AIR FORCE ACADEMY DEPARTMENT OF PHYSICS SPACE TECHNOLOGIES DEVELOPMENT AND RESEARCH

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ABSTRACT

As an integral part of the Air Force Academy's education of future officers and space professionals, Department of Physics faculty and undergraduate science, engineering, and management students are engaged in cutting-edge space research and technologies development. Activities include design and construction of a deployable membrane telescope for space-based imaging; aggressively miniaturized plasma sensors for acquiring space weather data and understanding spacecraft thruster plume dynamics; and a highly automated space operations center directing a global network of small, ground-based telescopes for novel satellite detection, tracking, identification, and characterization. The deployable membrane telescope, Peregrine, has a mass less than 1.7 kg and fits within a 1.5U volume for a 3U (10 cm x 10 cm x 30 cm) CubeSat. Peregrine consists of a 10-g Kapton polyimide, 20-cm diffractive primary optic; a unique double deployment structure with a moveable carriage plate and triangular pantograph painstakingly engineered for highly repeatable pantograph tip positioning and small spherical tolerance zones; an optical platform with secondary optics and primary camera; and mission electronics and software. Peregrine demonstrates key technologies to enable low-cost, compact form factor, lightweight, space-based imaging science and surveillance missions. Physics faculty and student researchers are also advancing the state-of-the-art in miniaturized, low-power, highly capable plasma ion spectrometers for efficient hosting on low earth orbit and geosynchronous earth orbit satellites, enabling ubiquitous space weather data collection and spacecraft thruster plume detection. The final Physics Department space technologies thrust highlighted in this paper is a student-faculty space operations center controlling a worldwide (12 sites across the U.S., South America, Australia, Europe, and Africa), fully networked configuration of 51-cm automated and robotic telescopes to explore and mature space object identification and characterization capabilities through spatially diverse, sometimes simultaneous, and temporally continuous optical observations of satellites.

INTRODUCTION

Most of the recent Department of Defense (DoD) strategic studies and the numerous speeches of senior leaders emphasize the United States has entered a protracted period of flat or, most likely, continually declining defense budgets as a result of decades of war expenditures and the worldwide financial and economic crisis of 2008-2009. Due to these severe fiscal constraints, senior officials are relying even more so than in past eras on innovation and superior technology development as critical enablers of the next generation of dominant military capabilities. This innovation and technology development must occur within and across government, industry, and academia from the smallest bench-level projects to the largest weapon systems acquisitions. Every organization can play an important role, no matter how large or small the organization's resources.

The United States Air Force Academy (USAFA), with its diverse, extremely talented mix of students and faculty, is an incubator for innovative, creative, and affordable technology solutions for Air Force (AF) warfighting needs. Specifically in the space superiority mission areas of importance to United States national security and global military operations, the USAFA Department of Physics faculty and undergraduate students from a variety of the

Academy's academic disciplines have been engaged for more than fifteen years in leading-edge space research, innovation, and technologies development. Leveraging the talents of eager and enthusiastic cadets, passionate faculty, and multiple research centers that are well equipped and thoughtfully integrated into the students' learning experiences as well as strategically focused on real-world AF and DoD needs, the Department of Physics provides creative and extremely affordable next generation solutions to some of the military's complex challenges. Highlighted in this paper are the design and construction of a deployable membrane telescope for space-based imaging, an effort involving both the department's Laser and Optics Research Center (LORC) and Space Physics and Atmospheric Research Center (SPARC); SPARC personnel and student development of miniaturized plasma sensors for ubiquitous space weather data collection and spacecraft thruster plume detection; and the Center for Space Situational Awareness Research (CSSAR) initiatives to develop a highly automated space operations center directing a global network of small, ground-based telescopes for novel satellite detection, tracking, identification, and characterization.

FALCONSAT-7: A LOW EARTH ORBIT CUBESAT MISSION WITH DEPLOYABLE SOLAR TELESCOPE

The USAFA Physics Department's SPARC is the program integrator for a low earth orbit (LEO) 3U (10 cm x 10 cm x 30 cm) CubeSat space-based imaging mission named FalconSAT-7 with the primary goal of developing and demonstrating revolutionary deployable membrane telescope technologies for applications to warfighter, intelligence, surveillance, reconnaissance, and scientific missions. The currently planned launch window is late calendar year 2015 to mid-year 2016. As part of the Academy's mission to "to educate, train and inspire men and women to become officers of character, motivated to lead the United States Air Force in service to our nation," another major objective permeating all FalconSAT-7 activities is educate and develop technically astute future AF officers and space professionals. A proven high-impact approach is to engage students alongside mentors in real-world, hands-on research and advanced technology development and thus "learn space by doing space." In executing the FalconSAT-7 program, SPARC personnel and Departments of Physics, Astronautics, Electrical and Computer Engineering, and Management faculty and students are collaborating with scientists, engineers, and technologists from the National Reconnaissance Office, Defense Advanced Research Projects Agency, Air Force Office of Scientific Research (AFOSR), Air Force Institute of Technology, MMA Design LLC, Air Force Research Laboratory Space Vehicles Directorate (AFRL/RV), National Aeronautics and Space Administration (NASA), and the Space and Missile Systems Center Space Development and Test Directorate (DoD Space Test Program (STP)).

The FalconSAT-7 3U CubeSat, with a nominal mission design life of 3 months, is comprised of the 1.5U spacecraft bus containing the flight processor; electrical power subsystem; attitude determination and control subsystem; telemetry, tracking, and command; and encryption module; and the 1.5U payload Peregrine. Peregrine is a deployable membrane telescope, an innovative combination of telescope technologies that, if proven successful in the space environment during the pathfinder FalconSAT-7 mission, will enable future space-based scientific imaging and military and national security surveillance missions using significantly lower cost, larger and less massive primary optical elements than traditional optical telescopes designed for space, with concomitant higher resolution capabilities. Specifically for the planned FalconSAT-7 proof-of-concept mission, the deployable membrane telescope will be used for narrow-band imaging of the sun's chromosphere at the hydrogen-alpha spectral line of 656.46 nm (vacuum wavelength)[1]. The FalconSAT-7 telescope technologies could enable affordable, very large space-based solar observatories with imaging resolutions sufficient to understand the small-scale spatial dynamical structures of the sun's chromosphere that contribute to the formation of solar flares and coronal mass ejections[2]. Understanding space weather and having better prediction capabilities is an important need for the military, national security, civil, and commercial space communities given the $200B capitalization and $75B replacement launch costs[3] of the approximately 1000 active satellites currently in orbit about the earth and constituting a $304B global space economy[4].

Peregrine is the first-ever deployable telescope payload for CubeSats. It is comprised of four subsystems: membrane primary optical element (developed and patented by a Department of Physics LORC researcher), deployment structure, optical platform containing the secondary optics and primary camera, and payload electronics and software (Exhibit 1). The membrane, deployment and support structure, secondary optics, cameras, and associated payload electronics and power management systems were designed and constructed for a 1.5U volume and have a mass of less than 1.7 kg. The membrane optical element and deployment structure subsystems are tightly linked with regards to the overall optical performance of the telescope[5]. (The coupled optical-mechanical modeling and performance is not discussed in this paper; a detailed analysis is in Reference 5.)

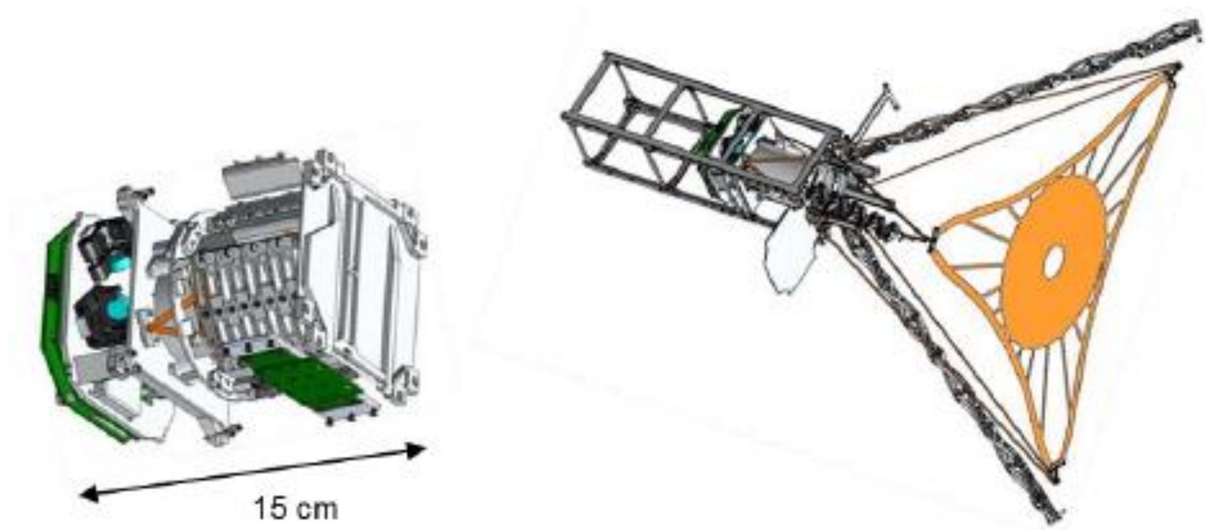


Exhibit 1: Stowed (1.5U) and deployed Peregrine payload schematics.

