INSPIRESat-1: A year of on-orbit operations

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ABSTRACT

INSPIRESat-1 (IS-1) was the first mission under the INternational Satellite Program In Research and Education (INSPIRE) program, a consortium of universities coming together to space science missions. IS-1 launched on February 14, 2022 at 00:30 UTC to a sun synchronous dawn-dusk orbit onboard the Indian Space Research Organization's PSLV C52 mission. The IS-1 spacecraft was primarily developed at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado with significant contributions from the Indian Institute of Space Science and Technology (IIST), NCU of Taiwan and Nanyang Technological University (NTU) in Singapore. The IS-1 carries two scientific instruments: The Compact Ionospheric Probe (CIP) developed at National Central University (NCU) for studying Earth's dynamic ionosphere and the NASA funded Dual-zone Aperture X-ray Solar Spectrometer (DAXSS) developed at LASP for studying the highly-variable solar X-ray radiation. DAXSS is a follow on from the highly successful MinXSS 1 &2 missions. First contact was established with the spacecraft 45 minutes after launch. The first science instruments were turned on by February 27th. DAXSS has now observed multiple solar flares in the current increasing phase of solar cycle 25 for a period of 16 months. In this paper we will present details on spacecraft performance in a unique dawn dusk orbit which presents thermal challenges not encountered frequently by nano-satellite platforms. We also present preliminary science results from CIP and DAXSS instruments from a year of on-orbit operations. Operations of the Spacecraft has also been unique with multiple universities commanding and downlinking science data.

INTRODUCTION

INSPIRESat-1 (IS-1) is a micro-satellite developed jointly by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado at Boulder in the United States, the Indian Institute of Space Science and Technology (IIST) in India, the National Central University (NCU) in Taiwan and the Nanyang Technological University (NTU) in Singapore[1].The IS-1 carries two scientific instruments: The Compact Ionospheric Probe (CIP) developed at NCU for studying Earth's dynamic ionosphere and the Dual-zone Aperture X-ray Solar Spectrometer (DAXSS) developed at LASP for studying the highly-variable solar X-ray radiation. The Spacecraft bus was jointly developed by LASP, IIST and NCU.

The science objectives of the INSPIRESat-1 are twofold. First, using CIP to characterize the temporal and spatial distributions of small-scale plasma irregularities like plasma bubbles in the ionosphere. Secondly, IS-1 aims to provide a greater understanding of why the Sun's corona is orders of magnitude hotter than the photosphere, why there is an abundance of elements change during different solar events, and how these events (observed with greater soft x-ray fidelity) affect the earth's ionosphere. The spacecraft's internal configuration and the assembled spacecraft with the two science instruments marked is shown in Figure 1. The spacecraft was initially designed as a 3U carrying only CIP. However, the DAXSS instrument was later added and the spacecraft dimensions changed to 30x20x15 cm.

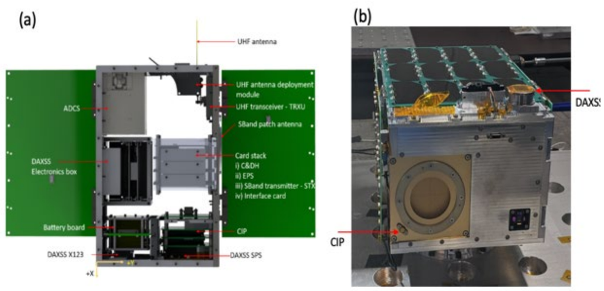

Figure 1: (a) INSPIRESat-1 internal structure and Co-ordinate axis (b) Assembled spacecraft.

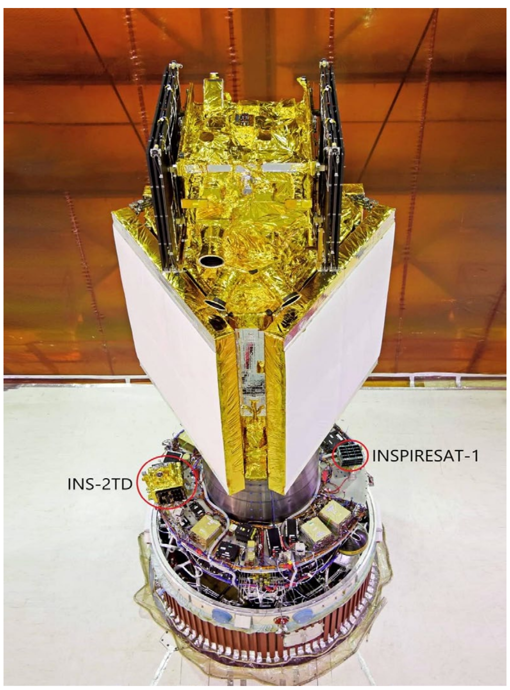

Figure 2: IS-1 spacecraft on the PSLV C-52 payload deck along with the main spacecraft RISAT-1A and INS-2TD small satellite.

