, SPATIUM-I, was developed and released into low earth orbit (LEO) from International Space Station (ISS). This paper provides an overview of the mission, satellite design and update of SPATIUM-I mission.

SATELLITE MISSION DEFINITION

The primary scientific objective of SPATIUM program is develop to a reliable platform that derives the three-dimensional global ionosphere plasma distribution with excellent spatial and temporal resolutions. In the program, key enabling technologies will be developed and demonstrated.

The main objective is to model the ionosphere total electron contents (TEC) based on multipoint measurements of phase-shift in satellite clock signal from a constellation of CubeSats carrying a high precision timing reference. It is known that the satellite signals that transmit through the ionosphere interact with ionospheric plasma which causes a propagation delay in the signal transmission. The induced phase delay is inversely proportional to the square of radio frequency. In addition, the radio signal is affected by the atmosphere and another phase delay is expected. Hence, ultra-high frequency (UHF) was selected for SPATIUM mission. The resolution is expected to be improved by one order of magnitude compared to the case which L-band GNSS signal is used. The signal is spread-spectrum (SS) modulated so that the single frequency can be shared simultaneously by multiple satellites. By measuring the phase difference in satellite signals between two satellites, or between satellite and ground station, the integral of the electron density distribution along the path length can be modelled using custom-designed computational modelling tools. In addition, the analysis is further reinforced with in-situ measurement of plasma density using Double Langmuir Probe (DLP) onboard each satellite.

SPATIUM-I is the first effort in this program to validate a few key enabling technologies in orbit for future mission:

- In-orbit demonstration of commercial off-the-shelf chip-scale atomic clock (CSAC) as reliable reference clock of CubeSat;
- In-orbit demonstration of transmission of SS-modulated 467 MHz signal with CSAC as a clock source;
- In-orbit demonstration of transmission and receive of 400 MHz signal as the second UHF band;
- Demodulation of SS Signal at ground station;
- Time-synchronization of multiple ground stations;
- Reading the carrier wave phases (400 MHz and 467 MHz) of SPATIUM-I satellite.

The success of SPATIUM-I and the developed capabilities will inevitably provide a strong fundamental for future missions.

PAYLOAD – CHIP SCALE ATOMIC CLOCK

The breakthrough CSAC technology that packages a Cesium vapor cell atomic reference oscillator in a unit several times smaller than its legacy products gives improved size, weight and power (SWaP) performance. Most importantly, CSAC provides better accuracy and stability compared to the conventional crystal oscillators such as temperature controlled crystal oscillators (TCXO) and oven controlled crystal oscillators (OCXO). Figure 1 shows the comparison of

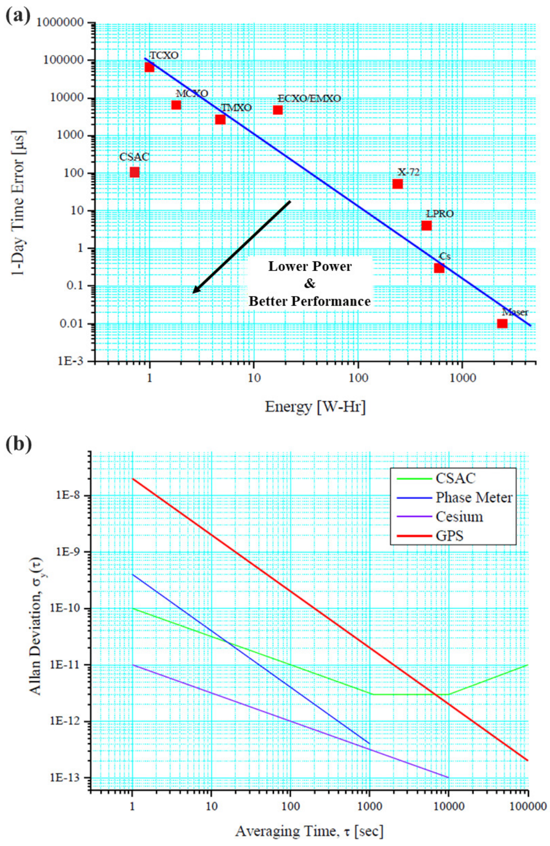

Figure 1: (a) Comparison of time error and power consumption of different oscillator technologies, and (b) Typical instability (Allan Deviation) of CSAC, Phase meter, GPS, and Cesium beam frequency standard[8].

the time error, power consumption and instability of various oscillator technologies[8]. Conventional high accuracy hydrogen maser and Cesium atomic clock are typically large size and high power consumption. The revolutionary CSAC technology has excellent time accuracy, stability and power consumption performance, making it a very suitable candidate for small satellite application, where space and weight limitations do not permit traditional atomic clocks on board for accurate timing references.

