The New Millennium Program Space Technology 5 (ST-5) Mission.

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ABSTRACT: The Space Technology 5 (ST-5) Project is part of NASA's New Millennium Program. ST-5 will consist of a constellation of three 25kg microsatellites. The mission goals are to demonstrate the research-quality science capability of the ST-5 spacecraft; to operate the three spacecraft as a constellation; and to design, develop and flight-validate three capable microsatellites with new technologies. ST-5 will be launched by a Pegasus XL into an elliptical polar (sun-synchronous) orbit. The three-month flight demonstration phase, beginning in March 2006, will validate the ability to perform science measurements, as well as the technologies and constellation operations. ST-5's technologies and concepts will enable future microsatellite science missions.

1   MISSION OVERVIEW

The Space Technology 5 (ST-5) Project is part of NASA's New Millennium Program. ST-5 will consist of a constellation of three micro-satellites, each of mass approximately 25 kg and size approximately 60 cm by 30 cm. The mission goals are to design, develop and flight-validate three capable micro-satellites with new technologies; to demonstrate the ability to do research-quality science with the ST-5 spacecraft; and to operate the three spacecraft as a constellation.

ST-5 will launch in late February/early March 2006 on a Pegasus XL launch vehicle. The orbits for the three spacecraft are elliptical polar sun-synchronous (105.6 deg inclination), with 300km x 4500km altitude. The constellation will have all three spacecraft flying in the same orbit plane, with the second spacecraft trailing the first (and the third trailing the second) by some tens of kilometers, a configuration known as "string of pearls." The planned mission duration is three months.

ST-5 had been originally designed to fly as a secondary payload on an Evolved Expendable Launch Vehicle (EELV, e.g. an Atlas or Delta booster) to an equatorial Geosynchronous Transfer Orbit (GTO). However, no secondary ride opportunities became available for the ST-5 timeframe. In early 2004 the mission was re-planned for a Pegasus XL dedicated launch into our elliptical polar orbit. The re-plan allows the mission to achieve the same high-level validation objectives with a dedicated launch vehicle. The new mission design involves a different orbit and different communication strategy, while minimizing changes to the ST-5 spacecraft itself. Some new hardware (known as the Pegasus Support Structure, or PSS) was required to adapt the three ST-5 spacecraft and the existing individual spacecraft deployer mechanisms to the Pegasus XL vehicle.

2   25-KG MICRO-SPACECRAFT

2.1   Spacecraft Bus

The ST-5 spacecraft was designed to be a general-purpose spacecraft for science constellation missions. ST-5's bus is developed in-house at Goddard Space Flight Center. The bus structure is octagonal, with body-mounted solar arrays. The top and bottom decks are machined aluminum, a central cast aluminum "card cage" houses the Command and Data Handling and Power System Electronics cards, and formed aluminum sheet side panels close out the structure and support the solar arrays. The spacecraft is spin-stabilized, with a passive nutation damper. The spacecraft thermal system is also completely passive. In order to reduce interference with the on-board magnetometer, strict magnetic cleanliness requirements were imposed on the spacecraft design. This involved careful selection of parts and materials, magnetic shielding of the battery, and careful wiring of certain components such as the solar arrays to minimize open current loop area.

A deployment mechanism releases each spacecraft from the GSFC-developed Pegasus Support Structure (PSS) mounted to the Pegasus XL launch vehicle. The deployer imparts an initial spin rate and linear velocity to each spacecraft, resulting in a spacecraft angular rate of approximately 20 RPM after the magnetometer boom is deployed. The PSS and spacecraft deployment mechanism were developed in-house at GSFC.

2.2 Spacecraft Technologies

ST-5's enabling technologies make it possible to build a spacecraft that achieves ST-5's weight and size goals, while providing the capabilities that make it possible for the mission to achieve its science validation goals.