The IS-1 spacecraft was launched by the Indian Space Research Organization (ISRO) into a sun synchronous 535 km orbit on February 14th at 00:30 UTC on the Polar Satellite Launch Vehicle (PSLV) C-52 mission. First beacons were received from the spacecraft at 01:15 UTC at the LASP Boulder ground station. IS-1 is a ring-deployed microsat of approximately 9U dimension and weighing 8.25 kg that used the ISRO IWL-150 ring deployer. Figure 2. Shows the spacecraft on the PSLV payload deck along with the main spacecraft RISAT-1A and INS-2TD small satellite.

IS-1 ON-ORBIT PERFORMANCE

The IS-1 spacecraft was launched into a sun-synchronous dawn-dusk orbit with 97.52^{o} inclination, altitude of 535 km, Local Time Descending Node (LTDN) of 6 AM local time.

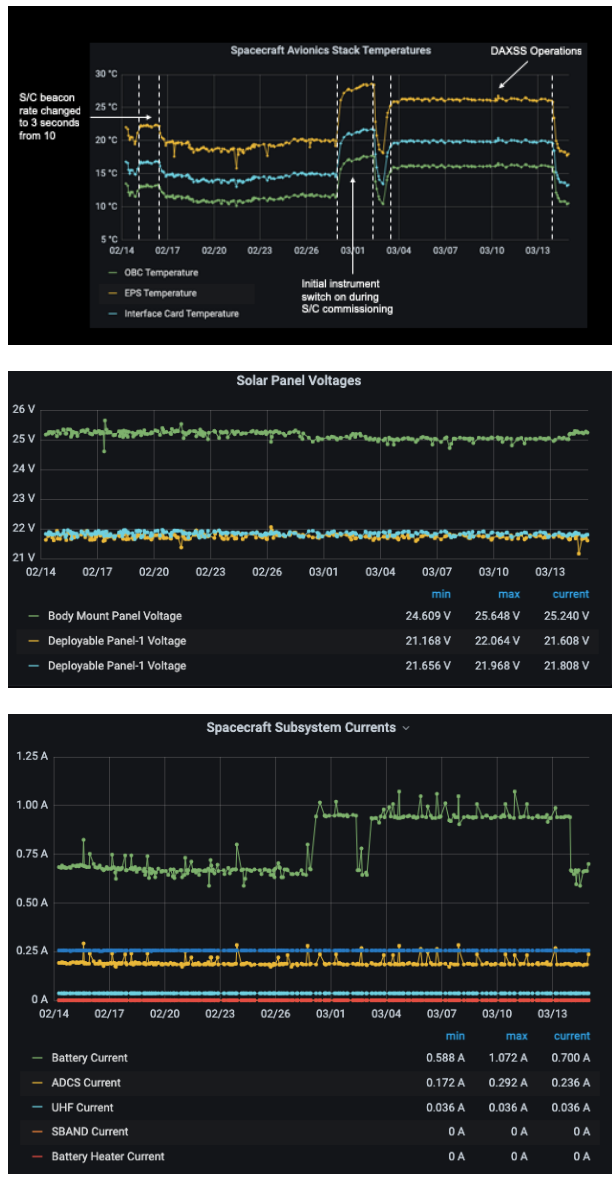

Figure 3: Shows the IS-1 spacecraft avionics stack (OBC, EPS and interface card) temperatures (top panel), Solar panel voltages and Spacecraft sub-system currents during the first month of operations.

The spacecraft was initially designed to be in a mid-inclination orbit to study travelling plasma disturbances and post-midnight temperature maxima in the ionosphere. However due to launch unavailability brought on by the pandemic, the assembled spacecraft was on the bench since June of 2020 awaiting a suitable rideshare opportunity. It was decided to make use of the sun-synchronous launch opportunity even though there were concerns on the spacecraft being in a harsher thermal and radiation environment than what it was originally designed for.