In 2011, Microsemi (previously Symmetricom Inc.) has launched the world's first commercially available CSAC, after eight years of participation in the Defense Advanced Research Projects Agency (DARPA) chip scale atomic clock (CSAC) program. The CSAC chip has extremely low power consumption of 120 mW and small volume of 16.4 cm^3. The promising frequency stability performance of CSAC with short-term stability of 3E-10 @ tau = 1 sec is essential for many satellite applications such as satellite timing and frequency control, satellite cross linking, navigation and earth observation.

For our project, the CSAC payload board is a custom-designed subsystem for SPATIUM-I CubeSat. It has the function to output precise CSAC 10MHz clock signal, 1 PPS signal and other operation data to the communication board (COM) for data transmission to ground station. The CSAC counter value will be used for analysis of the CSAC 10MHz clock signal throughout the CubeSat mission. Under normal operation, CSAC will output very stable 10MHz oscillation signal. Figure 2 shows the functional block diagram of the CSAC mission boards. The design is basically separated as two part: the CSAC mission board and the supercapacitor board, as illustrated in Figure 3. The CSAC mission board consists of a CSAC chip (Microsemi SA.45s CSAC), temperature sensor, ripple counter, micro-controller unit (MCU) and other electronic components required for CSAC operation. A low noise low-dropout voltage (LDO) regulator is used to provide a stable 3.3V voltage input to CSAC and other components on-board. A frequency counter is designed to count the 10 MHz oscillation signals from the CSAC. The counter value will be to validate the clocking performance of the CSAC and to derive the phase difference in the signal transmission for TEC modelling. The counter value data together with other useful data such as temperature sensor and supercapacitor voltage data will be captured by MCU every 1 second, as triggered by 1PPS signal from CSAC. The data will be processed in MCU and send to communication board (COM) through UART serial data communication.

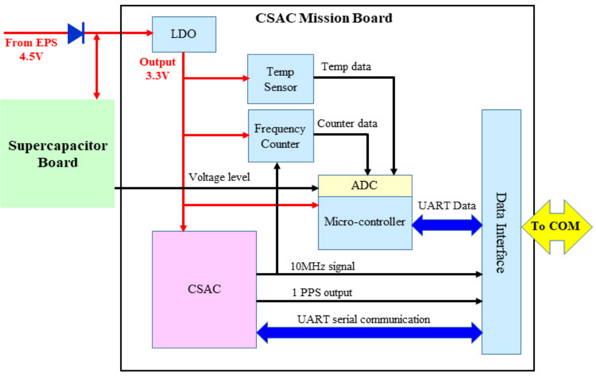

Figure 2: (a) Functional block diagram of custom-designed CSAC mission boards for SPATIUM-I.

(a) CSAC Mission Board

(b) Supercapacitor Board

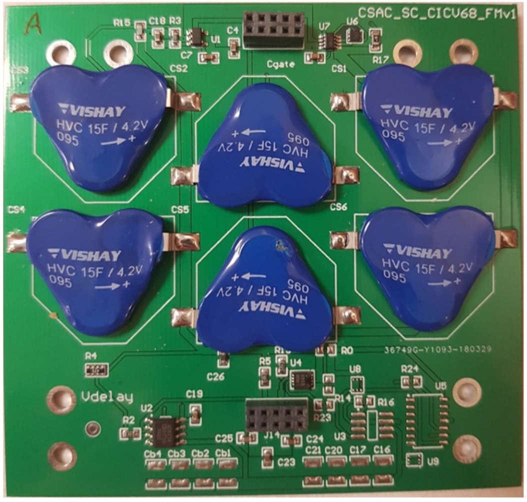

Figure 3: Photo images of (a) CSAC mission board and (b) supercapacitor board.

