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FASTSAT – Mission Results from the Space Test Program S26 Mission

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Space Test Program Mission S26 (STP-S26) was the twenty-sixth dedicated small launch vehicle mission of the Department of Defense (DoD) Space Test Program (STP). The mission of the DoD STP is to provide access to space for experiments from the DoD Space Experiment Review Board (SERB). Mission STP-S26 extended previous standard interface development efforts, implementing a number of capabilities aimed at enabling responsive access to space for small experimental satellites and payloads. The STP-S26 Minotaur-IV launch vehicle was configured with a Multi-Payload Adaptor which launched the Fast, Affordable, Science and Technology Satellite (FASTSAT) and six other spacecraft on November 19, 2010. This paper describes the FASTSAT spacecraft and key development and operations lessons learned from this ground-breaking mission. The FASTSAT commercial satellite bus was developed by Dynetics in Huntsville, AL, USA in partnership with the NASA Marshall Space Flight Center (MSFC) and the non-profit Von Braun Center for Science and Innovation (VCSI). The innovative approach allowed a small, co-located team to field this new bus on a very aggressive schedule: from authority-to-proceed to ready-for-ship in 15 months. Even with the fast pace, FASTSAT successfully completed both a DoD mission review and received a NASA Certificate of Flight Readiness. Launched on November 19, 2010, nominal operations are planned through August, 2011 and extended operations to reach a full year on orbit. FASTSAT was controlled from the NASA MSFC Huntsville Operations Support Center (HOSC) using three network sites: Wallops, Norway, and the University of Alaska Fairbanks. The six diverse instruments integrated onto FASTSAT bus were selected from the DoD SERB list. These included three Earth Science Instruments from NASA Goddard Space Flight Center: Miniature Imager for Neutral Ionospheric Atoms and Magnetospheric Electrons (MINI-ME), Plasma Impedance Spectrum Analyzer (PISA) and the Thermospheric Temperature Imager (TTI); two payloads from the U.S. Air Force Research Laboratory: Light Detection System and Miniature Star Tracker; and one joint NASA/DOD 3U CubeSat – Nanosail-D, the 1st successfully deployed solar sail by the U.S. The rapid FASTSAT development program allowed multiple instruments which were at a Technology Readiness Level (TRL) of 2 to progress to TRL 9 within 24 months.

I. INTRODUCTION

FASTSAT is a minisatellite weighing less than 180 kg developed to provide rapid access to space for a variety of scientific, research, and technology payloads. The spacecraft is designed to carry up to six instruments and launch as a secondary "rideshare" payload, greatly reducing overall mission costs.

FASTSAT was designed from the ground up to meet short schedules with modular components and configurable layouts to enable a broad range of payloads at a lower cost and shorter timeline than scaling down more complex spacecraft. The spacecraft can provide access to space in 18 to 24 months from authority to proceed.

Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adaptor (ESPA) defines a standard adapter ring and specifications for spacecraft developed by the U.S. DoD, specifically accommodating secondary spacecraft launch opportunities. As an ESPA-class spacecraft, FASTSAT is compatible with several different launch vehicles, including Minotaur I, Minotaur IV, Delta IV, Atlas V, Pegasus, Falcon 1/1e, and Falcon 9. These vehicles offer an array of options for launch sites and provide for a variety of rideshare possibilities.

Fig. 1: Fast Affordable Science & Technology Satellite – Huntsville (FASTSAT-HSV01)

FASTSAT-HSV01 (shown in Figure 1) launched on November 19, 2010, carrying six experiment payloads to low Earth orbit on the STP-S26 mission and provided valuable scientific data through successful mission operations. FASTSAT-HSV01 was developed in collaboration among Dynetics, NASA's MSFC, and the Von Braun Center for Science and Innovation (VCSI) in Huntsville, Alabama, for the DoD Space Test Program (DoD STP).

II. DEPARTMENT OF DEFENSE SPACE TEST PROGRAM STP-S26 MISSION OBJECTIVES

Space Test Program Mission S26 (STP-S26) was the twenty-sixth dedicated small launch vehicle mission of the Department of Defense Space Test Program. The objectives of the STP-S26 mission included:

- Demonstrating multi-payload capability on Minotaur IV, and
- Providing access to space for Space Experiment Review Board (SERB) experiments.

Mission STP-S26 extended previous standard interface development efforts, implementing a number of capabilities aimed at enabling responsive access to space for small experimental satellites and payloads. The STP-S26 Minotaur-IV launch vehicle was configured with a Multi-Payload Adaptor which carried FASTSAT and three other ESPA-class spacecraft, as well as two CubeSats and an auxiliary propulsion system shown in Figure 2. On November 19, 2010, the mission successfully launched all six spacecraft into low earth orbit. The STP-S26 mission is flying a total of 16 experiments on six satellites.