communications between components on the spacecraft as well as space-to-ground. The C&DH is a single double-sided board that consumes less than 4W of power. Its major components are a 12 MHz Mongoose V processor, two on-board Electrically Erasable Programmable Read Only Memory (EEPROM) chips,
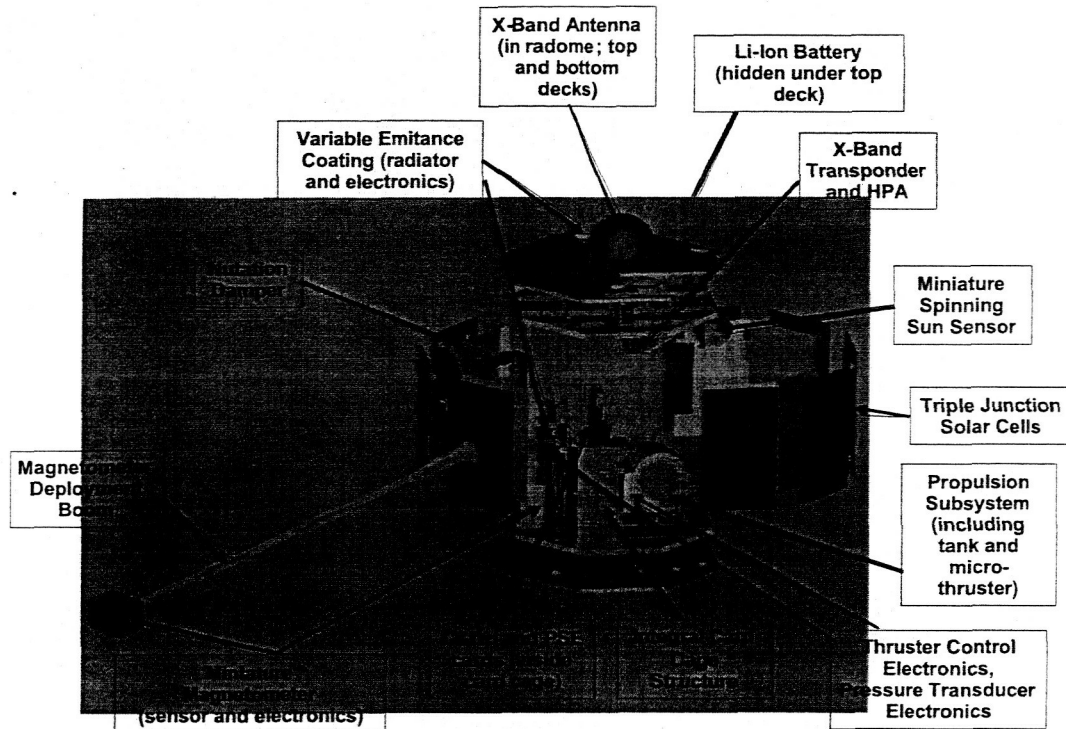

Figure 1 – ST-5 Exploded View

ST-5's technology components include a single-card Command and Data Handling (C&DH) computer featuring 0.5 V Complementary Metal Oxide Semiconductor (CMOS) Ultra Low Power Radiation Tolerant (CULPRiT) logic; a low primary voltage power system featuring triple-junction solar cells and a lithium-ion battery; a miniature communications system featuring an X-band transponder and an evolved antenna developed using a genetic algorithm; a passive nutation damper; a cold gas propulsion system using a single micro-thruster for both delta-V and attitude control; a miniature magnetometer; a digital miniature spinning sun sensor; and the Variable Emittance Coating (VEC) thermal surfaces. Figure 1 is an exploded view of the ST-5 spacecraft showing the technologies.

ST-5's C&DH provides the sophisticated command and data handling functionality found on larger spacecraft, but in a smaller package. It coordinates all

20 MBbyte of Dynamic Random Access Memory (DRAM), and three Field Programmable Gate Arrays (FPGA). Laying out this densely populated board was a significant design challenge, but was essential to the design of ST-5 as a highly capable smallsat. The C&DH was developed in-house at Goddard.

Incorporated into the ST-5 C&DH, CULPRiT logic was developed to operate at low voltage (0.5V supply voltage), while being radiation tolerant. For ST-5, CULPRiT technology is being used to implement a Reed-Solomon encoder. Future space missions may be able to benefit from reductions in overall electronics power dissipation of one to two orders of magnitude with widespread use of CULPRiT. The Center for Advanced Microelectronics and Biomolecular Research at the University of Idaho, AMI Semiconductor, and PicoDyne were involved in the development of this technology.

The low voltage power system helps ST-5 achieve its size and weight requirements. A triple-junction solar array, composed of 8 body-mounted panels, provides approximately 20-25W of power at approximately 9-10V. Lithium Ion batteries provide energy storage of 7-9 Ah at 6-8V. Both solar array and battery are controlled by a single Power System Electronics (PSE) board. In addition to providing power to all spacecraft components, the power system provides contingency recovery for over-current, over-voltage, and low battery charge conditions. The nominal unregulated spacecraft primary bus voltage is 8.4V maximum, and (as the battery state of charge decreases) can range down to 6.5V before automatic load-shedding occurs. The PSE supplies both the unregulated primary bus and regulated 5V services to the various onboard subsystems. The solar array was developed by Emcore, the battery by AEA Technology Space, and the PSE in-house at Goddard.