The IS-1 spacecraft is operated primarily from the IIST ground station located at Trivandrum, India. Support ground stations at Boulder, Fairbanks, Taiwan and Singapore supported commissioning and initial operations. Spacecraft commissioning and operations was immensely help by beacons received through the amateur Satnogs network. Satnogs operators have supported the mission by downloading 120,000+ beacons from the spacecraft from its amateur antenna network over the 16 months the spacecraft has been in orbit. The Satnogs data collected and visualization through the Grafana dashboard has helped for quick troubleshooting during early operations and for checking spacecraft resets and other anomalies during its operations to date.

The IS-1 spacecraft nominally boots into SAFE mode with the instruments switched off. The DAXSS instrument onboard computer is kept powered on while the solar X-ray spectrometer is off. The spacecraft operates the DAXSS instrument in sunlight and the CIP instrument in eclipse. Once the spacecraft has been put into nominal modes, it will toggle between science DAXSS (SCID) and science-CIP (SCIC) modes automatically based on eclipse determination done onboard using the ADCS coarse sun sensors. While the primary science for the spacecraft was supposed to ionospheric plasma irregularity measurement during eclipses, the dawn dusk orbit the spacecraft was put in made eclipses quite rare (during only NH summer months), which changed the science focus to solar flare observations in X-ray.

Figure 3 shows the IS-1 spacecraft avionics stack which comprises the On-Board Computer (OBC), Electrical Power System (EPS) and interface card temperatures (top panel), Solar panel voltages and Spacecraft sub-system currents during the first month of operations. Since the spacecraft is in a dawn-dusk orbit, it did not encounter an eclipse during this period. The spacecraft achieves thermal equilibrium and any change in operations including changing the beacon rate can result in a change in the spacecraft temperatures. Different operations are marked out in the top panel plot of temperatures. Changing the beacon rate from 10 to 3 seconds cadence resulted in a few degrees increase in temperature. The instruments were switched on initially for a 3-day period on February 28th. The DAXSS instrument was switched on for operations by March 3rd.

The solar panels on IS-1 spacecraft produces ~25V (body mount panel) and ~22V (deployable panels) in sun. The spacecraft sub-system currents were all nominal on spacecraft deployment and operations.

1. Spacecraft pointing performance

IS-1 uses the blue canyon XACT Attitude Determination and Control System (ADCS). The ADCS detumbled and sun pointed the spacecraft on deployment from the PSLV launch vehicle in less than five minutes. The XACT will go into a sun searching mode and point the spacecraft at the sun. It will rotate slowly about the third axis at about 0.0065 rad/s completing a rotation in ~16 minutes. The onboard GPS with the XACT was not functional requiring uploading an ephemeris and time to bring the spacecraft into fine point.

The spacecraft was first nominally put into fine point on March 19th. The spacecraft transition to fine point and the measured body rates as it went to fine point on March 19th is shown in Figure 4. Since March 19th, the spacecraft has been mostly in fine point except for brief periods of commanded spacecraft resets, changing to SAFE mode or ADCS resets due to Single Event Upsets (SEU's) which necessitated uploading ephemeris and commanding the spacecraft back to fine point.

Figure 4: The spacecraft transition to fine point and the measured body rates as it went to fine point on March 19th

2. Spacecraft Anomalies

In 15 months of operations, the spacecraft has encountered multiple ADCS resets assumed to be due to Single Event Upsets (SEU's). The DAXSS instrument has shown two instances of anomalously high current draws which were isolated to the OBC of the instrument caused by SEU's. Power cycling the instrument cleared these upsets. The spacecraft also experienced a hang up on the I2C line when the S-Band transmitter was switched on. Since primary science mission could be achieved by data downlink over UHF, it was decided to commission S-Band after the primary mission duration of 6 months. This has since been resolved by not beaconing on the UHF when S-band is in transmit mode. The UHF beaconing was causing noise in the I2C causing it to hang-up. However science data downlink over S-band has not been consistently done resulting large volume of science data still needing to be downloaded. Since October 2022, the spacecraft has had multiple issues with the on-board SD cards which include anomalous read pointer values for the science data partitions, Sd cards not being written to etc. Currently science data is being written to the 16 MB onboard flash memory and science data is downlinked daily before being over written. The SD Cards can still be read from and science data recorded previously is still being downlinked.