Fig. 2: Six Spacecraft Integrated on Minotaur IV at Kodiak Launch Complex

III. FASTSAT-HSV01 EXPERIMENTS

FASTSAT-HSV01 carried six unique experiments manifested by the STP and performed first launch of CubeSat from free-flying ESPA class satellite shown in Figure 3.

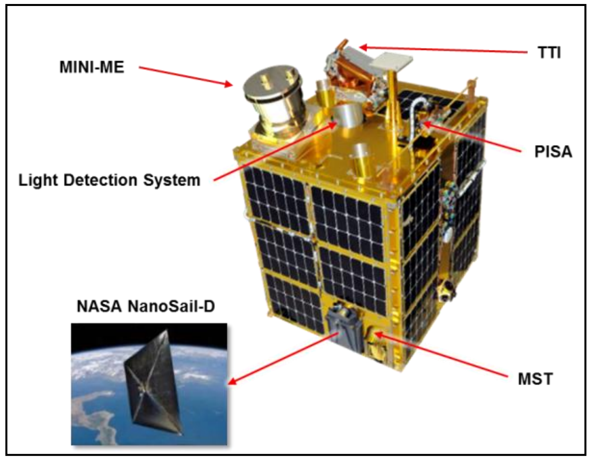

Figure 3: Six Instruments on FASTSAT-HSV01

Table 1 provides a description for each of the experiments that were flown on FASTSAT-HSV01.

Instrument Name	**Description**
Miniature Imager for Neutral Ionospheric Atoms and Magnetospheric Electrons (MINI-ME)	Improve space weather forecasting for operational use (NASA GSFC)
Thermospheric Temperature Imager (TTI)	Increase accuracy of orbital predictions for low-earth orbiting assets (NASA GSFC)
Plasma Impedance Spectrum Analyser (PISA)	Permit better predictive models of space weather effects on communications and GPS signals (NASA GSFC)
Nano Sail Demonstration (NanoSail-D)	Demonstrate deployment of a compact 10-m2 solar sail ejected as CubeSat and its deorbit capability (NASA MSFC + DoD)
Light Detection System	Evaluate atmospheric propagating characteristics on coherent light generated from known ground stations. (AFRL)
Miniature Star Tracker (MST)	Demonstrate small and low-power star tracker (AFRL)

Table 1: FASTSAT-HSV01 Experiment Descriptions

IV. FASTSAT-HSV01 SPACECRAFT BUS

FASTSAT-HSV01 was developed, integrated, tested, and ready-to-ship in 15 months using an innovative business model, tailored processes, collocated and experienced team. The key features of the spacecraft are shown in Table 2.

12-month LEO mission (650 km, 72°)
6 instrument capacity
Nanosat Payload Deployer (P-POD)
Spacecraft mass: 150 kg
Size 24" x 28" x 38" (ESPA)
Payload mass: 21 kg
Payload power: 30 W average
S-Band downlink 1 Mbps
S-Band uplink 50 Kbps
Stabilization: single axis (magnetic torque rods)
Pointing accuracy: 20°/3-axis; 10°/single axis
Pointing knowledge: 0.1°

Table 2: Key Features of FASTSAT-HSV01

The spacecraft was developed per NASA classification for Class D payloads and went through the certification for flight readiness (COFR) process. The Protoflight test program used to verify the spacecraft design included the following tests.

- 3-Axis Random Vibration
- Electromagnetic Interference & Compatibility
- Thermal Vacuum

V. FASTSAT-HSV01 DEVELOPMENT HUNTSVILLE BASED TEAM

The FASTSAT-HSV01 spacecraft was developed by a Huntsville, AL based team including Dynetics, NASA's MSFC, and the VCSI. The team was primarily collocated enabling the rapid development process. This innovative model of development using an integrated team from industry, non-profit, and NASA leverages the strengths of each teammate under a cooperative space act agreement. Dynetics provided key engineering support including RF communications, mechanical design, software development, avionics test bed, ground support equipment, and manufacturing. MSFC used its engineering and scientific expertise as well as safety and mission assurance to provide FASTSAT-HSV01 project leadership, its advanced space science facilities to provide structure and system testing, and it's Huntsville Operations Support Center (HOSC) for mission operations. VCSI is a not-for-profit research and development organization who provided overall program management and technical solutions through involvement of universities as well as other industry members.

Key to the short schedule was the use of existing manufacturing, integration, and testing facilities. As shown in Figure 4, the spacecraft structure was manufactured at Dynetics' Machine and Design Center. The assembly and integration was performed at the collocated facility clean room at the National Space Science & Technology Center (NSSTC) shown in Figure 5.

Figure 4: Machining & Design Center, Dynetics

Figure 5: Assembly & Integration Clean Room, NSSTC

FASTSAT was designed from the ground up to meet short schedules with modular components at a lower cost. The integration was completed within 10 months. Yet, a rigorous systems engineering and test approach was used to achieve flight readiness certification from NASA and DoD. Under MSFC leadership, the verification and validation program was executed involving significant NASA facilities including the EMI/EMC test facility shown in Figure 6, and the thermal vacuum test facility shown in Figure 7.

