

## Space Technology 5: Enabling Future Micro-Sat Constellation Science Missions

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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 micro-satellites, each approximately 25 kg in mass. 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 micro-satellites with new technologies. ST-5 is designed to measurably raise the utility of small satellites by providing high functionality in a low mass, low power, and low volume package. The whole of ST-5 is greater than the sum of its parts: the collection of components into the ST-5 spacecraft allows it to perform the functionality of a larger scientific spacecraft on a micro-satellite platform. The ST-5 mission was originally designed to be launched as a secondary payload into a Geosynchronous Transfer Orbit (GTO). Recently, the mission has been replanned for a Pegasus XL dedicated launch into an elliptical polar orbit. A 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 then be transferred to future micro-sat 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.

### 2 MISSION REPLAN

ST-5 was originally designed for a Geosynchronous Transfer Orbit (GTO). This orbit was to be roughly equatorial, with ~300km perigee and ~36000km apogee. The three satellites were to be launched as a secondary payload on an Evolved Expendable Launch Vehicle (EELV).

After four years of searching for a secondary launch commitment, the project was directed by NASA Headquarters to replan for a dedicated Pegasus XL launch. Because of the inherent flexibility of the ST-5 design, and the broad project goals, we were able to replan the mission for a new orbit and a new science demonstration without major changes to the spacecraft or ground system design.

The new orbit is polar sun-synchronous, with ~300km perigee and ~4500km apogee. In this orbit, a different

region of the Earth's magnetosphere is of interest. A different constellation configuration is required in order to take suitable scientific measurements. A new support structure for the spacecraft on the Pegasus launch vehicle was designed. However, the only change to the spacecraft itself involved modifications to the passive thermal design, e.g. changed radiator size. The ground operations are changed dramatically for the 136 minute (vs. 10 hours 50 minutes) orbit. However, the Mission Operations Center architecture that supports these operations is the same.

### 3 RESEARCH-QUALITY SCIENCE DEMONSTRATION

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

#### 3.1 Science Validation Strategy

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.

### **3.2 Spacecraft Science Capabilities**

ST-5 includes 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.

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.

### **3.3 Constellation Configuration**

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. The orbit will be polar sun-synchronous, approximately 105.6 degrees inclination, 300km perigee, and 4500km apogee. 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 is approximately 25km between spacecraft 1 and 2, and 75km between spacecraft 2 and 3. A somewhat further spacing (~50 and 100km) is planned for later in the mission. The final separations may be based on the results obtained from early measurements.

## **4 CONSTELLATION OPERATIONS**

The ST-5 spacecraft will be operated as a constellation. The spacecraft and ground system provide evolvable steps along the road to future constellation missions.

### **4.1 Plug and Play Ground System Architecture**

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.

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.

### **4.2 Automated Ground Operations**

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.

### **4.3 Spacecraft Autonomy**

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.

### **4.4 Ground Communications**

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 planning to upgrade a NASA Ground Network site to support ST-5. A challenging feature of ST-5's orbit is that the initial argument of perigee is approximately 160 degrees, and rotates 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.

## **5 25-KG FULL SERVICE SPACECRAFT**

One of ST-5's mission goals is to design, develop and flight-validate three capable micro-satellites with new technologies. Thus, ST-5 is intentionally designed to include components that measurably raise the utility of small satellites by providing high functionality in a small package. All ST-5 components are low mass, low power, and low volume. However, the whole of ST-5 is greater than the sum of its parts: the collection of components into the ST-5 spacecraft allows it to perform the functionality of a larger spacecraft on a micro-satellite platform. The ST-5 spacecraft was designed to be a general-purpose spacecraft for science constellation missions.