The Peregrine membrane primary optical element is an *f*/2, 20-cm diameter photon sieve, a diffractive optic consisting of more than 2.5 billion cylindrical holes each of depth 0.47 µm with varying diameters (2 to 277 µm) and radial and angular positioning on a 30-µm thick transparent Kapton polyimide (index of refraction, n =1.62) substrate. The photon sieve is essentially a Fresnel zone plate in which the diffraction rings are replaced with the billions of individual cylindrical “divots”. Thus, the light gathered by the telescope is focused via diffraction as opposed to refraction or reflection of traditional lenses or mirrors, respectively. The Peregrine photon sieve is binary in nature (diffraction grating is either on or off, i.e., photons travel through either 30-µm thick Kapton or 29.53-µm thick Kapton) and is a phase-type diffraction grating, with modifications to the incident light wave phase and not its amplitude. The grating fill factor is 50% resulting in a 33% focusing efficiency.

Detailed discussions and analyses of photon sieves are discussed in other papers[6,7,8]. Membrane photon sieve optical elements have several distinct advantages compared to traditional optics: (i) diffraction limited or perfect focusing can be achieved from extremely lightweight, low areal density polyimide sheets that can be gently rolled and folded into compact volumes and then unfurled on orbit; (ii) the flatness, or out-of-plane deformation, requirements of the membrane surfaces are significantly less stringent than for refraction and reflection optical element surfaces; and (iii) fabrication costs of membranes are much lower than for comparable quality lenses and mirrors. However, these advantages are accompanied by some disadvantages that must be carefully accounted for in the telescope design: (i) decreased optical efficiency, and (ii) extremely large dispersion resulting in narrow imaging bandwidth. The Peregrine photon sieve has a spectral bandwidth on the order of one Angstrom, thus only grayscale images can be obtained. Exhibit 2 illustrates the performance of a Peregrine-like photon sieve evaluated by focusing, imaging, and interferometry[9]. The Peregrine photon sieve telescope, consisting of the photon sieve, collimating lens, hydrogen alpha filter, focusing lens, three fold mirrors, and charge-coupled device (CCD) camera has an angular resolution of 4μrad (approximately 630 km at the sun's surface) and diffraction limited field of view of 0.013deg (roughly one-fifth the diameter of the sun's disk). Exhibit 3 is a schematic of the telescope optical layout[10].

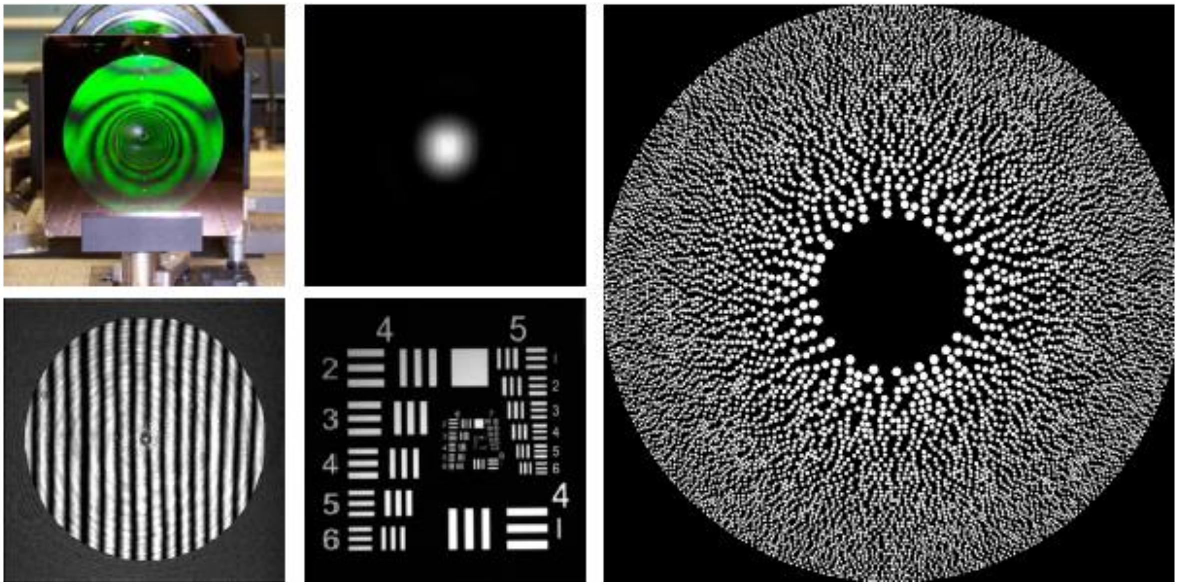


Exhibit 2: Clockwise from top left: A 10.2-cm chrome-coated, quartz plate master photon sieve illuminated by Nd:YAG laser light (532nm). Resultant focal spot at the designed 1-m focal length. A magnified image of the central 25 mm of the photon sieve (which contains a total of 10^7 holes). An image of a resolution chart produced by the sieve which demonstrates sharp imaging capability over a useful field of view. An interferogram of the wavefront that indicates perfect (diffraction-limited) focusing capability.

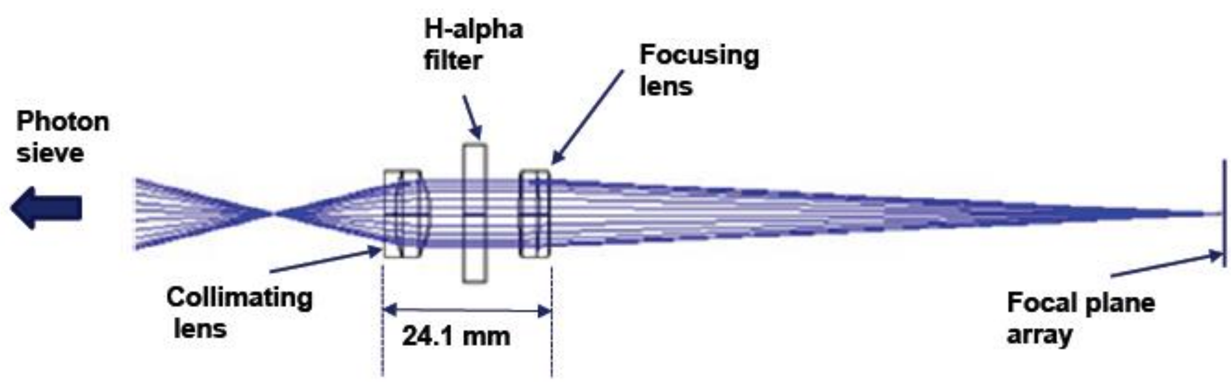
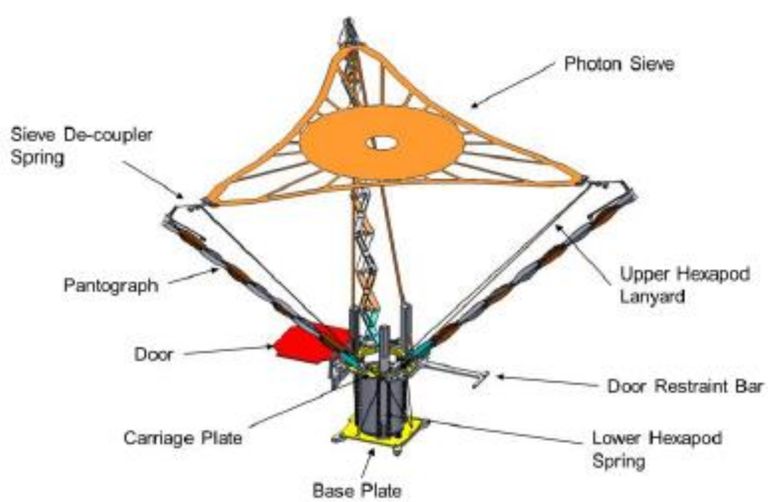


Exhibit 3: Peregrine telescope schematic. Focused light from the photon sieve to the left (not shown) passes through two lenses and filter. The collimated beam is approximately 10 mm in diameter, and the final focal distance from the second lens to the camera focal plane is about 100 mm. The three fold mirrors after the final lens are not shown.