OVERVIEW OF DAXSS INSTRUMENT AND SCIENCE

The DAXSS is one of two scientific instruments aboard the INSPIRESat-1 small satellite. The DAXSS includes a compact X-ray spectrometer to observe the solar soft X-ray (SXR: 0.3-12 keV) spectral irradiance in order to explore the energy distribution in the highly variable SXR range and reveal its impact on Earth's ionosphere and thermosphere. The science and instrument heritage for DAXSS is from NASA's Miniature X-ray Solar Spectrometer (MinXSS) CubeSat missions that flew between 2016 and 2019[2,3,4,5,7] (The DAXSS measurements with its improved energy resolution provide accurate elemental abundances for Ca, Fe, Mg, Si, and S through fitting spectral models to the measured SXR spectra[6]. The Ca, Fe, Mg, and Si emissions are of particular importance because they are First-Ionization-Potential (FIP) elements whose abundances change the most during flare events. Therefore, studying the coronal abundance changes with DAXSS spectra is providing improved insight into the coronal heating processes during flares. For example, the improvement of DAXSS energy resolution over MinXSS-1 is allowing abundance calculations with DAXSS spectra to have an uncertainty of better than 2%, which is over 20 times better than possible with MinXSS-1 spectra.

As mentioned already for the INSPIRESat-1 operations, the DAXSS instrument is on all of the time but its solar X-ray spectrometer, the Amptek X123 Silicon Drift Detector (SDD), is typically power cycled once per orbit to make the solar measurements when INSPIRESat-1 is in sunlight. The satellite's Sun-Synchronous Orbit (SSO) has provided some periods with no orbit ellipse periods, so there are times when DAXSS is making continuous solar observations over a day. When the DAXSS X123 channel is on, the DAXSS science packets are generated every 9 seconds and then stored on one of the satellite's SD-cards in a ring buffer. The SD-cards are big enough that the first 15 months of observations are still on-board and available for downlink. The amount of the DAXSS science packets downlink has been limited so far because UHF communication has only been used for the prime mission, but more (even all) of the data is anticipated to be downlinked once reliable S-band radio is commissioned.

The primary observation with DAXSS are solar SXR spectra in the energy range of 0.3 keV to 12 keV (4 nm to 0.1 nm). These solar spectra also have secondary science results as related to being in space. One is the measurement of energetic particles (mostly electrons) when flying through the aurora and in the South Atlantic Anomaly (SAA) region. These energetic particles are best detected in the 12-20 keV range where there are no solar signals in the DAXSS spectra. The energetic particles are not always detected but do show up during the larger geomagnetic storms. The energetic particle signal is removed so that the remaining spectrum is useful for solar science. Another measurement is atmospheric absorption in the thermosphere when the solar view is down through the atmosphere.

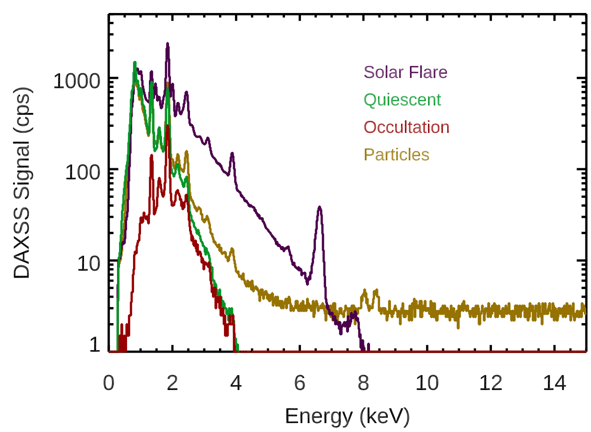

Figure 5: Example X-ray spectra from DAXSS are shown for a solar flare, quiescent solar activity (not-flaring), solar occultation with atmospheric absorption, and a solar spectrum with a high background at the higher energies due to energetic particles. The spectral features above the continuum are from hot coronal emissions from Ca, Fe, Mg, Si, and S.

Figure 5 shows four example spectra. The solar science spectra shown are example spectra for when the sun is flaring on March 15, 2022 and not flaring (quiescent sun) on May 24, 2022. A solar occultation spectrum is also shown for May 24, 2022, whereby the lower energy part of the spectrum is greatly reduced due to atmospheric absorption. The relative change of the solar spectrum before occultation and during occultation provides a measure of the atmospheric density (which is dominated by atomic oxygen for the thermosphere). With DAXSS 9-sec cadence, the ground resolution is about 70 km for studying the solar occultation data. The fourth spectrum shown is one showing a strong detection of energetic particles on April 29, 2022 when flying through the aurora at 74° latitude and 19° longitude. Of the 20,000 spectra downlinked so far, 59% include good solar spectra, 15% solar occultation data, 13% energetic particle data, and 13% other data (dark or saturated solar spectra for flares larger than M3 class).