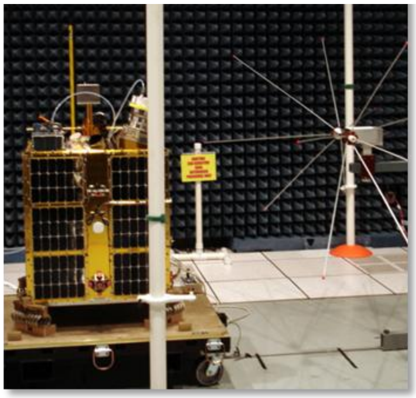

Figure 6: EMI and EMC Test Facility, MSFC

Figure 7: Thermal Vacuum Test Facility, MSFC

VI. FASTSAT-HSV01 GROUND SEGMENT

NASA's Near Earth Network (NEN) and the HOSC provided all space communications and data processing for FASTSAT-HSV01. As shown in Figure 8, the ground stations used for this mission included ASF in Fairbanks, Alaska, SKS/SGS in Svalbard Norway and WGS in Wallops, Virginia.

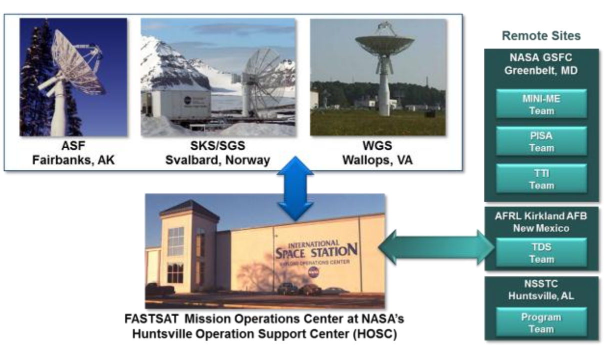

Figure 8: Ground System for FASTSAT-HSV01

FASTSAT's nominal downlink data rate is 1 Mbps with additional lower speed options of 250 kbps and 500 kbps which were used for contingency operations to improve the link margin. The lower rates were used at launch while the spacecraft was stabilizing after tip-off and during the ejection of the NanoSail-D.

The FASTSAT MOC supports remote access for the experiment teams at GSFC and AFRL as well as spacecraft engineering at NSSTC. Through secure and limited access network connections, the remote sites had both real-time voice communications loops and telemetry. This capability enabled the experiment PI's to monitor the instruments during critical operations without being on-site. In addition, the mission portal provides access to the downloaded science files and archived spacecraft data.

VII. FASTSAT OPERATIONS

All spacecraft operations planning, commanding, telemetry, and data processing are performed from the FASTSAT Mission Operations Center at the HOSC shown in Figure 9. The flight operations team includes the following positions: spacecraft manager, flight director, assistant flight director, science operations, orbital analysis, spacecraft analysis, thermal and power. During launch and commissioning, the operations center was fully staffed and the first week was operated 24 hours per day. After spacecraft checkout, the mission operations staff was reduced to a limited crew with additional support during special operations.

Prior to launch, the mission operations team developed the FASTSAT-HSV01 Satellite Operations Handbook (SOH) to define standard operating procedures (SOPs) for performing ground and on orbit operations of the FASTSAT-HSV01 satellite. This includes the SOPs for the satellite subsystems and payloads, on orbit commissioning of the satellite, planning cycles, contingency, external interfaces, and administrative operations. Documentation and training needs were reduced through the use of spacecraft engineers from the development for key positions and engaging the flight operators in the testing of FASTSAT. Prior to launch, the team held three mission sequence tests using the ground software and satellite to close out remaining verifications and achieve operations readiness.

Figure 9: FASTSAT-HSV01 Mission Operations Center

NASA's Telescience Resource Kit (TReK) was utilized for telemetry and command processing functions that include:

- Receive, Process, Display, Record, Forward, and Playback Telemetry
- Monitor incoming Telemetry for exceptions
- Manage (Build, Transmit, Record) Commands and Command Loads

The TReK ground software has been used for over ten years by International Space Station payload users. An upgraded version of TReK was developed to support FASTSAT small spacecraft operations.

The Enhanced HOSC System Personal Computer (EPC) software was used to create custom telemetry displays such as the power display shown in Figure 10. Telemetry displays such as this were used in the MOC and remotely by the payload teams.