The photon sieve telescope is a very novel approach to space-based optical imaging with great promise for future space-based solar observatories, surveillance telescopes, or exoplanet telescopes. Such an approach requires a painstakingly engineered deployment structure to unfurl without damage the compactly stowed, catenary-shaped photon sieve, position the polyimide membrane at the precise location required, and produce a uniform stress field across the flexible membrane to minimize both out-of-plane and in-plane deformations of the optical sieve. The very creative and unique double deployment structure, designed by MMA Design LLC, Boulder, Colorado to meet the photon sieve telescope optical and mechanical requirements, is described in detail in a previous paper[11]. This structure consists of a central tube (5-cm diameter, 7.8-cm length), anchored to the deployment structure baseplate, that houses and protects the compactly folded photon sieve and is surrounded symmetrically by three spring-loaded pantographs stowed under compression. Once FalconSAT-7 is on-orbit and readied for the solar imaging mission, the hinged end panel of the CubeSat is commanded to open using a melt wire release mechanism and the pantographs automatically deploy due to the stowed spring forces. The membrane is pulled to within the required flatness requirements by a 0.5-N radial tension provided by the pantographs and upper Vectran lanyards that form a tensioned upper hexapod as shown in the Exhibit 4 CAD drawings. Final positioning of the membrane photon sieve critically depends on the lengths of these lanyards which form a spatially determinate system (3 points uniquely determine the photon sieve plane) for the three reinforced vertices of the triangular (catenary-shaped edges) membrane. Decoupling of the membrane from the pantographs is accomplished with springs. In order for the pantographs to correctly deploy from their stowed configuration within the CubeSat, completely free of interference from the bus structure, they are mounted to a carriage plate that moves the base of the stowed pantographs 7.75 cm from within the bus to the end of the CubeSat. The carriage plate deployed position is also critical for the final optical positioning of the membrane photon sieve and is therefore determinately placed using a second tensioned lower hexapod. The tension for the lower hexapod is provided by springs that also provide the force for the movement of the carriage plate. As the carriage plate is moving the pantographs clear of the bus structure, a simple deployment constraint prevents the pantographs from extending up and out from the axis of the CubeSat. The MMA Design, LLC double deployment structure is expected to provided repeatable pantograph tip positioning to within a spherical tolerance zone of less than 2-mm radius.



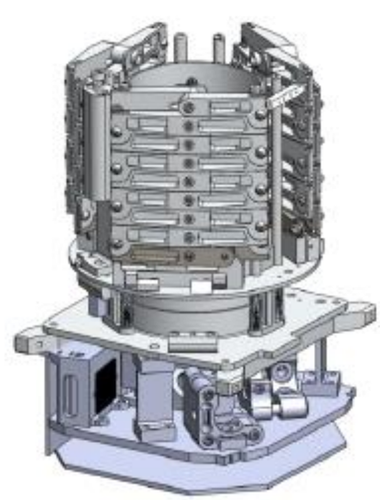


Exhibit 4: Left CAD drawing illustrates the double hexapod deployment structure and final positioning of the membrane. Right CAD drawing shows the stowed configuration of the pantographs symmetrically surrounding the central tube which houses the folded photon sieve. The secondary optics and CCD camera are located on the lower platform which is pinned and bolted to the base plate of the deployment assembly.

While on orbit, to confirm that the membrane photon sieve has deployed without tangling, tearing, creasing, or undergoing any other malfunction that would significantly impact or prevent imaging the sun, an analog commercial camera (Lawmate CM-SS40) attached to the top corner of the CubeSat bus structure will image the membrane deployment at a rate of 19 frames per second. The camera cannot be used to determine if the membrane deploys to the correct optical position.

The secondary optics of the photon sieve telescope (Exhibit 3) collimate the focused beam from the photon sieve for transmission through a narrowband Andover filter (1.5 angstroms FWHM, 35% peak transmission) and change the effective *f*-number of the system to *f*/10. The narrowband hydrogen alpha filter eliminates the majority of non-focused light at the focal plane array (FPA) of the camera. A Zemax analysis indicated that stray light represents less than 1.25% of the total light energy at the at the FPA. Reflecting through three fold mirrors, the beam illuminates a 10-bit monochrome CCD camera manufactured by Sentech. Radiometric analysis reveals there should be sufficient light to obtain images of the sun at an acceptable signal-to-noise ratio greater than 20. The secondary lenses are mounted to an electronically controlled Micronix USA vacuum rated mechanical translation stage with encoder providing 8 mm of travel in increments of 1.5 nm. This variable focusing capability allows for changes in defocus due to on-orbit thermal effects (expansion and contraction) of the photon sieve optical pattern. The suite of secondary optics, translation stage, and main CCD camera are packaged on an optical platform approximately 9.4-cm square and 3.5 cm total height as shown in Exhibit 5.

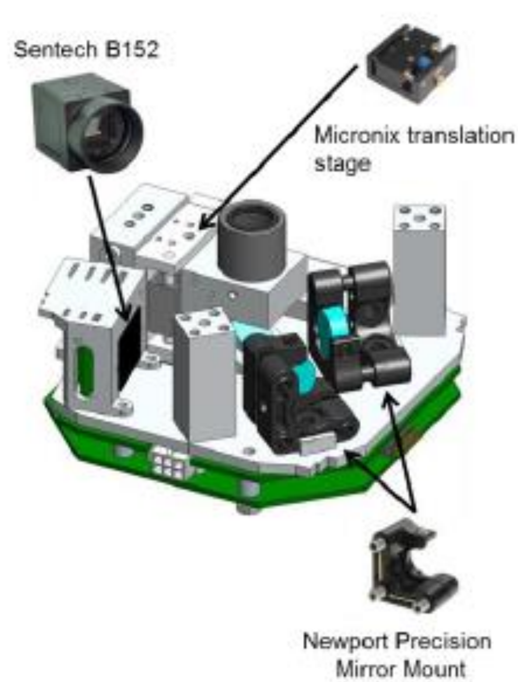


Exhibit 5: Left CAD drawing illustrates the double hexapod deployment structure and final positioning of the membrane. Right CAD drawing shows the stowed configuration of the pantographs symmetrically surrounding the central tube which houses the folded photon sieve. The secondary optics and CCD camera are located on the lower platform which is pinned and bolted to the base plate of the deployment assembly.

The Peregrine payload electronics must provide command and control (C&C) of the payload, as well as data handling. C&C requirements include the operation of the main CCD camera and inspection camera, field-programmable gate array (FPGA) control, and movement and reading of the translation (focusing) stage. Exhibit 6 is a block diagram of the payload electronics.

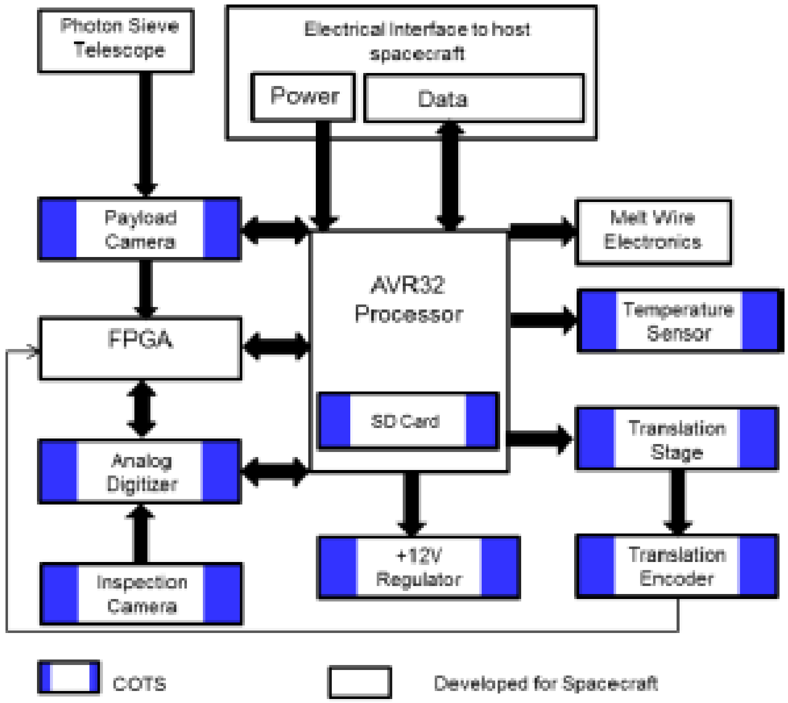


Exhibit 6: Peregrine payload electronics block diagram. Arrows indicate C&C signal flow.