ST-5 communicates with ground stations via an X-band uplink at 1 kbps and downlink at 1 Kbps, 100 kbps, and 200 kbps. One of the new technology components is a miniature transponder that offers a substantial decrease in weight, power, and volume over current operational systems. The transmit scheme uses Binary Phase Shift Keying (BPSK) encoding and no subcarrier to maximize efficiency. The Consultative Committee for Space Data Systems (CCSDS) recommendations have been amended to incorporate this scheme. The transponder is used in conjunction with a high power amplifier, diplexer, band pass filter and two X-band antennas. The communications system is compatible with the Deep Space Network, the NASA Ground Network station at McMurdo in the Antarctic, or small aperture off-the-shelf antennas. The transponder and high power amplifier were developed by AeroAstro.

Two different types of antennas are being developed for ST-5: a quadrifilar helix (QFH) antenna developed by New Mexico State University (NMSU), and an "evolved" antenna designed with genetic algorithms developed by NASA's Ames Research Center and JEM Engineering in partnership with NMSU. The radiator for the evolved antenna was designed by a computer program using what is known as a genetic algorithm. Using language borrowed from genetics the algorithm is a "genotype" that designs a wire form radiator based on a fitness function optimizing Voltage Standing Wave Ratio (VSWR) and gain over the angles of interest. The end result "phenotype" is lightweight, optimized for the application, and looks rather like a small tree made from a bent paper clip. The big advantage of the evolved antenna for ST-5 is its higher and more uniform gain across a wider range of elevation angles and its extremely high efficiency (>

90%) since there is no matching network required. In addition the evolved antenna is very simple, with radiator soldered directly to the connector and a plain aluminum ground plane instead of the microstrip printed circuit board and collection of passive components required for the QFH matching network. Both antenna designs (QFH and evolved) have near-omni coverage, and are coupled equally to the diplexer. One antenna is mounted on each deck (top and bottom) of the ST-5 spacecraft.

A passive damper controls any nutation of the spin axis that might occur due to initial deployment, on-orbit maneuvers, or dynamic imbalance. The damper is a welded titanium unit without a bellows, fully filled with silicone fluid at a maximum design pressure of 10,000 psi. The nutation damper was developed in-house by GSFC.

A single cold-gas micro-thruster provides all ST-5 orbit and attitude maneuver capability. The propulsion system also includes a lightweight composite tank, a fill-and-drain valve, an in-line filter and a pressure transducer. Thruster Control Electronics (TCE) and Pressure Transducer Electronics (PTE) are used to control the system. Hardware safeguards ensure that the latching thruster valve cannot be opened unless there is sufficient energy stored in the TCE to close the valve. The TCE and PTE were developed in-house by Goddard; the micro-thruster was developed by Marotta Scientific Controls, and the composite tank was developed by Carleton Technologies.

The ST-5 science validation instrument is a miniature fluxgate magnetometer, which produces high resolution three-axis magnetic measurements. The magnetometer sensor head is mounted at the end of a deployed low-mass boom constructed of graphite composite tube sections with beryllium-copper "carpenter tape" hinges. ST-5's magnetometer was designed and built by the University of California at Los Angeles (UCLA). The boom was developed in-house at Goddard.

A digital-output miniature spinning sun sensor (MSSS) is used to measure the elevation angle of the sun with respect to the ST-5 spin axis. The spacecraft is capable of autonomously repositioning itself to within 10 degrees of the sun line to ensure adequate sunlight on the solar arrays. The MSSS was developed for ST-5 by Adcole.

The VECs are radiators with switchable emittance states to vary the amount of heat that they radiate to space. Future space missions may be able to efficiently adapt to wide ranging thermal conditions with radiators based on these technologies. The Micro Electro-