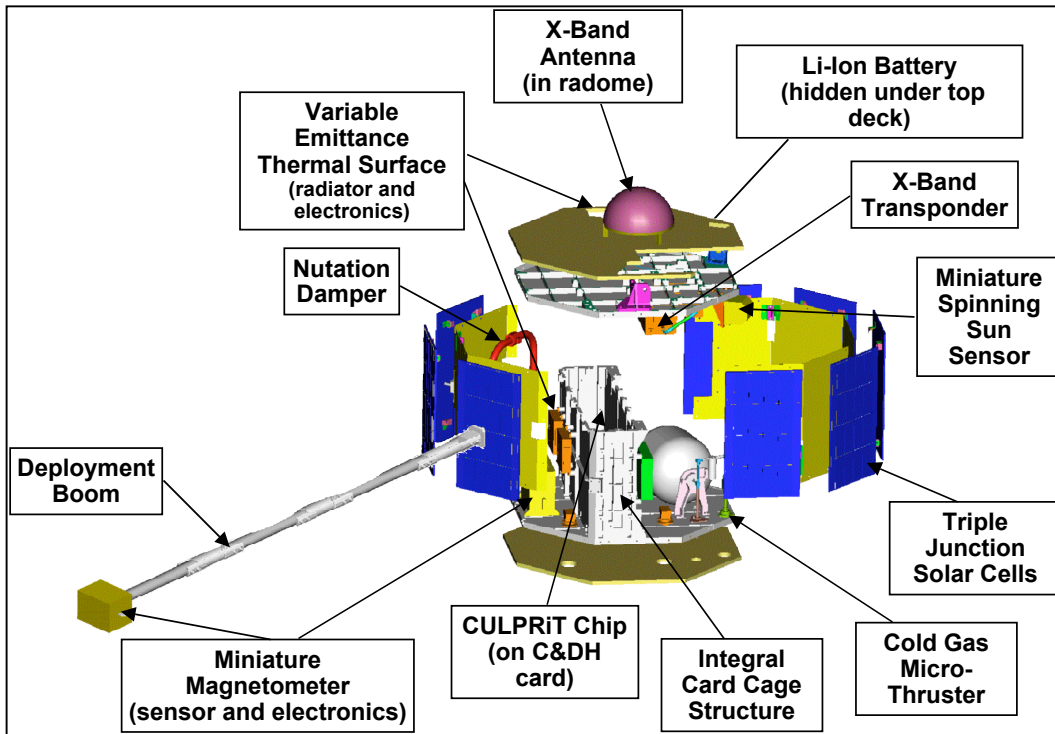


Figure 1, ST-5 Spacecraft Overview

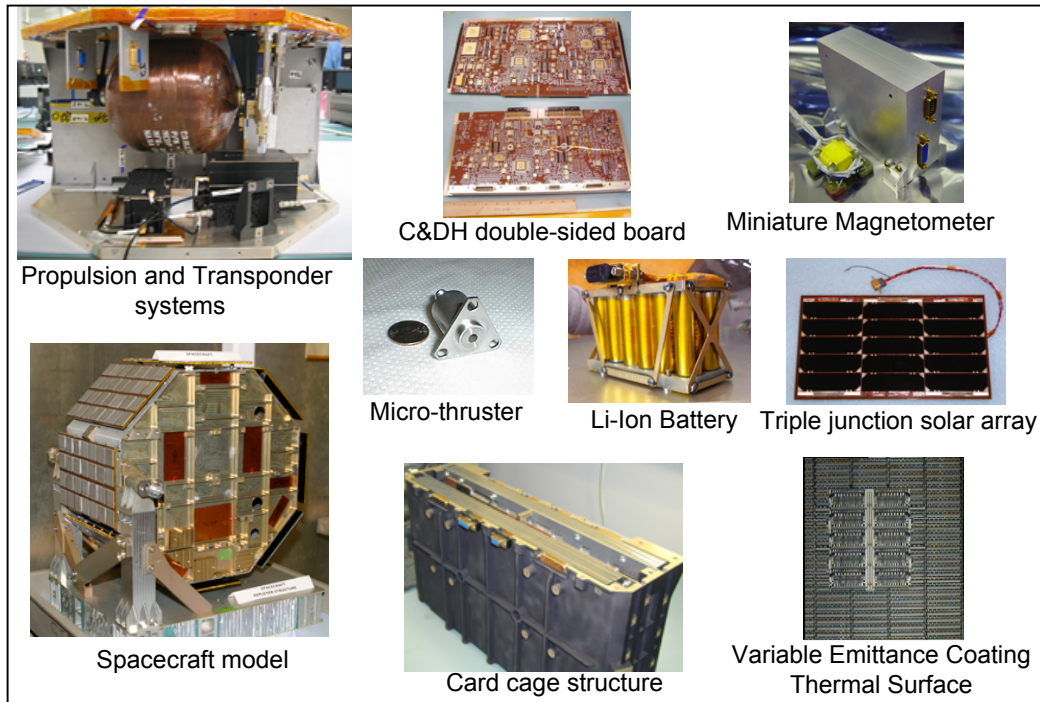


Figure 2, ST-5 Components

## 5.1 *Spacecraft Overview*

ST-5's spacecraft bus is developed in-house at Goddard Space Flight Center. Some components are developed in-house, and others by university and industry partners. The ST-5 spacecraft is octagonal, with body-mounted solar arrays. The top and bottom decks are removable, and a central "card cage" houses the Command and Data Handling and Power System Electronics cards. The spacecraft is spin-stabilized, with a passive nutation damper to damp out any "wobble." The spacecraft is also passively thermally controlled. 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, shielding of the battery with Metglas™, and careful wiring of certain components such as the solar arrays to minimize open current loop area.