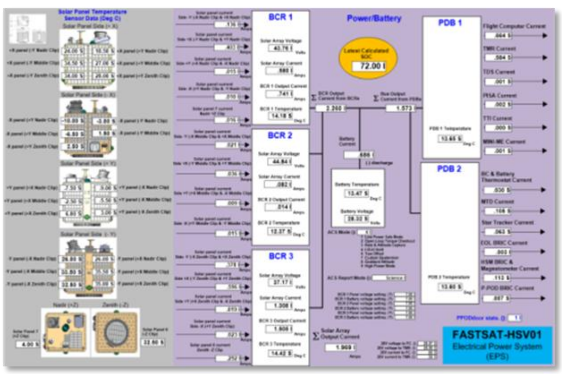

Figure 10: Power Telemetry Display for FASTSAT-HSV01

Planning inputs for flight were submitted to the operations team for review and checkout. Any operations requiring new commands or timelines were first verified by the spacecraft analyst using the avionics test bed which was collocated at the HOSC. Planning for operations over specific ground sites or needing special attitude control modes used orbital analysis data and visualization displays as shown in Figure 11.

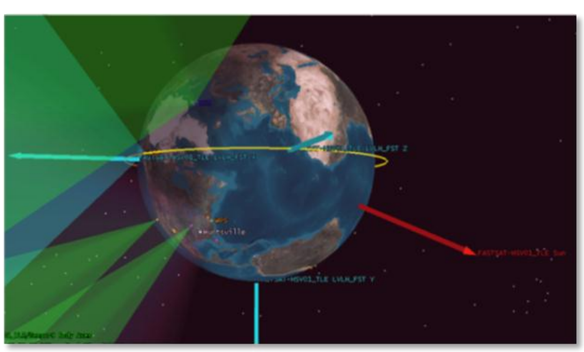

Figure 11: Orbital Analysis & Planning Products

VIII. FASTSAT-HSV01 MISSION STATUS

On August 19, 2011, FASTSAT-HSV01 completed 9 months of mission operations on orbit demonstrating capabilities of an affordable ESPA class satellite. Currently the mission has been extended to a full year and enhanced mission objectives are being performed.

During the first 9 months of spacecraft operations, FASTSAT-HSV01 completed the launch and commissioning phases successfully and is currently supporting science operations. Key performance measures of the spacecraft operations are listed below.

- 9 Months Operations
  - Launch Nov 19 at 7:25 pm CST
  - 280 days mission elapsed time
  - 4,132 orbits at 650 km
- Command & telemetry operations
  - Telecommunications operational at 1 Mbps, 500 kbps, and 250 kbps
  - Downlinked 117-M packets for over 8 GB
  - Uplinked 300,000 commands
- Power generation higher than predicted
  - Greater than 50 W orbit average
  - Enabled full time operations of multiple payloads
- Thermally slightly hotter than predicted
  - 5°F hotter than planned
  - Required changes to battery state of charge settings
- All attitude control modes functional
  - Pointing accuracy less than design goal of 3°single axis, but able to meet science
  - Some light reflection issues on sun sensors and star tracker
- Command & data handling functional
  - 9 software updates
  - Several reboots due to memory performance issues
  - Magnetometer interface anomaly worked around through alternate sensor

FASTSAT-HSV01 provided access to space for six payloads raising the technology readiness level (TRL) and providing scientific data in less than 2 years. The plan for payload operations included the ejection of NanoSail-D right after commissioning and then sequential payload operations phase for the five remaining experiments. Key accomplishments for the payload operations are listed below.

- Payload hardware checkout done day 10
  - Initial power up and communications to each instrument
- Ejected NanoSail-D CubeSat
  - First ESPA spacecraft to launch CubeSat on-orbit
  - P-POD door opened day 16

    - NanoSail-D released 43 days later
    - Recovery from 3-deg spin in 3 orbits
    - TRL from 6 to 9
- MINI-ME
    - 3,424 hours
    - 167 MB data
    - Threshold and enhanced goals
    - TRL from 2 to 9
- TTI
    - 1,224 hours
    - 250 MB data
    - Threshold science goals
    - TRL from 2 to 9
- PISA
    - 3,717 hours
    - 914 MB data
    - Threshold and enhanced goals
    - TRL from 2 to 9
- Light Detection System
    - 591 hours
    - 262 MB data
    - TRL raised to 7
- AFRL Miniature Star Tracker
    - 4,577 hours
    - 774 MB data
    - Threshold goals
    - TRL from 6 to 8

IX. NANO SAIL DEMONSTRATION (NANOSAIL-D)

The Nano Sail Demonstration experiment is led by principal investigator Dean Alhorn from NASA MSFC. The primary objective was to demonstrate deployment of a compact 10-m^2 solar sail ejected as 3U CubeSat shown in Figure 12.