Payload command and control electronics have been developed in-house (SPARC) and packaged onto two printed circuit boards, each less than 82 mm x 82 mm and less than 1.5 cm high. Some of the design has flown successfully on orbit with other SPARC payloads. The remainder has been purchased as commercial-off-the-shelf components with some repackaging to fit the restrictive form factors of a CubeSat or designed from scratch specifically for FalconSAT-7 specifications. Central to the payload electronics is an Atmel AVR32 microcontroller. The AVR controls a Xilinx Spartan 3AN FPGA which captures the digital images from the Sentech CCD camera at rates up to 19 frames per second, saves the images to intermediate random-access memory, and provides a buffer for transmitting images back through the AVR to a 2GB secure digital memory card used for flash storage (storage for approximately 700 images). Configuring the FPBA on orbit can be accomplished with the AVR. The microcontroller also (i) operates the melt wire circuitry which activates the membrane photon sieve deployment; (ii) controls the main CCD camera analog and digital gains, scanning, binning, and exposure settings (10 µsec and longer); (iii) using a digitizer, executes and downloads images from the deployment inspection camera; (iv) drives and records positional information from the focusing stage of the optical platform; and (v) communicates with the CubeSat bus via a 422 asynchronous bus.

SPARC personnel and Departments of Physics, Astronautics, Electrical and Computer Engineering, and Management faculty and students, working with AF, DoD, NASA, and industry partners, are constructing and testing the Peregrine payload for integration with a 3U CubeSat. The mission goal for this payload is to demonstrate the effectiveness of deployable membrane photon sieve telescopes for space-based imaging missions. The membrane photon sieve technology can potentially be scaled to large apertures (up to 20 m) and hosted on larger spacecraft. Most of the analysis and optical-mechanical modeling of the payload has been completed along with a large amount of laboratory testing. Results to date indicate the Peregrine payload will achieve acceptable imaging performance on orbit and thus successfully demonstrate the technologies for space-based deployable membrane telescopes.

MINIATURIZED PLASMA SENSORS FOR SPACE MISSIONS

The USAFA Physics Department's SPARC personnel, faculty, and students, collaborating with AFOSR, AFRL/RV, John Hopkins University Applied Physics Laboratory (JHU/APL), Office of Naval Research, and the DoD STP Program Office, have been developing and flying aggressively miniaturized space plasma sensors for almost 15 years. Better understanding of the LEO plasma environment in which spacecraft are constantly immersed and the space weather events that can impact space operations is a significant space superiority need. Spacecraft charging can be detrimental to the overall spacecraft or subsystems health and interfere with payload/sensor operations. More accurately forecasting space weather, particularly forecasting the naturally occurring ionospheric plasma irregularities ("plasma bubbles"), is important for planning military operations. These low latitude irregularities lead to degradation or outages of satellite communications; position, navigation, and timing signals; and synthetic aperture radar imaging. Low size, weight, and power (SWAP) plasma sensors (measuring plasma densities and temperatures) with ubiquitous hosting on military, national security, civil, and commercial satellites constitute a comprehensive approach to these issues.

The enabling technologies for a low SWAP space plasma sensor were developed and patented by a SPARC researcher[12] and have been steadily advanced over the past 12 years. The current version of the sensor, referred to as the Integrated Miniaturized Electrostatic Analyzer (iMESA), is a package (sensor-head array, printed circuit boards with amplifier array electronics and AVR microcontroller, power supply, and chassis) of volume approximately 10 cm x 10 cm x 4 cm, mass less than 1 kg, and power less than 2 W. The electronics design of the iMESA instrument was accomplished, prototyped, and tested by students and faculty of the USAFA Department of Electrical and Computer Engineering. Photographs of the iMESA are shown in Exhibit 7. iMESA contains a detector head and supporting electronics board[13]. The detector head consists of 3 sets of collimating plates and 2 offset electrostatic deflection chambers through which charged particles (ions or electrons) of the correct "bandpass"

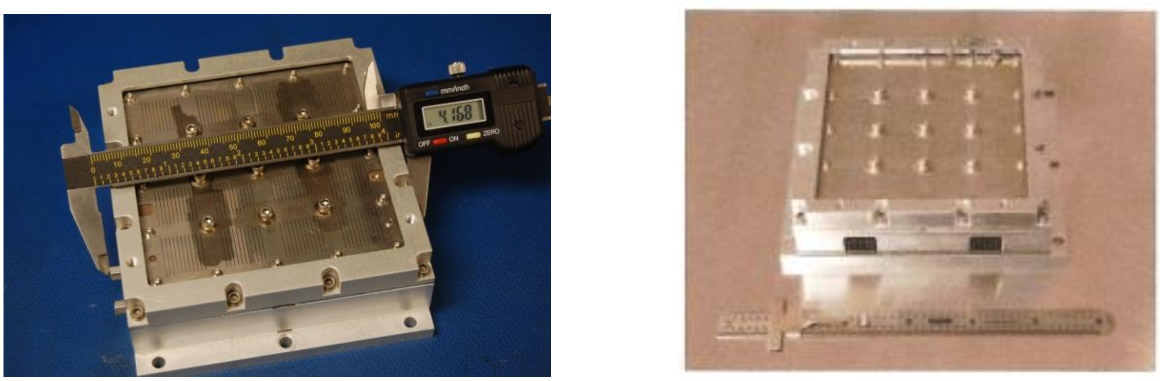


Exhibit 7: Photographs of the iMESA instrument flown on the International Space Station during 2009-2001 onboard the MISSE7 platform. The ion entrance slits are on top of the instrument.

energy successfully traverse (Exhibit 8). Entering the far left set of grounded collimation slits (entrance aperture), the charge particles are deflected by a saddle electrostatic field established in the left chamber (with scalloped edges) suing a biased plate. The bias voltage required to steer the charged particles of energy E (in eV) through a second set of grounded collimation slits is proportional to E. Particles are steered through a double S-turn trajectory by a second mirrored biased plate (right deflection chamber) and third set of grounded collimation slits (exit aperture) and impinge on an anode or collection plate (not shown in Exhibit 8). A transimpedance amplifier measures the anode current and the output voltage (proportional to current and hence charge particle density) is digitized. An AVR microcontroller sets and sweeps the deflection voltage, and the detected signal at each step is measured and stored in flash memory, thereby producing charged particle energy spectra. Subsequent analysis of the energy spectra yields plasma densities and temperatures as well as quantity of spacecraft charging. iMESA instruments measure low-energy plasma ions and electrons, with E $\lesssim$ 100 eV.

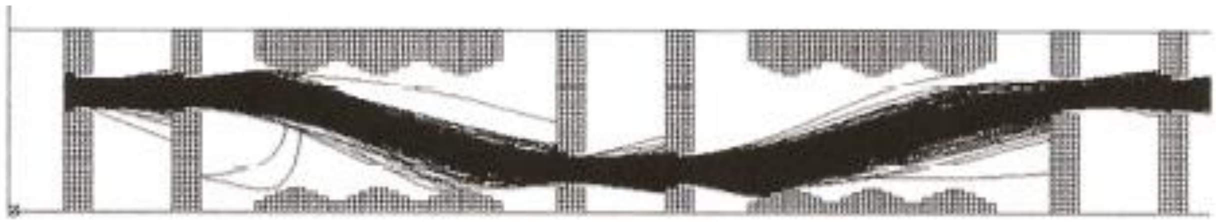


Exhibit 8: Cross-section of iMESA instrument detector head, consisting of 3 sets of grounded collimating plates (left, center, and right) and 2 biased electrostatic deflection chambers (with scalloped edges and between the sets of vertical collimating plates). Charged particles enter at the left and exit at the right.

