

## INSPIRESat-1: An Ionosphere Exploring Microsat

William Evonosky, Amal Chandran, Spencer Boyajian  
 Laboratory for Atmospheric and Space Physics, University of Colorado Boulder  
 1234 Innovation Drive, Boulder, CO 80303; 813-334-4770  
 william.evonosky@lasp.colorado.edu

Priyadarshan Hari, Ankit Verma, Niwashini Nandagopan, Kaustubh Kandi  
 Indian Institute of Space Science and Technology  
 Valiamala Road, Valiamala, Thiruvananthapuram, Kerala 695547, India; 91-471-256-8452  
 priyadarshan.hari@gmail.com

Loren Chang, Yi Duann, Ya-Chih Mao, Rong Tsai-Lin, Shih-Chi Shiu  
 Center for Astronautical Physics and Engineering, Institute of Space Science, National Central University  
 No. 300, Zhongda Road, Zhongli District, Taoyuan City, Taiwan 320; 866-3-422-7151  
 loren@ncu.edu.tw

### ABSTRACT

The International Satellite Program in Research and Education's (INSPIRE) first satellite is an ionosphere exploring microsat slated for launch in November of 2019 onboard an ISRO Polar Satellite Launch Vehicle. The microsat is a custom designed structure fitting on a PSLV ring deployer. The payload is the Compact Ionosphere Probe (CIP) which will take in-situ measurements of ion density, composition, temperature, velocity, and electron temperature. The CIP is a smaller version of the Advanced Ionosphere Probe (both developed in Taiwan) currently operating onboard the FORMOSAT-5. These instruments take measurements in four modes sampling the ionosphere at 1 or 8 Hz. The primary science objectives of the INSPIRESat-1 are twofold. First, enabling a greater understanding of the temporal and spatial distributions of small-scale plasma irregularities like plasma bubbles and second a characterization of the Midnight Temperature Maximum (MTM) in season, location, and time. In this paper, we present science expectations for the INSPIRESat-1 and consider the potential for coordinated measurements between three platforms carrying the same instrument (INSPIRESat-1, IDEASat/INSPIRESat-2, FORMOSAT-5). We also highlight the program management strategy used by the INSPIRE program in developing an internationally developed microsat.

### INTRODUCTION

The International Satellite Program in Research and Education (INSPIRE) is an international collaboration between institutions and universities all over the world which leverages the expertise of individual participants to enable satellite development and capacity building<sup>1</sup>. The INSPIRE program's first satellite dubbed the INSPIRESat-1 (IS1) is slated for launch in late 2019 with the Indian Space Research Organization (ISRO) and is a collaboration between the University of Colorado Boulder in the United States, the National Central University in Taiwan, and the Indian Institute of Space Science and Technology in India. Other partners in the program include Nanyang Technological University in Singapore, Sultan Qaboos University from Oman, Kyushu Institute of Technology in Japan, and the Laboratoire Atmosphères, Milieux Observations Spatiales (LATMOS), France. The IS1 will take in-situ measurements of the Earth's ionosphere using the Compact Ionosphere Probe (CIP)

which is a miniaturized version of the Advanced Ionosphere Probe (AIP) currently operating onboard the FORMOSAT-5 (FS5)<sup>2</sup>. Both AIP and CIP have been funded by the National Space Organization (NSPO) of Taiwan. The science goals of the IS1 are to better understand the variability and distribution of small plasma irregularities (plasma bubbles, spread F) and the midnight temperature maximum (MTM) in time, location, and season. There have been numerous satellite missions carrying similar payloads including C/NOFS<sup>3</sup>, FORMOSAT-1<sup>4</sup>, and DMSP<sup>5</sup>, but most of these programs operate at high altitudes which miss plasma irregularities and the MTM. The IS1 will be put into a  $500 \pm 50$  km and  $50^\circ \pm 5^\circ$  inclination orbit enabling the mission to fully sample these properties of the Earth's ionosphere over longitude and time. In addition to the IS1, the second INSPIRE satellite called the IDEASSat (Ionospheric Dynamics Exploration and Attitude Subsystem Satellite) or INSPIRESat-2 is targeted for launch in 2020 into a polar orbit and will

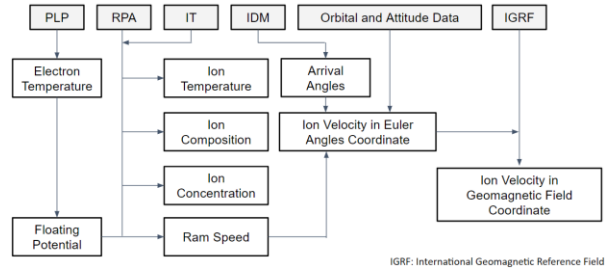
carry the same instrument as IS1. IDEASSat is funded by NSPO and being built at NCU, Taiwan. By the end of 2020, there will be three satellites, IS1, IS2, and FS5, carrying the same instrument in different orbits enabling high density measurements closely coupled in time of the evolving ionosphere.