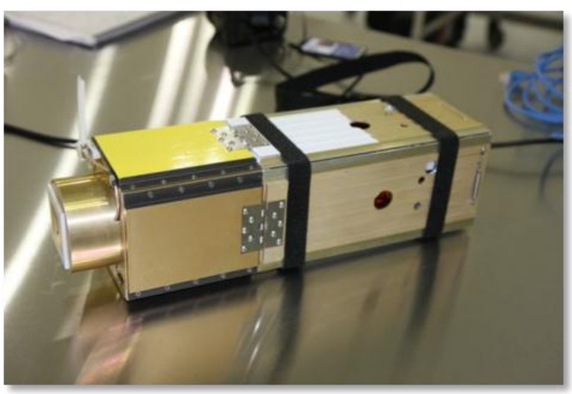

Figure 12: NanoSail-D 3U CubeSat Pre-encapsulation

NanoSail-D was ejected from FASTSAT on January 17, 2011, demonstrating the first CubeSat launched on-orbit from ESPA-class satellite. The solar sail was deployed 72 hours later when the on-board timer expired. This sail deployment on January 20, 2011, demonstrated ability to deploy highly compacted solar sail/boom system. Figure 13 shows a ground test of the sail deployment.

Confirmation of the sail deployment was obtained through a combination of telemetry data from NSD and data obtained by space tracking systems. In addition, on orbit images have been captured from independent sources indicating the larger surface area such as the image in Figure 14 from the Clay Center Observatory.

A secondary objective for NanoSail-D was to validate the technology as a passive (non-propulsive) deorbit technology. For low earth orbit small satellites, a large surface area deployable like the NanoSail enables the spacecraft to deorbit within the required 25 years eliminating the need for an on-board propulsion system. With the sail deployed, the NanoSail-D spacecraft altitude has lowered over 130 km in 215 days as shown in Figure 15. Based on the current predictions, NSD will achieve deorbit in less than 12 months from sail deployment instead of the 26 years required without the sail.

Figure 13: Ground Deployment Test of 10-m^2 Solar Sail

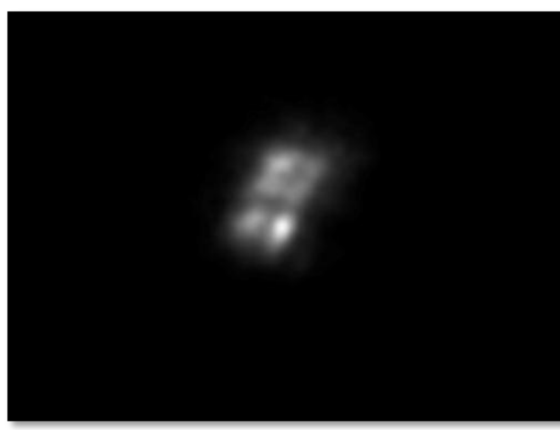

Figure 14: NanoSail-D In-orbit Image Captured Clay Center Observatory

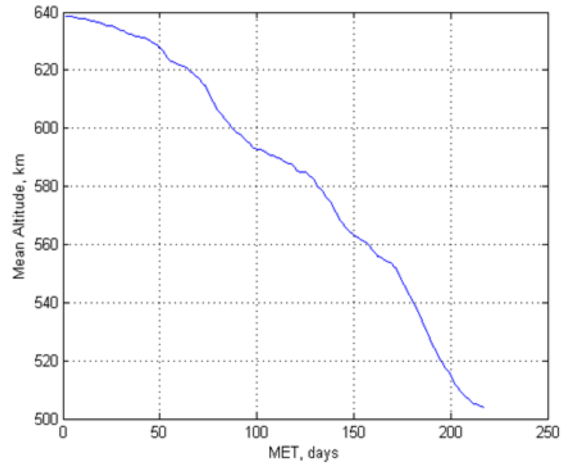

Figure 15: 130-km Mean Altitude Drop of NSD

The NanoSail-D mission has raised the technology readiness to 9 for compact deployable de-orbit systems for future satellites and deployable booms for thin film solar arrays.

X. PLASMA IMPEDANCE SPECTRUM ANALYZER (PISA)

The PISA experiment shown in Figure 16 integrated on FASTSAT was led by principal investigator Doug Rowland from NASA GSFC. The primary objective was to use novel, "white noise" technique to measure electron number density and electron temperature in the Earth's ionosphere. The use of this instrument technique would permit better predictive models of space weather effects on communications and GPS signals.

PISA has achieved minimum and comprehensive success criteria through on-orbit operations on FASTSAT. A single impedance spectrum collected in December 2010 shown in Figure 17 demonstrates resonance as predicted.