The iMESA instrument flew on the International Space Station (ISS) as part of the Materials ISS Experiment-7 (MISSE-7), launched in November 2009 on STS-129 and retrieved by STS-134 in May 2011 (Exhibit 9). iMESA measured ion energy spectra when the ISS was in the normal (+XVV) attitude with the instrument pointed in the direction of the ISS velocity vector, i.e., ram facing. Exhibit 10 is a representative ion spectrogram in energy-time format (energy increasing up the vertical axis and time increasing across the horizontal axis). The vertical color-

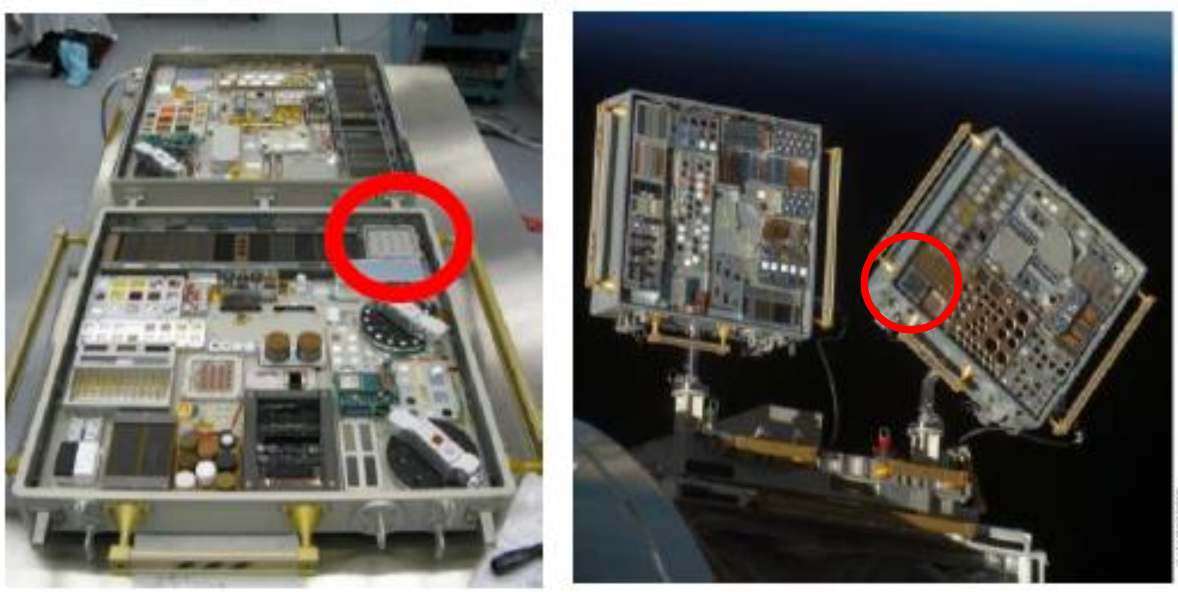


Exhibit 9: Photograph of iMESA instrument being installed on the MISSE-7 platform/cluster of experiments (left), and a photograph of the experiment cluster on the ISS (right). The red circles highlight the iMESA instrument location.

coded bar shows relative ion current magnitudes. The horizontal black line is the expected response assuming zero ISS spacecraft charging. ISS spacecraft charging over two orbital periods is clearly seen in the two energy peaks; the ISS charges during eclipse and discharges during the sunlit portion of the orbit. Exhibit 11 displays the

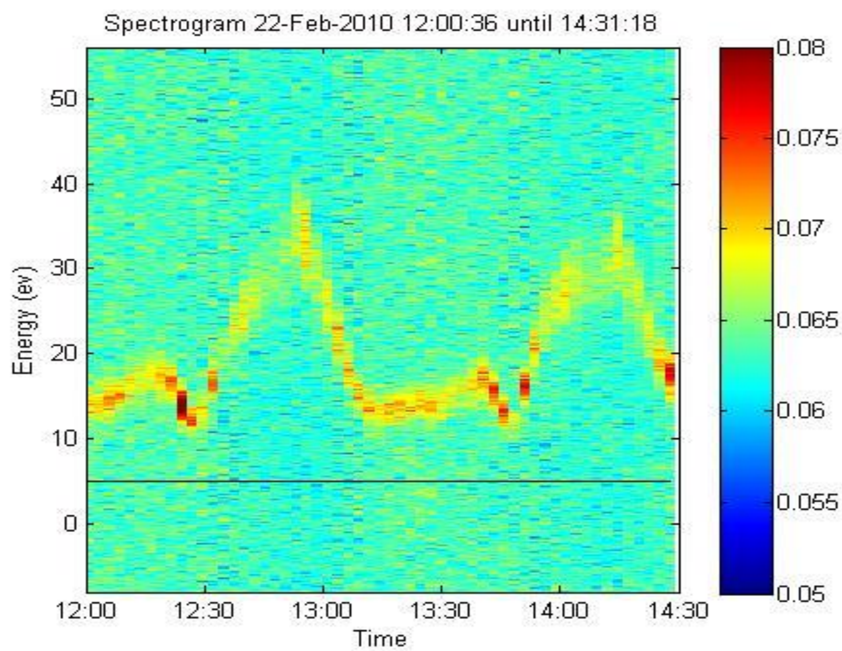


Exhibit 10: MISSE-7 iMESA ion spectrogram.

iMESA measured plasma density over four ISS orbital periods along with densities calculated using the Global Assimilation of Ionospheric Measurements (GAIM) model. The temporal agreement is good (within the 3-minute cadence of data taking), showing equatorial anomaly crossings and the sunlit/eclipse cycles.

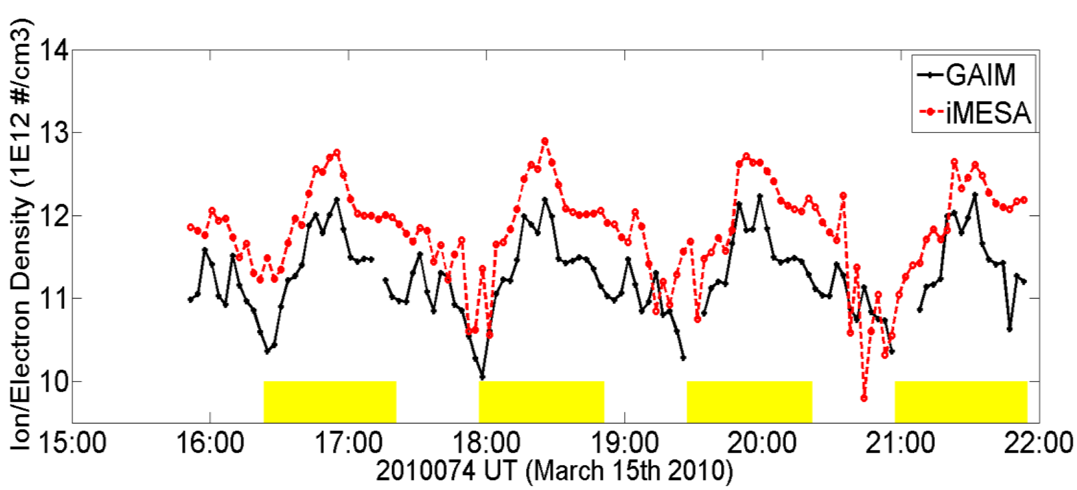


Exhibit 11: MISSE-7 iMESA plasma density data plotted with GAIM derived density data interpolated onto the ISS/MISSE-7 orbital track over four orbital time periods. Sunlit periods are shown by the yellow bars.

Additional iMESA instruments are currently flying and under development. The STPSat-3 satellite, launched in November 2013 by the DoD STP, carries an iMESA instrument as one of its five payloads approved by the DoD Space Experiments Review Board as demonstrating space technologies with high potential for providing new warfighting capabilities or enhancing existing capabilities. The sensor is operating with great success. USAFA Departments of Physics and Electrical and Computer Engineering faculty and students are constructing 10 more iMESA instruments with DoD STP flights already confirmed for three. A variant of the iMESA, which includes a miniaturized dosimeter, is under development for a 2015 launch through the DoD STP on the Surrey Satellite Technology US LLC Orbital Test Bed.

SPARC researchers, in conjunction with JHU/APL scientists, developed and flew another miniaturized, more sophisticated, plasma measurement device referred to as Canary. Canary is an extremely miniaturized (7 separate sensor heads in approximately 8 cm x 8 cm square frontal area compared to 1 sensor head in 10 cm x 10 cm square for iMESA) electrostatic analyzer configured for measuring plasma ion energies up to 1500 eV[14]. Exhibit 12 illustrates the important features of a Canary sensor head. Plasma ions enter one of the 7 sensor heads (ESAs) through the collimator aperture. The cross-sectional geometry of the aperture, characterized by width d and length l, ensures that only ions of divergence angle $\theta_D \leq d/l$ relative to the collimator centerline enter the ESA. These ions traverse the top entrance aperture (top energy selector mask) and exit the ESA through the exit aperture (bottom energy selector mask). Ions with the appropriate energy determined by the ESA bias voltage impact the microchannel plate (MCP) which greatly amplifies the ion current. The range of ion energies passing through each ESA (or sensor head) results in a piece-wise representation of the total ion current collected over the energy spectrum of the sensor.