**PAYLOAD**

The CIP will measure properties of the Earth’s ionosphere including ion velocity, composition, density, and ion and electron temperature in four different measurement modes as in Table 1. The four hardware modes of the CIP are Retarding Potential Analyzer (RPA), Ion Trap (IT), Ion Drift Meter (IDM), and Planar Langmuir Probe (PLP) with two software enabled measurement modes which cycle through three of the four hardware modes at either 1 or 8 Hz (slow and fast operating modes). Some measurements of the CIP are dependent upon only a single measurement mode while others are dependent on multiple and or external data (supplied by the ADCS subsystem) seen in Figure 1. The default measurement mode of the CIP is to cycle in slow operating mode between PLP, RPA, and IT.

**Table 1: Measurements and Modes of the CIP**

Modes	Raw Data	Science Data
Retarding Potential Analyzer (RPA)	Total ion current (controlled by retarding voltage)	Ion Temperature Ion Ratio Ion Ram Velocity
Ion Trap (IT)	Total ion current (controlled by constant voltage)	Ion Density
Ion Drift Meter (IDM)	Two sets of ion currents (controlled by constant voltage)	Arrival Angles
Planar Langmuir Probe (PLP)	Electron current (controlled by sweeping voltage)	Electron Temperature



**Figure 1: Science Data and Derived Sources**

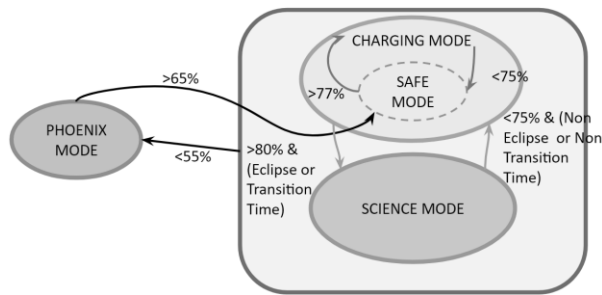
**THE INSPIRESAT-1**

The IS1 is an ~9U microsat slated for launch in late 2019 onboard a Polar Satellite Launch Vehicle (PSLV) with ISRO. The IS1 will be mounted using the ISRO developed IWL 150 Separation System which utilizes a separable ring assembly to deploy the spacecraft. Since the IS1 does not need to conform to Cubesat standards and future INSPIRE satellites will launch via the same ISRO deployer (except IS2), the IS1 was built with custom dimensions. This flexibility in satellite size allowed for more space in future missions without alteration of the satellite bus. The IS1 has a minimum mission duration of 6 months with plans to continue operation either until the spacecraft fails or the orbit degrades and the satellite reenters the Earth’s atmosphere.

The IS1’s various sub-systems are either being procured from outside vendors or developed internally at one of the three participating institutions as detailed in Table 2. The IS1 will carry both a UHF and S-band radio where UHF is used for command and control and beaconing while S-band is used exclusively to downlink science data. The IS1 will operate in one of three modes where switching between modes is controlled by battery depth of discharge percentages (thresholds to be finalized via testing), day/night, and/or an anomaly/resolution as seen in Figure 2. For more detailed engineering information on the IS1, please see the paper titled “INSPIRESat-1 Nanosat Mission” (Ankit Verma first author) available in the 2018 SmallSat section of the Utah State University Institutional Repository.

**Table 2: Subsystems and Procurement**

Subsystem	Component Used
C&DH	Custom Design (IIST)
EPS	Custom Design (NCU)
ADCS	Blue Canyon Technologies XACT
CIP-Payload	Custom Design (NCU)
UHF	Spacequest TRXU
S-band	Clyde Space
Structure and Thermal	Custom Design (LASP)
Flight Software	Custom (IIST/LASP/NCU)



**Figure 2: Mode Flow Diagram for IS1**

**SCIENCE OBJECTIVES**

The IS1 formal science objectives are as follows:

1. What are the occurrence rates and characteristics of plasma irregularities at low and mid latitudes?
2. What are the spatial and temporal variations of the midnight temperature maximum?
3. How do the ionospheric density and electric field respond to the MTM thermospheric dynamics?