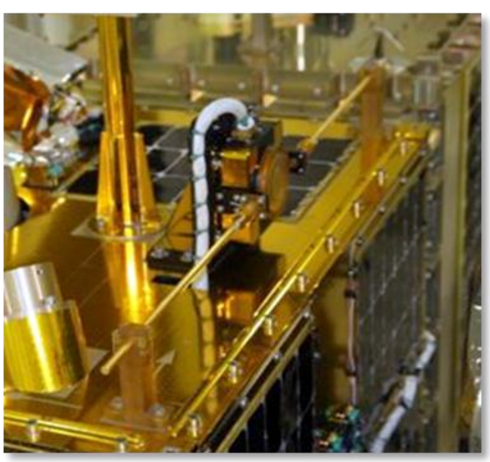

Figure 16: PISA Pre-encapsulation Kodiak Launch Complex

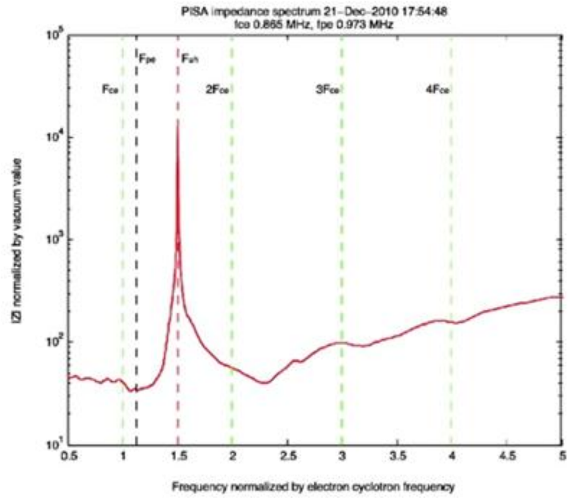

Figure 17: Single PISA Impedance Spectrum, Showing Resonance

PISA has over 3,717 hours of on-orbit operation producing well over 1 GB of raw data. Figure 18 shows an entire orbit of spectral data collected by PISA in January 2011.

The TRL of PISA has been raised to 9 through successful on-orbit operations. The PISA data has been analysed to show derived electron density values illustrated in Figure 19 from data correlated to an MINI-ME outflow event in March 2011.

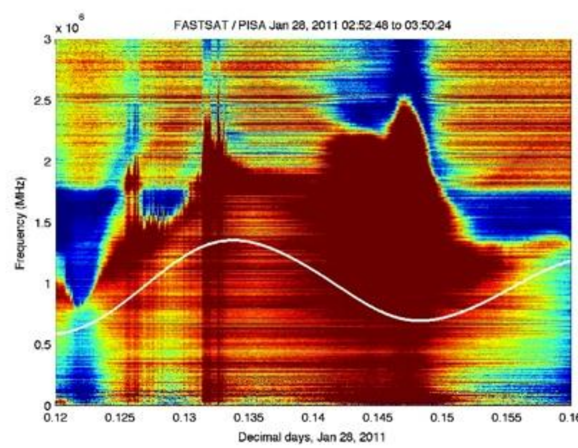

Figure 18: One orbit of spectra measured by PISA

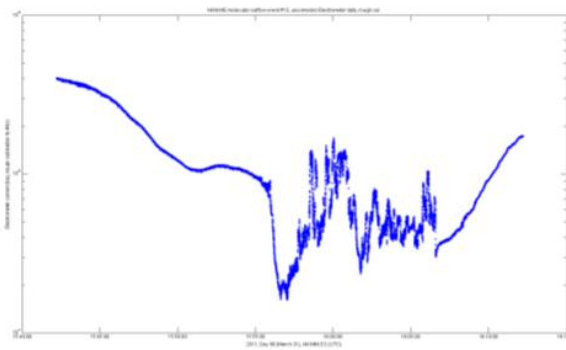

Figure 19: Derived Electron Density During MINI-ME Outflow Event

XI. MINIATURE IMAGER FOR NEUTRAL IONOSPHERIC ATOMS AND MAGNETOSPHERIC ELECTRONS (MINI-ME)

The MINI-ME experiment shown in Figure 16 integrated on FASTSAT was led by principal investigator Michael Collier from NASA GSFC. MINI-ME remotely senses magnetospheric plasma populations to improve space weather forecasting for operational use.

Figure 21 shows the MINI-ME concept of operation for remote sensing of ions.

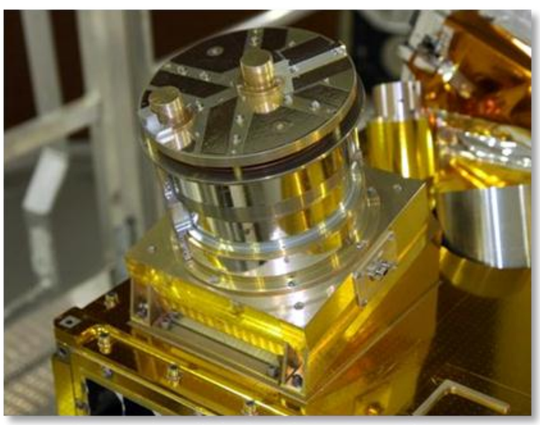

Figure 20: MINI-ME Pre-encapsulation Kodiak Launch Complex

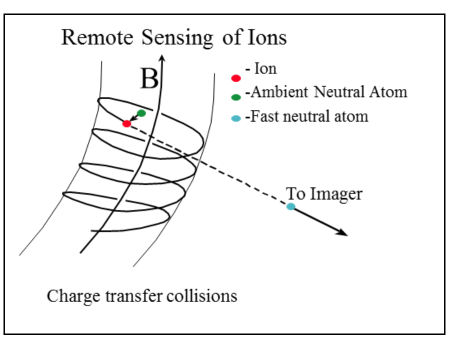

Figure 21: MINI-ME Concept of Operation

Charged particle populations are confined to particular regions of space by electric and magnetic fields. In the past, detecting these charged particle populations required in-situ observations. Neutral atom imaging using the MINI-ME instrument configuration shown in Figure 22 allows us to detect these charged particle populations remotely by detecting the charge exchange products.