Mechanical Systems (MEMS) VEC consists of multi-layered silicon shutters that open and close to vary their emittance. The Electro-Static Radiator (ESR) is a thermal control film that varies its radiation by switching heat transfer mechanisms between two plates internally by the use of an electrostatic field. When the plates are in contact, the mechanism between them is conduction and the ESR is in a high-emittance state; when the plates are separated, the mechanism is radiation between them and the ESR is in a low emittance state. ST-5 can accommodate two VECs per spacecraft—one each on the top and bottom decks. Due to the technology development schedule, ESR VECs will be flown on the second and third spacecraft, and MEMS VEC on the third spacecraft only. The MEMS VEC is developed by the Johns Hopkins University Applied Physics Laboratory (JHU-APL), using shutters provided by Sandia National Laboratories. The Electro-Static Radiator (ESR) is developed by Sensortex, with control electronics from JHU-APL.
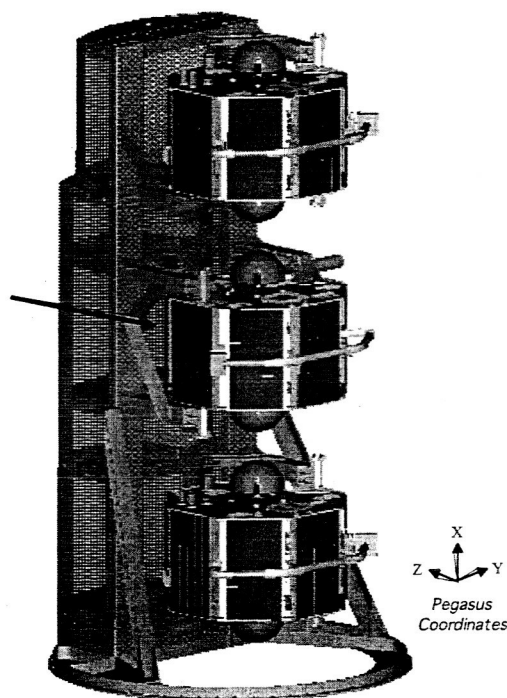

X
Z — Y
Pegasus
Coordinates

Figure 2 – ST-5 Spacecraft in PSS

3 PEGASUS SUPPORT STRUCTURE AND DEPLOYMENT MECHANISMS

The ST-5 spacecraft are accommodated on the Pegasus XL vehicle via the GSFC-developed Pegasus Support Structure (PSS). The PSS is a bolted and riveted aluminum sheet structure that forms a stiff backbone cantilevered from the circular Pegasus XL mounting interface. The ST-5 deployment mechanisms are mounted to the PSS so that the ST-5 spacecraft are ejected normal to the longitudinal axis of the Pegasus. The spacecraft are deployed sequentially approximately 200 seconds apart after Pegasus third stage burnout. Figure 2 shows the three ST-5 spacecraft in launch configuration on the PSS.

4 SCIENCE DEMONSTRATION

One goal of the ST-5 mission is to demonstrate the ability to do research-quality science with a microsatellite.

A primary application for NASA's constellation missions is the in situ measurement of critical scalar and vector quantities over large volumes of space. Examples from the Earth's high altitude plasma environment include the determination of plasma flow fields and vorticity, the propagation characteristics of blast waves from solar flares, electric current density, magnetic flux tube topology and the magnetic channeling of solar wind energy into the upper atmosphere.

ST-5 will validate the constellation measurement concept by determining the vertical electric current density over the Earth's northern and southern auroral zones through the evaluation of the curl of the local magnetic field. These electric currents have been previously inferred to exist from single-spacecraft measurements, but quantitative knowledge of their intensity and spatial distribution is limited. ST-5 will directly measure many important spatial and temporal characteristics of the electric currents that power the striking optical emissions from the auroral zones and heat the high latitude ionosphere.

ST-5's flight software is capable of detecting science events of interest, i.e. when the rate of change of the ambient magnetic field increases beyond a given threshold. When this occurs, the spacecraft changes the science data collection mode to a higher rate.

ST-5 will be deployed into a string of pearls constellation with all three spacecraft in the same orbit plane in the same nominal trajectory (described earlier). The initial separation between the spacecraft will be on the order of meters after deployment from the launch vehicle. The on-board propulsion system will be used to maneuver the spacecraft into two or three different spacings, to better study the auroral ovals. The first constellation configuration of interest (to be achieved approximately two weeks into the mission) is approximately 25km between spacecraft 1 and 2, and 75km between spacecraft 2 and 3. A somewhat further

spacing (~50km and 100km) is planned for later in the mission (approximately 8 weeks after launch), and a third configuration may be planned near the end of the three month mission. The final separations may be based on the results obtained from early magnetic measurements.

5 CONSTELLATION OPERATIONS

The three ST-5 spacecraft will be operated as a constellation by coordinating maneuvers and the constellation configuration to enable the mission science validation demonstration. The spacecraft and ground system provide evolvable steps along the road to future constellation missions.

Goddard has developed a GSFC Mission Services Evolution Center (GMSEC) architecture to allow "plug and play" of ground system components. The GMSEC architecture features "socket" specifications and generic messaging between components.