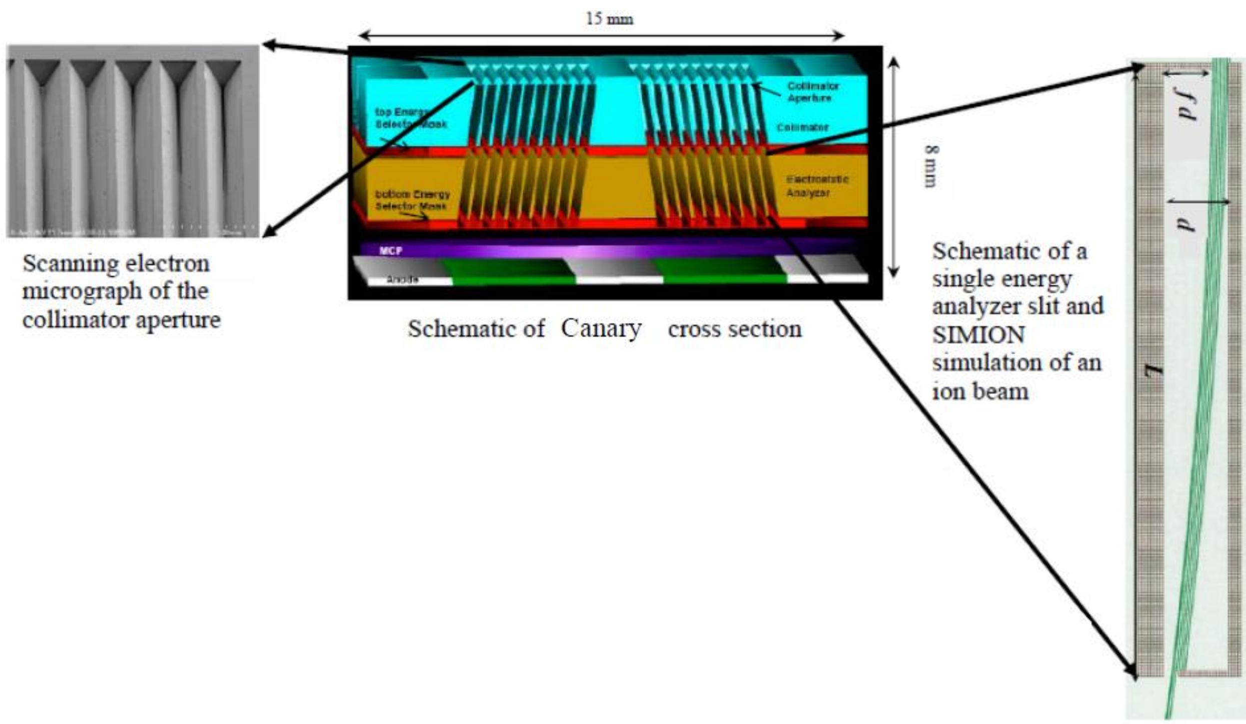


Exhibit 12: Important features of the Canary ESA instrument. Space plasma ions enter through the collimator at the top of the sensor head, pass through the ESA plates, MCP, and collect at the anode at the bottom.

Canary was transported to the ISS on the final flight of Space Shuttle Endeavor, STS-134 and successfully operated for 2 years and 3 months (May 2011 – August 2013) on the ISS's port-side truss. The instrument was part of the DoD STP's STP-H3 experimental suite of experiments designed to test concepts in LEO for potential long duration space applications (Exhibit 13). USAFA Department of Physics SPARC faculty, students, and staff commanded the Canary experiment and downloaded data to a USAFA ground station using NASA's Telescience Resource Kit (TReK) payload interface.

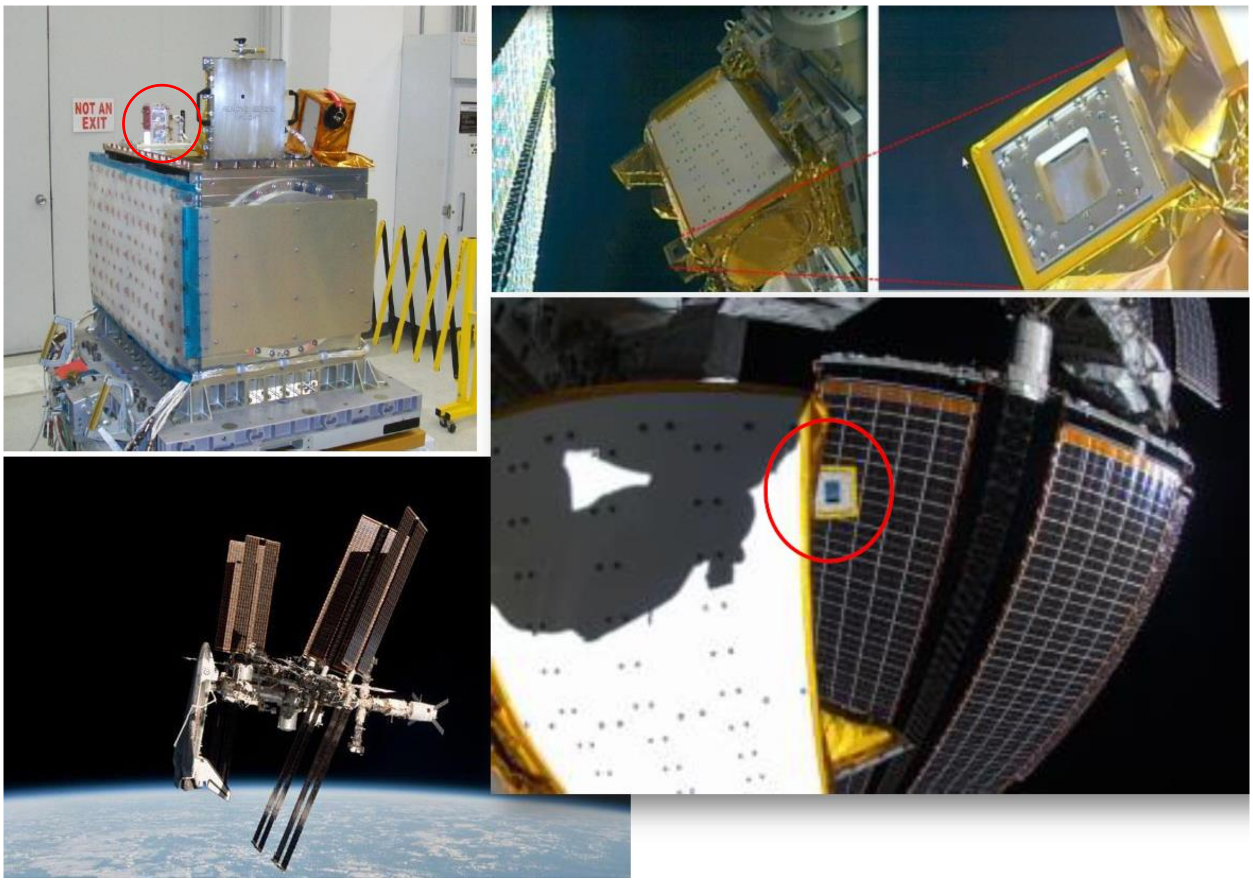


Exhibit 13: Clockwise from top left: The Canary instrument integrated on the STP-H3 ExPA pallet. ExPA pallet and Canary experiment mounted on the port-side truss of the ISS. Canary instrument photographed by astronaut whose shadow is visible on the left of the photograph. The STS position with respect to the Canary boresight.

The purpose of the Canary experiment was to investigate the interaction of approaching spacecraft thruster plumes with the rarefied plasma environment of LEO and directly measure the ambient background plasma environment surrounding the ISS. A fundamental understanding of spacecraft thruster plume dynamics in the LEO plasma environment is important for developing both prediction and mitigation capabilities to avoid plume contamination of critical spacecraft surfaces such as sensitive payload optics or solar panels. USAFA researchers collected plasma ion density versus ion energy sweeps (energy spectrograms) for a wide range of interesting events. One of the first and most dramatic events was a fly-around maneuver made by Endeavour on its departure from the ISS on 30 May 2011. A distinct response was obtained from the Canary instrument temporally corresponding to the reaction control system (RCS) thruster burn for the shuttle's NH2 maneuver that occurred at 06:39 UTC time at a distance of approximately 5 km downstream and 1 km above the ISS[15]. Endeavor was decelerating with respect to the ISS, thus the RCS thrusters were firing upstream into the ambient ionospheric plasma flow (ram flow configuration). The shuttle was approaching the ISS located 164° east and 51° south at the time of the Canary detected event. Relative to the earth and its geomagnetic filed lines, the ISS and shuttle velocity vectors were aligned east-west, orthogonal to the local field lines.