In order to avoid unwanted power disruption to the CSAC operation during eclipse, a supercapacitor module is used as power back-up for CSAC board operation. This is essential to ensure that the CSAC is functioning continuously throughout the whole CubeSat mission and the CSAC will not be reset due to power interruption. The detailed specification of the fabricated CSAC mission boards flight model (FM) are summarized in Table 1.

Table 1: Specifications of CSAC mission board.

Specifications	
Dimension	86.3mm x 90mm x 21mm
Weight	113 g
Voltage Supply	4.5 V
Power Consumption	0.35 W
Warm Up Time	< 180 s
Data Interface with COM	CSAC data: UART serial communication. Baud rate: 57,600 bps Operation data: UART serial communication. Baud rate: 128,000 bps

SATELLITE DESIGN

SPATIUM-I satellite adopted the generic 2U CubeSat design with a dimension of 20 cm x 10 cm x 10 cm weighing no more than 2.66 kg. The dimension and weight of the satellite must strictly adhere to the requirements of the Japanese Experiment Module (JEM) Small Satellite Orbital Deployer (J-SSOD). The satellite structure and configuration of SPATIUM-I CubeSat is illustrated in Figure 4. The CubeSat structure was designed based on the Kyutech's BIRDS project satellite's bus system[9]. It contains electric power system (EPS), battery module, communication board (COM), CSAC main mission board, supercapacitor board and front access board (FAB). The satellite uses an "harness-free" approach, which an backplane board (BPB) was designed to electrically connect all subsystems together. In order to reduce risk and system complication, the EPS, COM, battery module, FAB and BPB extensively utilizes existing designs that were fight proven aboard the BIRDS's satellite. Modifications were made to incorporate the CSAC mission board and supercapacitor board in the design. A pairs of deployable UHF monopole antennas are used for data transmission at two different UHF frequencies, i.e. 401 MHz and 467 MHz. The monopole antennas are restrained using nylon fishing string tied around an burning element.

SPATIUM-I CubeSat is designed to be deployed from ISS using J-SSOD. The CubeSat will be powered off while inside the J-SSOD using the remove-before-flight (RBF) pin and the deployment switch located at the base of the J-SSOD. After released from ISS, the EPS will start working and supplying voltage to turn on the CSAC mission board and supercapacitor board. The CSAC will warm-up for around 2 to 3 minutes and start sending stable clock signal to other subsystems. Due to restriction of transmission near ISS, no satellite communication will be made in the first 30 minutes after satellite is released from ISS. After 30 minutes, the burner circuit will be activated to deploy the monopole antennas. Since uplink and beaconing will not be possible until the antennas are deployed, the burning circuit will be activated for multiple times to ensure successful deployment. After antennas deployment, COM will be turned on and start data transmission at nominal operation mode, which is 467 MHz transmission with 20% duty cycle. Operation modes with different frequencies and duty cycles could be changed using uplink command when necessary.

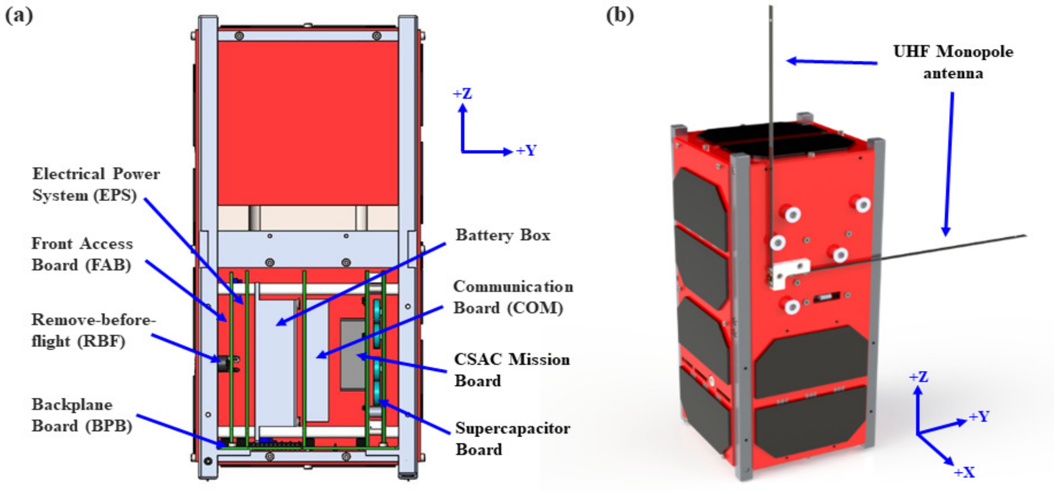

Figure 4: (a) Internal configuration and (b) external satellite design of SPATIUM-I CubeSat.