ST-5 ground operations are automated through the use of several components. The Advanced Mission Planning and Scheduling (AMPS) system is a multi-satellite planning and scheduling system. Komodo is a paging system that monitors telemetry and alerts the Flight Operations Team if needed. A Simulink™ model is used for memory/downlink and power management.

The ST-5 ground system is based on the GMSEC architecture, and integrates heritage ground system components with new components developed in support of this mission.

ST-5 ground operations are automated through the use of several new technology components. The Advanced Mission Planning System (AMPS) is a multi-satellite planning and scheduling system. Komodo 2 is a paging system that monitors telemetry and alerts the Flight Operations Team (FOT) if needed. A Simulink model is used for onboard solid state recorder and power management.

The spacecraft will monitor and correct for excessive thruster firing, transponder interface problems, C&DH hang-ups, low battery or voltage conditions, and excessive sun angle. They are capable of surviving without ground contact for weeks if necessary.

ST-5's transponder communicates via X-band uplink and downlink. Currently, only the Deep Space Network (DSN) supports X-band uplink, but we are upgrading the NASA Ground Network site at McMurdo in the Anatarctic to support ST-5. A challenging feature of ST-5's orbit is while the initial argument of

perigee is approximately 160 degrees, the orbit line of apsides (and therefore the position of the apogee over the Earth) precesses approximately 1.2 degrees per day into the southern hemisphere. Thus, DSN's Canberra ground station or the NASA Ground Network McMurdo ground station is best suited to ST-5 communications since the longest passes will occur nearest those stations during our three month mission.

6 CONTRIBUTION TO FUTURE SCIENCE MISSIONS

NASA's Sun-Earth Connection science theme in the Science Mission Directorate has the goal of understanding how solar activity affects the interplanetary medium, the magnetosphere, the ionosphere, and the upper atmosphere of the Earth. In order to better understand this science, NASA plans constellation missions of small spacecraft to collect data at various points in space. As an example, the Magnetospheric Constellation Mission is planned to deploy 30-40 small spacecraft in the Earth's magnetosphere.

ST-5 contributes to future science missions by demonstrating the ability of a micro-satellite to be maneuvered into and maintained in a constellation configuration; validating the suitability of the micro-satellite platform for taking research-quality scientific measurements; and demonstrating constellation operations concepts.

The technologies and components being developed by ST-5 are already being incorporated into future science missions. In particular, the transponder, propulsion system components, magnetometer, sun sensor, solar cells, and battery were developed to be useful for future micro- and nano-satellite missions. ST-5 technologies are already being incorporated into future missions.
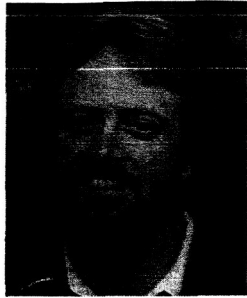
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BIOGRAPHY

Evan Webb is the ST-5 Mission Systems Engineer. Before working on ST-5 he was a participant in the GSFC-AETD Systems Engineering Education Development (SEED) program, and worked as a systems engineer on the Landsat Data Continuity Mission. He was the lead engineer for the SpaceLAN rad-hard Ethernet development effort at GSFC, and prior to that he was the hardware lead engineer for the WARP solid state recorder on EO-1. His interests outside of work include wine collecting, classical piano, and sports car racing. He has Master's and Advanced Master's of Science in Electrical Engineering from Johns Hopkins University, and a BS in Electrical Engineering from the University of Maryland.

Candace Carlisle is the ST-5 Deputy Project Manager at NASA's Goddard Space Flight Center. Prior to ST-5, she worked in System Engineering roles on the Earth Observing Data and Information System and the Network Control Center for the Tracking and Data Relay Satellite System. She has a BS in Computer Science and Physics from the College of William and Mary, and MS degrees in Computer Science and Technical Management from the Johns Hopkins University.
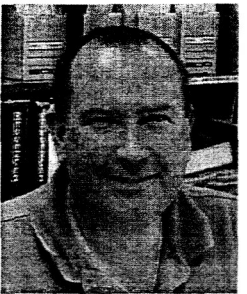
James A. Slavin is the ST-5 Project Scientist, as well as Head of the Electrodynamics Branch at the NASA/GSFC Laboratory for Extraterrestrial Physics, Senior Project Scientist for Solar Terrestrial Probes and Senior Advisor to the Living with a Star Project. He received his doctorate in Space Physics from the University of California at Los Angeles. His previous positions include staff scientist at the Caltech/Jet Propulsion Laboratory and Discipline