A detailed analysis and simulation of the Space Shuttle Endeavor's RCS firings, interaction of the resultant neutral plumes with the ambient ionospheric flow in LEO, generation of a relatively high-density ion plume through charge exchange (CEX) reactions, and detection of the ion plume with the Canary instrument is lucidly described in Reference 15. The shuttle RCS thrusters eject a high-density plume of neutrals/ions (mostly water vapor and molecular nitrogen) which expands into the surrounding ambient ionospheric plasma flow of neutrals/ions. Interaction of the plume neutrals with the ambient ionospheric oxygen ions (O^+) (primary ion species at the ISS altitude of 370 km) leads to the formation of spacecraft thruster plume ions through CEX. If the Canary instrument is located in the correct position, these plume ions are then detected and categorized by their energies. The modeling of the physics of the spacecraft thruster plume generation, CEX dynamics, ion plume evolution, and ion detection by the Canary ESA is a complex endeavor that requires detailed understanding of the collisional CEX processes, incoming plume morphology and ion temperature, local electromagnetic fields, as well as ISS spacecraft charging in the vicinity of the Canary instrument. For the Space Shuttle Endeavor NH2 maneuver on 30 May 2011, the simulated total current for a Canary instrument measuring the ion plume resulting from the RCS thruster firings compares very well to the actual total current measured by Canary (Exhibit 14). The simulation results were generated for the entire duration of the NH2 maneuver based on the real-time RCS chamber pressure data provided by NASA. There is a 1.5 sec time-of-flight delay for the ion plume to propagate from the shuttle position to the location of the Canary sensor on the ISS.

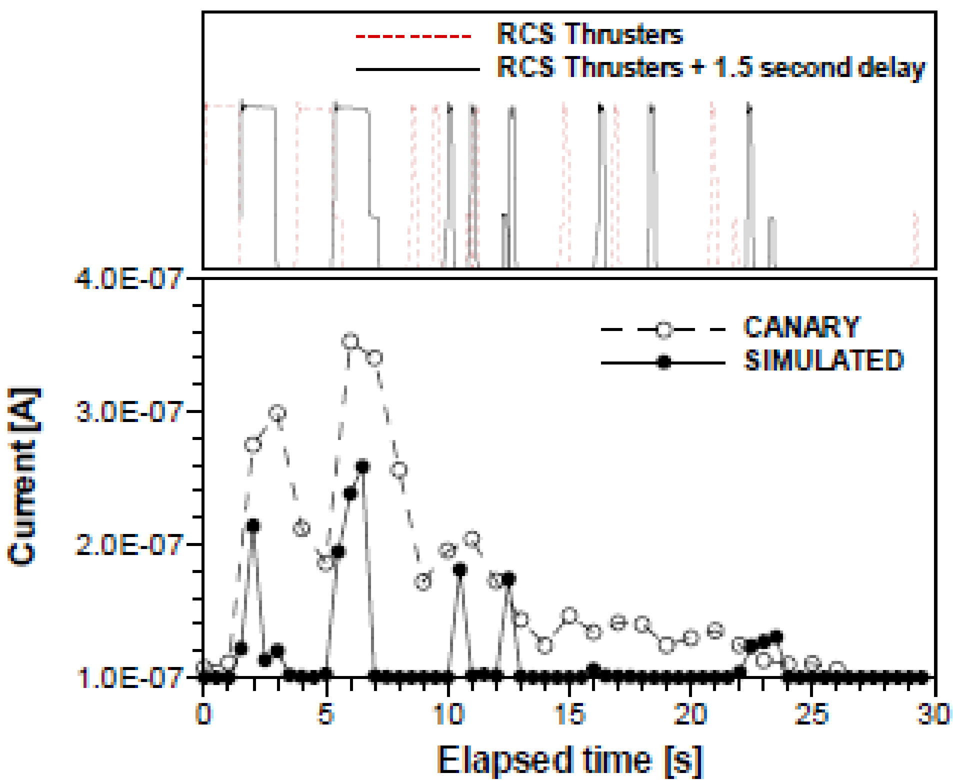


Exhibit 14: Comparison of Canary and simulated ion current as a function of time during the 30 May 2011 Space Shuttle Endeavour NH2 maneuver. RCS thruster chamber pressure as a function of time is also shown.

WORLD-WIDE NETWORK OF SMALL TELESCOPES FOR SPACE SITUATIONAL AWARENESS

Nations around the globe have made Earth's space environment increasingly congested, contested, and competitive as they continue to develop and launch satellites for commercial, civil, and military purposes. The U.S., in particular, is economically and militarily reliant on space-based assets providing fundamental services such as precision positioning, navigation, and timing; communications; weather data; missile warning; and intelligence, surveillance, and reconnaissance. Consequently, space situational awareness (SSA)* is critical to preserving current and future U.S. space capabilities. A recent, very well written and fairly comprehensive article on the U.S.'s past and current SSA capabilities, with recommendations on a strategic direction for future SSA, is in the September-October 2013 issue of *Air & Space Power Journal*[16]. Currently, the U.S. Space Surveillance Network maintains orbital information on more than 23,000 resident space objects, approximately 1,200 of which are active satellites. As more powerful SSA sensors become operational, estimates show the space catalog will increase another order of magnitude. Maintaining SSA requires a migration from catalog maintenance to full characterization and assessment of resident space objects. Clearly, SSA is an ever increasingly important AF mission area that is central to U.S. national security.

To help meet the need for future AF leaders knowledgeable about SSA, the Department of Physics formally established a USAFA Center for Space Situational Awareness Research (CSSAR), which provides faculty and students high-impact research opportunities embedded within the academic culture of the department. With a CSSAR focus and vision of "Eyes on Space," CSSAR faculty and staff are currently acquiring world-class facilities and capabilities to detect, track, identify, and characterize space assets; determine features and detect changes in satellites; and provide actionable information to commanders for space operations. Central to the maturation of these capabilities is a Cadet Space Operations Center (CSOC)[17]. Currently in its infancy, the CSOC will be a central control room from which students, faculty, and staff will be able to remotely task world-wide, ground-based SSA sensors, perform data analysis, and maintain a "space catalog" of a limited number of resident space objects. CSOC operators will maintain an SSA catalog and manage an SSA sensor network for both educational/research and training purposes. The CSOC catalog will include satellite characterization and capability information in addition to orbital track information. Using an operational software foundation, the CSOC can be used as an SSA test bed for CSSAR personnel and partner organizations (currently, MITRE, AFRL, Air Force Space Command, Universities Space Research Associates, and Pennsylvania State University). Commercial software tools, such as TheSky and MATLAB, are available in the CSOC for image/data analyses, programming, and control of hardware such as telescopes and cameras.

A major initiative of the CSSAR is the $2.3M Falcon Telescope Network (FTN) co-funded by USAFA and AFOSR. The FTN is a global, fully networked configuration of small aperture (51-cm or 20-inch), automated and robotic telescopes for development of cutting-edge SSA capabilities, innovative astronomical research, and worldwide community outreach for STEM† education and activities. FTN-based SSA research builds on the CSSAR researchers' decades of expertise in the use of small-aperture telescopes for satellite characterization using techniques adapted from the astronomical community, specifically photometry, spectroscopy, and polarimetry. A global network of automated and robotic optical sensors enables development of novel techniques and algorithms for space object identification and characterization using multiple observations from spatially diverse locations that are sometimes simultaneous or temporally continuous. As an example, through a major research effort in the Department of

* A very useful definition of SSA is "understanding and maintaining awareness of the Earth orbital population, the space environment, and possible threats." This definition is espoused by the European SSA Preparatory Programme, which incorporates the three areas of space surveillance and tracking, space weather effects, and near-Earth objects. (*2012 Space Situational Awareness Education Series* document, the Space Safety & Sustainability Working Group, Space Generation Advisory Council, Austria, www.spacegeneration.org)

† Science, Technology, Engineering and Mathematics

Physics, students and faculty advanced a promising SSA technique for automatically determining satellite shape from a combination of photometric signatures acquired from small aperture telescopes located at four spatially diverse locations[18]. Continued development of such observational techniques and algorithms for satellite characterization, when combined with pre-existing methods of space object identification, will yield significant improvements in SSA.