The IS1 will attempt to answer these science questions via measurements taken by the CIP in a 50% duty cycle defined by power requirements. The CIP will be turned on during periods of day to night and vice versa transition periods and throughout the local night time. Both the plasma irregularities and the MTM are transition/nighttime phenomena allowing for a

decreased power requirement of the spacecraft by putting CIP in standby mode in the local day time.

**Plasma Irregularities**

Plasma irregularities like plasma bubbles (also known as spread f) occur primarily around the magnetic equator in the early evening (transition period) and around midnight<sup>6</sup>. Plasma bubbles occur when less dense plasma at low altitudes, caused by high recombination rates, shoots up into the more dense plasma above it (like oil sitting on top of water)<sup>6</sup>. These plasma depletions follow magnetic field lines allowing them to spread to latitudes far from their initiation site and can be hundreds of kilometers wide in longitude and altitude<sup>6,7</sup>. These plasma bubbles can cause scintillation (large drops in signal intensity and a shift in phase) in GPS or radio signals as they traverse from high to low and back to high plasma densities causing drops in communication or loss of GPS satellite acquisition<sup>8</sup>.

Plasma bubbles are identifiable in the ion density measurements taken by instruments like the CIP since the satellite will pass through the bubble at some incident angle at which point the density drops considerably. Smith and Heelis<sup>9</sup> in 2017 used CNOFS data to identify plasma bubbles in the ion temperature collected by the Ion Velocity Meter (IVM) instrument. The CNOFS platform was placed into an eccentric orbit spending most of its time at altitudes which miss plasma bubbles and was still able to identify trends in plasma bubble frequency through time and solar activity conditions<sup>9</sup>. The IS1 will always be operating at altitudes where plasma bubbles occur and therefore should enable similar characterizations of plasma bubble morphology in time and longitude.

**The Midnight Temperature Maximum**

The Midnight Temperature Maximum is a neutral temperature bulge in the Earth’s otherwise cooling ionosphere that occurs primarily around midnight local time and between 300 to 500 km in altitude. The MTM is a low-latitude phenomenon that generally originates around the geographic equator and travels to higher latitudes over time<sup>10</sup>. The magnitude of the MTM was first reported by Spencer et al in 1979<sup>11</sup> via measurements taken by the Neutral Atmosphere Temperature Experiment (NATE) of up to 200°K in the summer and 120°K in the winter. The MTM’s temperature peak is also associated with a pressure bulge and reversal of meridional neutral winds poleward<sup>12</sup>. While the MTM has been studied extensively since the 1960’s, the cause of the MTM is still not well understood. The best theory, supported by modeling efforts<sup>13</sup>, is that migrating waves deposit

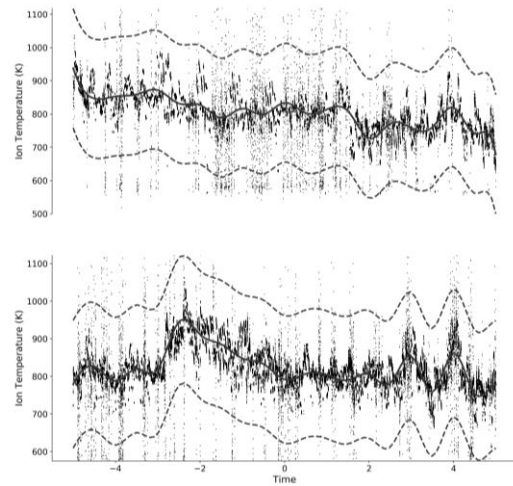
energy into the nighttime ionosphere producing the resultant temperature bulge and associated wind pattern<sup>14</sup>.

Characterization of the MTM via satellite data is notoriously difficult due to its transient nature. A satellite like the IS1, can only ‘see’ profiles in it’s various measurements and must distinguish a small 100°K signal from the background environment and inherent measurement noise. It is also possible that the satellite will pass through the MTM one orbit and miss it entirely in the next causing a large gap in possible MTM passes over time.