The original DAXSS science team (NASA MinXSS CubeSat team) has expanded to include several more scientists involved with the INSPIRE program in India, Singapore, and Taiwan. There is much international collaboration in studying the DAXSS spectra and preparing to publish the many science results with the DAXSS data.

OVERVIEW OF CIP INSTRUMENT AND SCIENCE

The CIP instrument is a miniaturized version of the Advanced Ionosphere Probe flying on-board the FORMOSAT-5 mission[8]. The CIP instrument is operated during eclipse as the plasma density can cause saturation of the instrument measurements during daytime. When the CIP instrument is operated, the spacecraft face with the CIP instrument is pointed in the RAM direction. Since the IS-1 spacecraft is in a dawn-dusk orbit, the spacecraft does not see eclipse very often. The IS-1 spacecraft encountered an eclipse season with eclipses ranging from a few minutes to a maximum eclipse duration of 22 minutes between May – August 2022. The next eclipse season is expected in 2023 summer.

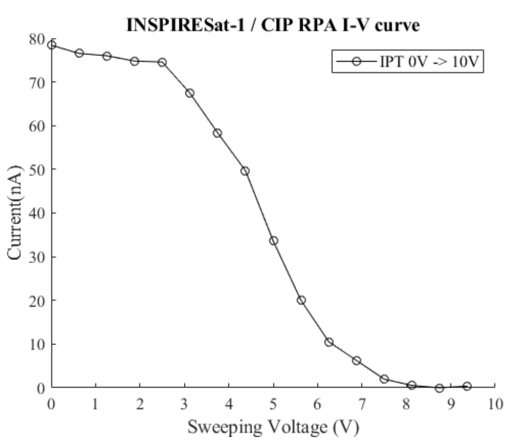

Figure 6: The CIP I-V curve generated with the instrument running in RPA mode.

The CIP instruments was powered on during eclipses and data collected. Currently the CIP team is analyzing the data. A preliminary IV curve with the instrument running in the retarding potential Analyzer (RPA) mode is shown in Figure 6.

CONCLUSIONS

The IS-1 mission was a paradigm for collaboration between space institutes to do a space science missions with significant student training. The objectives were to collaborative develop a spacecraft capable of doing significant science with high precision pointing and high data rate downlink. The programmatic objectives of international space collaboration, student training were completed when a fully integrated and tested spacecraft was developed to the launch service provider. The IS-1 spacecraft completed its primary mission when it completed six months of science operations by August 30th, 2022 to achieve comprehensive success. The spacecraft has measured many solar flare events within 15 month on-orbit period and ionosphere plasma measurements during the brief eclipse period the spacecraft encountered between May-August, 2022. Science journal articles have been submitted for publication and are expected to be published shortly. The IS-1 spacecraft has primarily been developed with all engineering details available in the open domain. The INSPIRE program has four missions currently on orbit; IS-1, IS-2, IS-5 and Is-7. Future missions currently under development; IS-3 and IS-4 also uses this now TRL 9 spacecraft architecture.

The IS-1 mission had three primary objectives; To demonstrate a model of international academic collaboration between space science institutes with contributed hardware developed at various institutions; To train the next generation space scientists and engineers to develop a microsat through extensive student involvement; To obtain high quality science data from the spacecraft for a primary mission duration of six months. The IS-1 mission has achieved comprehensive mission success through achievement of all three objectives. The IS-1 spacecraft continues to perform nominally. A preliminary data release on the spacecraft and science data products is already available through the INSPIRE program and MinXXS pages at https://lasp.colorado.edu/home/inspire/

Acknowledgments

The INSPIRESat-1 Mission was funded at the University of Colorado, Boulder by a University seed grant for the INSPIRE program. IIST acknowledges funding from the Indian Department of Space and support from the Indian Space Research Organization for funding and review. The DAXSS team is very grateful for the opportunity to fly DAXSS on the INSPIRESat-1 satellite and for the

INSPIRESat-1 team outstanding support during satellite development and mission operations. The DAXSS science team is supported by NASA grant NNX17AI71G to the University of Colorado (CU). The CIP instrument was funded at NCU by grants 105-2111-M-008 -001 -MY3 and 108-2636-M-008-002 from the Taiwan Ministry of Science and Technology, the Higher Education Deep Cultivation Grant for the NCU Center for Astronautical Physics and Engineering from the Taiwan Ministry of Education, and contract NSPO-S-106035 from the Taiwan National Space Organization. The INSPIRE team acknowledges support from ISRO for ride opportunity onboard the PSLV C-52 mission, support with flight readiness reviews and support during the Launch vehicle spacecraft integration process.

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