MINI-ME has achieved minimum and comprehensive success criteria on the FASTSAT mission raising the TRL to 9. Based on calibration data, MINI-ME has a very prominently and easily-identified response to molecules. So far, the team has identified 12 molecular outflow periods. These periods all occur between 65° and 82° geomagnetic latitude and are more common when geomagnetic activity is high. Figure 23 shows a possible molecular outflow from high latitude ionosphere during FASTSAT operations in February 2011.

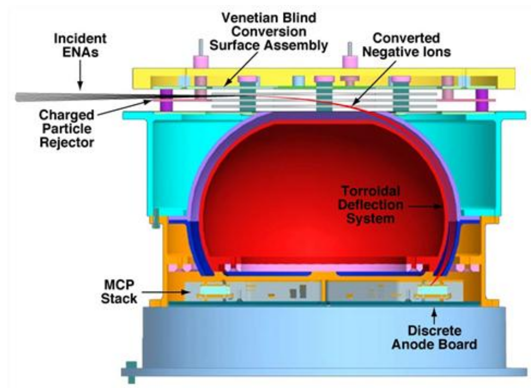

Figure 22: MINI-ME Instrument Configuration

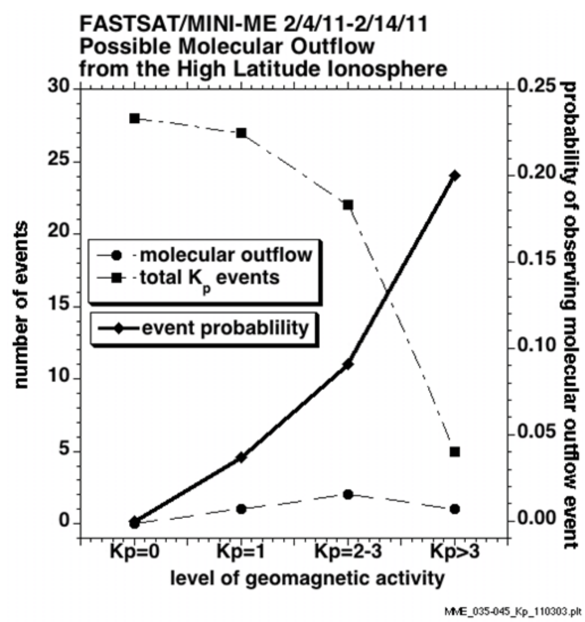

Figure 23: Possible Molecular Outflow from High Latitude Ionosphere

XII. THERMOSPHERIC TEMPERATURE IMAGER (TTI)

The TTI experiment led by principal investigator Sarah Jones from NASA GSFC is shown integrated on FASTSAT in Figure 24. The objective of TTI is to obtain remote sensing measurement of neutral atmospheric temperature. Aerodynamic drag experienced by space assets is controlled by the temperature profile in the thermosphere which in turn sets atmospheric density at orbital altitudes. Sudden solar flares raise the temperature of the thermosphere resulting in unexpected decay of low altitude orbits and premature de-orbit of affected platforms.

TTI is first to perform UV interferometric determination of thermospheric temperature through measurement of the Doppler-widening of auroral and airglow emissions. Figure 25 shows how the TTI field of view is oriented to achieve the measurements.