The FTN, with an initial operational capability targeted for 2015, will consist of 12 fixed telescope sites and 2 mobile telescope observatories. Substantial fields of regard are obtained for both LEO and GEO space objects with well-chosen geographical sites (Exhibit 15). Five telescope sites are within the continental U.S. (CONUS); the remainder will be outside the CONUS. All FTN partners will be educational institutions and will have access to the entire network to support their own educational curriculum, research, and STEM outreach to the local community.

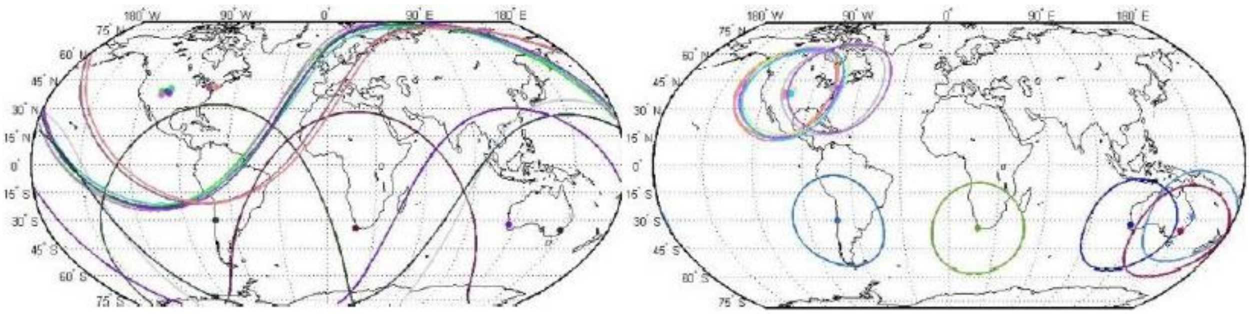


Exhibit 15: Notional GEO (left) and LEO (right) coverage for FTN network of 12 fixed telescope sites. Some of the illustrated sites are actual FTN sites; others are currently notional.

Current FTN partners include Colorado Mesa University, Grand Junction, CO; Fort Lewis College, Durango, CO; Northeastern Junior College, Sterling, CO; Otero Junior College, La Junta, CO; Penn State University, University Park, PA; Universidad de La Serena, La Serena, Chile with Observatorio Mamalluca, Vicuña, Chile; and University of New South Wales with EOS Space Systems, Canberra, Australia (Exhibit 16). Potential partners include educational institutions in Perth, Australia; South Africa; and Kauai, Hawaii.

Exhibit 16: Semi-operational FTN sites at Otero Junior College, La Junta, CO (left) and Mamalluca Observatory, Vicuña, Chile (right).

All of the components of an FTN observatory are commercially available. Each telescope node will be nearly identical in configuration, allowing easier maintenance and enabling automated and robotic operations. The

USAFA CSSAR, through a Cooperative Research and Development Agreement (CRADA), provides all telescope equipment (telescope, mount, dome, and camera instrument) (Exhibit 17) to each educational institution, while the partner institution provides the land, power, communications, and building. Currently, 7 CRADAs are in place (the 4 Colorado colleges/universities, Penn State, Chile, and Australia), 6 observatory sites are completed or under construction, 8 telescope equipment suites have been delivered to USAFA, and 3 telescopes have been installed.

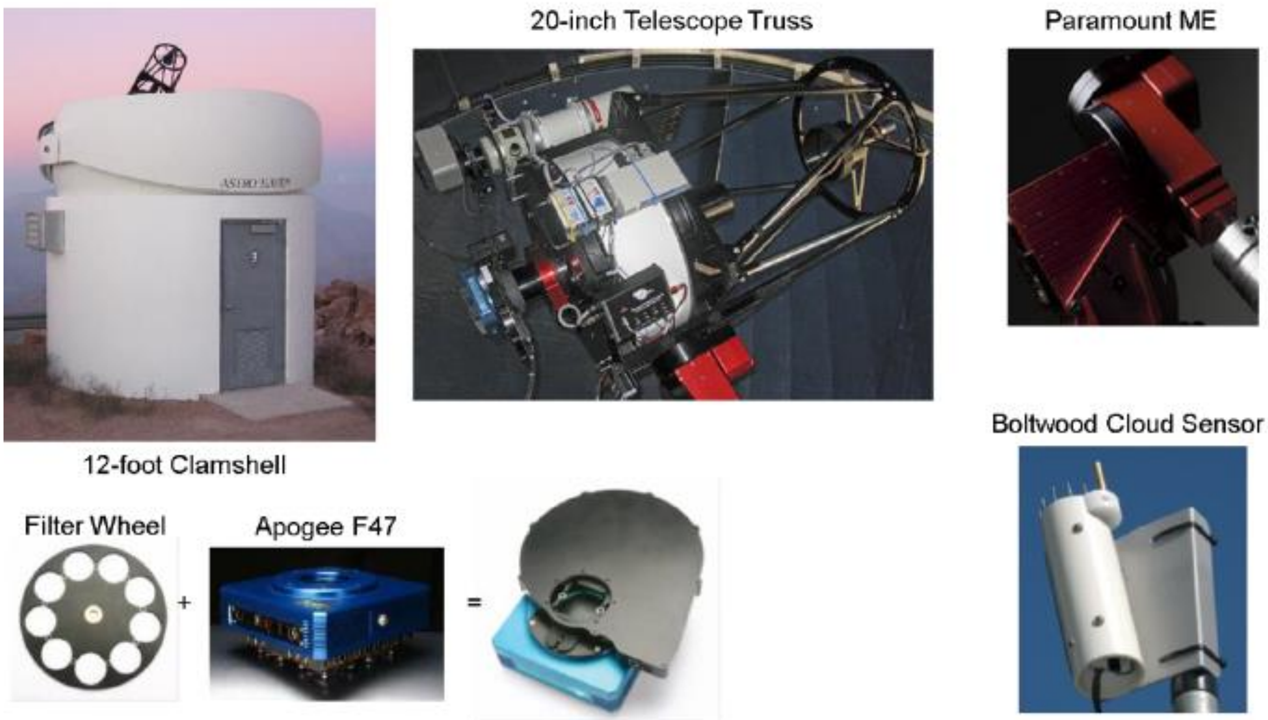


Exhibit 17: Representative telescope equipment suite provided by the USAFA CSSAR to each FTN partner institution.

SUMMARY

The United States Air Force Academy (USAFA) in Colorado Springs, Colorado is a four-year undergraduate school of approximately 4000 students and 560 highly-educated and professional faculty with the mission to educate, train, and inspire men and women to become officers of character, motivated to lead the United States Air Force in service to the nation. Academic requirements for all cadets include a comprehensive, STEM-based core curriculum. Science and engineering disciplinary majors' programs offer students and faculty high-impact research opportunities through research centers embedded within the culture of academic departments. In the USAFA Department of Physics, four research centers are integrated throughout the educational experiences of the students to provide real-world, hands-on activities in a variety of AF space mission areas. These centers are the Space Physics and Atmospheric Research Center (SPARC), Laser and Optics Research Center (LORC), Center for Space Situational Awareness Research (CSSAR), and the Astronomical Research Group and Observatory (ARGO) (not discussed in this paper). Over the past two decades, the AF and other DoD organizations have wisely invested in these research centers and the associated faculty and students, with the goal of seeding advanced technology developments and the next generation of AF space professionals. These agencies realize that the diverse, extremely talented mix of USAFA students and faculty is an incubator for innovative and affordable technology solutions for AF warfighting needs. In this paper, a sample of these incubated efforts have been highlighted, each having yielded exciting, alternative approaches that will help ensure the AF keeps its warfighting readiness despite significant, ongoing budget cuts. The Peregrine deployable membrane telescope, pioneered by faculty and students of the Department of Physics SPARC and LORC has the potential to revolutionize space-based imaging and reduce costs of large-aperture telescopes by orders of magnitude. SPARC development of miniaturized, low SWAP, yet extremely capable plasma ion sensors offers extremely affordable options for ubiquitous, in situ space weather data collection and spacecraft thruster plume detection for protection of sensitive satellite surfaces and payloads. And the CSSAR's ground-breaking construction of a global, fully networked configuration of small aperture, automated and robotic telescopes, along with novel astronomy-based techniques to identify and characterize resident space objects will provide powerful SSA capabilities. USAFA Department of Physics faculty and students are leading the charge in innovative and affordable solutions for sustaining and enhancing the space-based capabilities our nation and warfighters depend upon every day.

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