## 5.2 *Enabling 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. ST-5's enabling technology components include: single-card Command and Data Handling (C&DH) computer, power system featuring triple-junction solar cells and a lithium-ion battery, miniature communications system featuring an X-band transponder, cold gas propulsion system using a single micro-thruster for both delta-V and attitude control, miniature magnetometer, miniature spinning sun sensor, and a "plug and play" ground system architecture.

### 5.2.1 *Single Card Command and Data Handling (C&DH) Computer*

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 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, 20 MByte 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 built in-house at Goddard.

### 5.2.2 *Low Voltage Power System*

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 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 unregulated and regulated 5V/5.25V 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.

### 5.2.3 *Miniature Communications System*

ST-5 communicates with ground stations via an X-band uplink at 1 kbps and downlink at 100 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, and 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 Ground Network, 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 antenna developed by New Mexico State University (NMSU), and an "evolved" antenna designed with genetic algorithms developed by NASA's Ames Research Center and Linden Innovation Research in partnership with NMSU. The two antenna designs 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, and system testing is underway to determine the best combination of antennas in each position.

### 5.2.4 *Guidance and Navigation Control (GN&C), including Cold Gas Propulsion System*

ST-5 is spin stabilized. 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 (~30 RPM) and linear velocity (~ 0.4 m/s relative to the launch vehicle) to each spacecraft. The spin rate is reduced to ~24 RPM when the magnetometer boom is deployed.

A passive nutation damper damps any “wobble” that might occur due to initial deployment, on-orbit maneuvers, or dynamic unbalance. The damper is a welded titanium unit fully filled with silicone fluid at a maximum design pressure of 10,000 psi, and avoids the use of a bellows.

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 and Pressure Transducer Electronics are used to control the system.

A sun sensor 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 PSS, deployment mechanism, nutation damper, Thruster Control Electronics and Pressure Transducer Electronics were developed in-house by Goddard. A new, smaller, sun sensor was developed for ST-5 by Adcole. The micro-thruster, developed by Marotta Scientific Controls, was developed as one of the transferable technologies for the mission. The composite tank, developed by Carleton Technologies, is also being used for other missions.

### **5.3 Demonstration Technologies**

The demonstration technologies are not essential to the ST-5 spacecraft. They are being flown on ST-5 to demonstrate their usefulness for future missions. These ST-5 demonstration component technologies include 0.5 V CMOS Ultra Low Power Radiation Tolerant (CULPRiT) logic, Variable Emittance Coating thermal surfaces, and an evolved antenna developed using a genetic algorithm.

#### **5.3.1 CMOS Ultra Low Power Radiation Tolerant (CULPRiT) logic**

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 housed on the C&DH card. 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.

#### **5.3.2 Variable Emittance Coatings**

The Variable Emittance Coatings (VECs) are radiators designed to vary the amount of heat that they radiate (emittance). 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 is developed by the Johns Hopkins University Applied Physics Laboratory, using shutters provided by Sandia National Laboratories. This radiator consists of multi-layered silicon shutters which open and close to vary their emittance from 0.4 to 0.8 (TBR). The Electro-Static Radiator (ESR) is developed by Sensortex. This radiator is a thermal control film that varies its emittance from 0.4 to 0.7 (TBR) based on an electrostatic force. ST-5 accommodates two VECs per spacecraft—one each on the top and bottom decks.

#### **5.3.3 Evolved Antenna**

The radiator for the evolved antenna was designed by a computer program. 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 like a small “tree” made of paper clips. The evolved antenna has the potential to achieve a higher gain across a wider range of elevation angles and more uniform coverage than conventional antennas. The ST-5 evolved antenna is designed by NASA’s Ames Research Center and Linden Innovation Research. NMSU is assisting in the implementation and testing of this antenna for ST-5.

## **6 CONTRIBUTION TO FUTURE SCIENCE MISSIONS**

NASA’s Sun-Earth Connection science theme in the Space Science Enterprise 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; validate the suitability of the micro-satellite platform for taking research-quality scientific measurements; and demonstrate constellation operations concepts.

The components being developed by ST-5 are useful for technology transfer to 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 the following future missions:

- THEMIS—sun sensor, propulsion tank
- DAWN—propulsion tank
- GEC—magnetometer boom
- SDO—solar arrays and lithium-ion battery
- MagCon—spacecraft bus

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