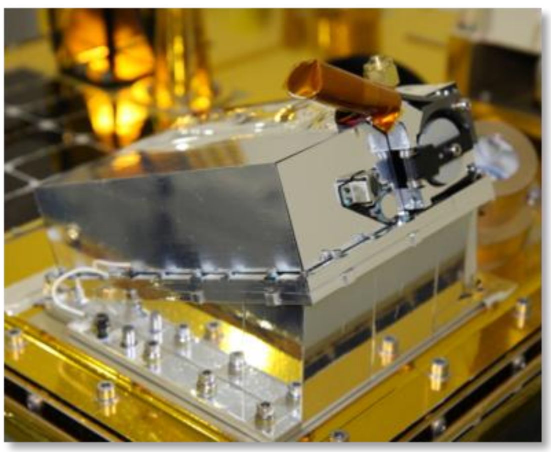

Figure 24: TTI Pre-encapsulation Kodiak Launch Complex

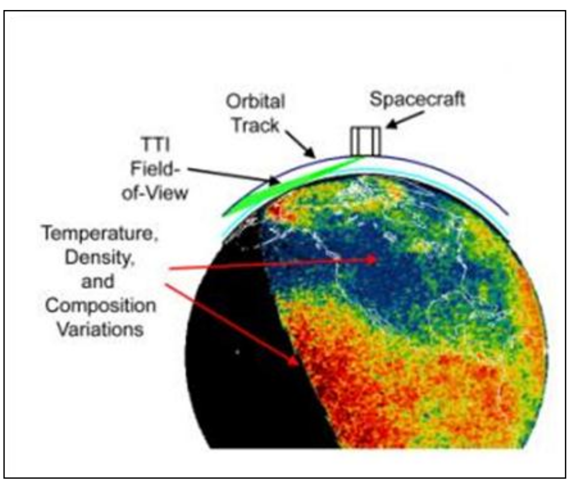

Figure 25: TTI Concept of Operation

The TTI experiment has achieved minimum success criteria and demonstrated preliminary science. TTI is measuring UV signatures of aurora and airglow for determination of thermospheric temperature raising the TRL to 9.

XIII. KEY LESSONS FROM RAPID SPACECRAFT DEVELOPMENT

Some of the key lessons learned from the rapid development and testing of a Class D spacecraft in 15 months are listed below:

- Co-located, flat team model greatly improved efficiency
- "Faster and cheaper" from "ground up" easier than optimizing "slow and expensive"
- Get Class-D risk buy-in from leadership up-front to avoid scope creep
- Streamline approval processes to eliminate waiting on signatures
- 3D collaboration tools facilitated rapid spacecraft and payload layout
- Multiple avionics test beds are needed to accelerate hardware and software testing
- "Test as you fly" early including long duration runs to avoid system test problems

XIV. KEY LESSONS FROM SMALL SPACECRAFT OPERATIONS

FASTSAT-HSV01 has completed 9 months of operations providing additional lessons learned for the preparation and execution of small spacecraft operations on future missions listed below.

- Transitioning engineering from development to support commissioning reduced documentation and training needs
- Early involvement of operations team and ground software are essential to the flight software development and testing
- Maintaining a spacecraft analyst for several months after commissioning allowed for rapid identification and resolution of issues
- Data flow testing before launch with ground sites is critical but did not uncover RF configuration problems at launch
- Automating ground contacts is needed so that operations team can focus on spacecraft and payload operations

XV. FASTSAT MISSION CONCLUSIONS

The primary objectives of the FASTSAT-HSV01 project are to provide low Earth orbit opportunities for the satellite experiments, to demonstrate the satellite bus and mission integration approach, and to demonstrate PPOD launch capability of a "nanosat" class spacecraft from the satellite bus. Not only did FASTSAT meet these objectives, but it also demonstrated the ability of ESPA class satellites to support multiple payload technology demonstration and Earth science research. Lastly, the project proved a "first time build" of a Class-D spacecraft in less than 15 months with six new payloads for less than ½ of the typical cost.

New FASTSAT models under development will leverage the heritage design and rapid development processes while providing significant improvements in capabilities to meet future mission requirements providing affordable and rapid access to space. For example, Figure 26 shows an Earth Imager Concept design of FASTSAT which increase payload power with additional solar arrays and provide better pointing capabilities with reaction wheels.

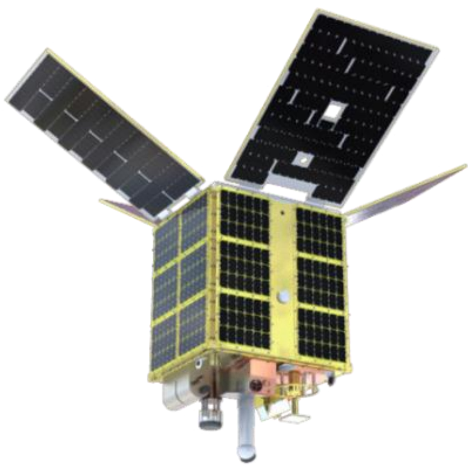

Figure 26: FASTSAT Earth Imager Concept

Another FASTSAT model under development is the Mothership concept shown in Figure 27. The mothership extends the CubeSat launching capability of FASTAT to deploy four to six of the 3U nanosatellites. The Mothership provides greatly enhanced mission options for CubeSat including staggered and delayed deployment, constellation deployment and even formation flying distributed architectures.

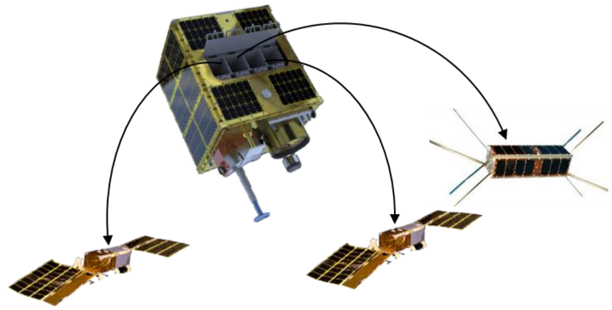

Figure 27: FASTSAT Mothership Concept