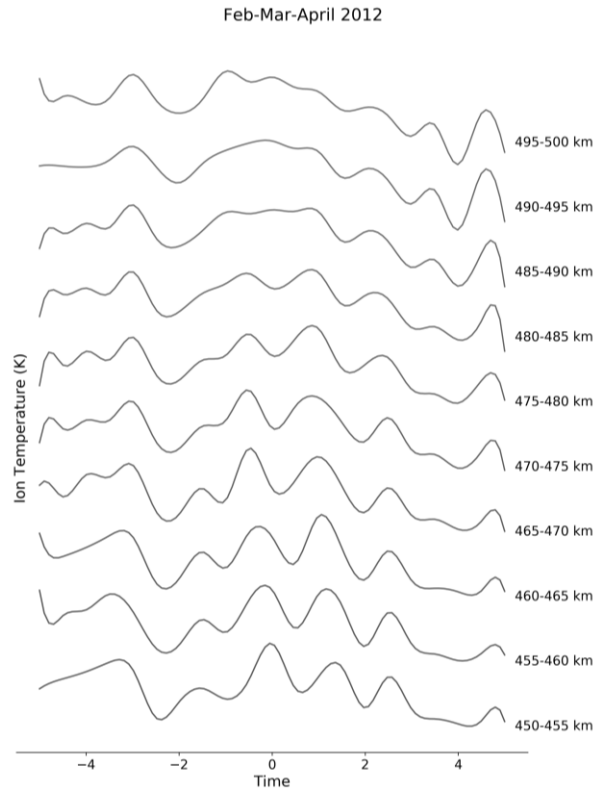
The CNOFS IVM data produced between 2008 and 2015 provide an example of the sort of data the IS1 hopes to collect. To identify the types of analysis techniques that will be useful in identifying the MTM in IS1 data, efforts over the past year have focused on IVM ion temperature data (a good proxy for the MTM neutral temperature bulge). Analyses which do not take a statistical approach to the data have been unsuccessful in identifying the MTM. A current approach groups the ion temperature data into small altitude bins for a season and removes data that are not  $\pm 5$  hours from midnight local time before fitting the data with a penalized b-spline model. This machine learning technique is applied to several altitude ranges for the same season allowing for the morphology of ion temperature to be analyzed in altitude.

Figure 3 shows an example of such a spline fit (solid curve) for the February, March, April (FMA) season in 2012 for ion temperature data (black dots) in the geographic northern hemisphere which have altitudes between 400 and 405 km. The dashed curves are the 95% confidence interval of the mean and the x-axis is in hours from midnight local time. These fits alone are not entirely useful so stacking the spline fits in altitude provides an easy way to see how these curves vary. Figure 4 shows the same season, hemisphere, and year for data between 450 and 500 km with each 5km altitude range’s spline fit stacked on top of each other. Each curve’s y-axis has been constrained to have a lower and upper bound of 500°K and 1000°K.

Figure 4 shows hints at what might be the MTM in the CNOFS IVM data as temperature peaks around approximately -1, 0, and +1 local time which dissipate with altitude. These are preliminary results but shed light on the type of analyses these data make possible.



**Figure 3: Example Spline Fit for FMA 2012 and 400 to 405 km**



**Figure 4: Stacked Spline Fits for FMA 2012 and Altitudes Between 450 to 500 km**

## INSPIRESAT-1 MANAGEMENT PLAN

Since the IS1 is being developed in three different countries, management of the project is particularly important. There are unique challenges that come with this collaboration including document versioning and tracking and hardware licensing restrictions between institutions. The IS1 has chosen to tackle these issues using a variety of technologies and management strategies. First, each participating institution has a faculty principle investigator (PI) which serves as the lead contact and a student project manager (PM) (also serving as a system engineer) which handles the bulk of the communications and engineering plans between institutions. Below the PM's are the individual subsystem engineering teams. The IS1 utilizes this vertical to horizontal management plan to create effective communication channels. The PI's meet periodically as needed and the PM's teleconference weekly to update everyone on the progress made and discuss any problems.

The program also uses platforms like Slack to allow for instantaneous communications when questions arise that cannot wait until the next PM meeting. Google documents is also utilized to allow for easy document version control and to provide a central document repository for the program.

## COORDINATED MEASUREMENTS ACROSS THREE PLATFORMS

The IS1 is scheduled for launch in November 2019, the IS2 launches in the middle of 2020, and FORMOSAT-5 is already in orbit operating it's AIP. The IS2 expected orbit is 500 km with a 97° inclination and the FORMOSAT-5 orbit is at 720 km with a 98° inclination. Since the orbits of all three platforms are different, there will be a recurring period in which all three platforms are relatively close together in space and time taking the same measurements. These coordinated measurements are a unique opportunity to potentially see the same plasma irregularity via three different profile directions and altitudes. Such measurements may provide three-dimensional information about the size and growth rate of plasma bubbles.

Furthermore, this constellation measurement opportunity provides a model for small satellite missions of the future. Coordinating with larger missions and carrying a miniaturized version of their

instrument provides the ability to cluster in-situ measurements relatively cheaply. This model also allows for relatively rapid development of instrumentation technology by leveraging the expertise of the primary missions engineering team. Student led satellite missions are always looking for guidance and having a baseline to compare to on orbit is invaluable.

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