The EPS is responsible for the electrical power management for the satellite including generation, storage, regulation and distribution of electrical power. It is comprised of solar panels, battery module and a custom-designed power management board. The main requirement of the EPS is to effectively distribute power supply to support CubeSat operation while maintaining healthy power storage. As shown in Figure 4, all six external panels are covered with total 18 pieces of solar panels, except half of the +X panel is used for mounting of monopole antennas. The average power generation is 2.3W according to STK simulation. The generated power will be supplied to all subsystems for CubeSat operation. Extra energy will be stored in a 2000 mAh nickel-metal hydride battery module, which later will be used to support CubeSat operation during eclipse. A temperature sensor is attached inside the battery box to monitor the battery temperature, given the fact that the batteries have the most stringent temperature constraint aboard the entire CubeSat.

Satellite communication for SPATIUM-I CubeSat is based on UHF transmissions for uplink of command and downlink of housekeeping data and clock data. As discussed earlier, SPATIUM-I uses both 401 MHz and 467 MHz frequencies for data downlink, and 401 MHz for uplink. The COM board is custom-designed to perform SS modulation for the 467 MHz clock signal. With SS modulation of satellite signal, single frequency can be shared simultaneously by multiple satellites. Hence, the SS modulation and demodulation of satellite signal are the key enabling technologies for our future SPATIUM-II mission which a constellation of CubeSats will be deployed. On the other hand, widely used phase modulation (PM) will be used for the 401 MHz housekeeping data. The satellite signals will be captured and demodulated at multiple ground stations which have the synchronized reference CSAC and GPS clocks.

DEPLOYMENT AND INITIAL OPERATION STATUS

SPATIUM-I CubeSat flight model (FM) was fabricated and assembled in May 2018. The photo images of the SPATIUM-I FM is shown in Figure 5. The satellite passed the Japan Aerospace Exploration Agency (JAXA) safety review and fulfilled all the safety requirements for released from ISS Japanese Experiment Module Remote Manipulator System (JEMRMS). The satellite was carried to ISS by KOUNOTORI HTV7 cargo transporter which was successfully launched on 23 Sep 2018. The satellite was released from ISS Japanese Kibo module on 6 Oct 2018 at 15:45 pm SGT (UTC+8h)

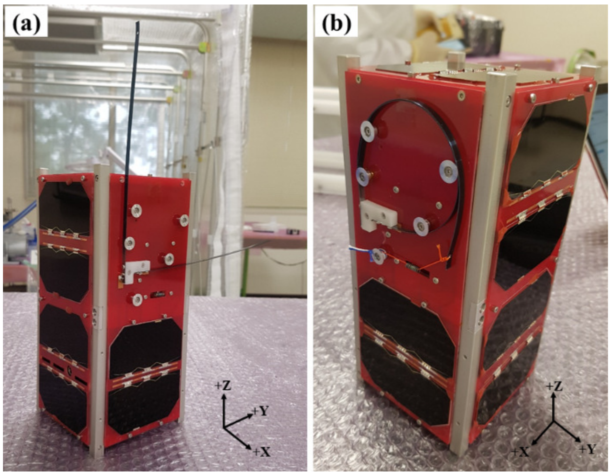

Figure 5: Photo images of SPATIUM-I CubeSat Flight Model.

The satellite signal of was first detected at Kyutech ground station on 7 October 2018 at 20:14pm SGT, which was one day after the satellite released from ISS. For the first contact, only spread spectrum signal was captured using spectrum analyzer. However, no signal demodulation was achieved. After some adjustments on Doppler shift correction, first demodulated data was successfully obtained on 17 Oct 2018 at 08:17am SGT. The obtained data was analyzed in detailed. The accumulated CSAC counter value is 9233951493551, which is equivalent to 10 days 16 hours and 30 minutes. This duration is tally with the total CubeSat operation period since the its release from ISS. From the obtained satellite data, it can be assured that the SPATIUM CubeSat is working properly as per design.

SPATIUM-I CubeSat is functioning well since release from ISS until now (more than 8 months). We are consistently collecting satellite data to evaluate the operating condition of the CubeSat. Figure 6 shows the accumulated CSAC counter data and calculated count per second since the deployment of the CubeSat. The accumulated CSAC counter count the 10MHz signal continuously. By divided the data by 10M, the operation duration (in the unit of seconds) could be determined. As illustrated in Figure 6(b), no visible drift is observed in the count per second, indicating that the CSAC is working properly until now. Other satellite operation data such as supercapacitor voltage level, CSAC, temperature, battery temperature and COM temperature were also analyzed to understand the working condition of the CubeSat. It is important to understand the environment condition and battery voltage level of the CubeSat. When needed, an uplink command can be sent to change the operation duty cycle and power consumption of the CubeSat. It is observed that the supercapacitor is always in fully charged condition (~4.2V), indicating that the solar generated power is sufficient to support the CubeSat operation. In addition, the temperature for the CSAC, battery and COM board are well-kept within very healthy range of -10 to +40 ºC.

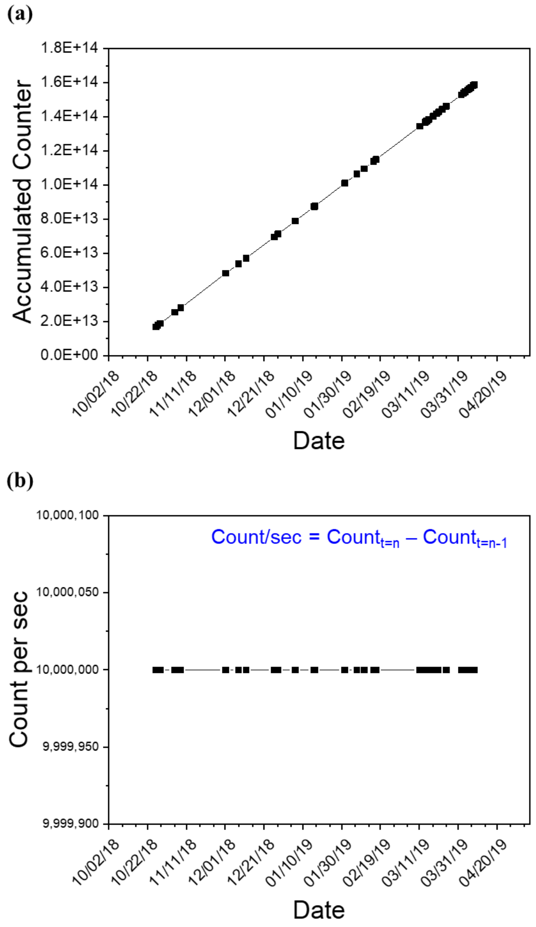

Figure 6: The demodulated SPATIUM CSAC data: (a) accumulated CSAC counter data and (b) calculated count per second.

CONCLUSIONS

SPATIUM program provides a technology demonstration for development of a reliable ionospheric plasma density mapping platform with excellent spatial and temporal resolutions. The proposed final operation system would be a constellations of CubeSats carrying a CSAC for precise time reference, a GNSS receiver for satellite positioning, an UHF transceiver to transmit and receive satellite signal and a Double Langmuir probe for in-situ plasma density measurement.

In this contribution, the mission, objectives, CubeSat design and preliminary operation status of SPATIUM-I have been presented. The main objectives of this 2U CubeSat are to demonstrate a few enabling technologies such as CSAC as reliable timing reference, dual-UHF data transmission, SS modulation and demodulation of UHF signal, and derivation of ionosphere TEC using the phase differences of satellite signals detected at multiple ground stations.

After a 2 years efforts of design optimization and satellite testing, SPATIUM-I flight model was released from ISS on 6 October 2018. The satellite is working as per design until now and the project team is consistently collecting satellite data. Detailed analysis on the captured satellite data is on-going and more results will be published soon. At the same time, the project team is also planning for the next phase, SPATIUM-II, which is a CubeSat constellation mission for ionosphere plasma monitoring.

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