Space Technology 5—Changing the Mission Design without Changing the Hardware[1]

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Abstract—The Space Technology 5 (ST-5) Project is part of NASA's New Millennium Program. The validation objectives 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, test and flight-validate three capable micro-satellites with new technologies. A three-month flight demonstration phase is planned, beginning in March 2006.

This year, the mission was re-planned for a Pegasus XL dedicated launch into an elliptical polar orbit (instead of the originally-planned Geosynchronous Transfer Orbit.) The re-plan allows the mission to achieve the same high-level technology validation objectives with a different launch vehicle. The new mission design involves a revised science validation strategy, a new orbit and different communication strategy, while minimizing changes to the ST-5 spacecraft itself. The constellation operations concepts have also been refined.

While the system engineers, orbit analysts, and operations teams were re-planning the mission, the implementation team continued to make progress on the flight hardware. Most components have been delivered, and the first spacecraft is well into integration and test.

TABLE OF CONTENTS

1. INTRODUCTION

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 approximately 25 kg. The validation objectives 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, test and flight-validate three capable micro-satellites with new technologies. The new technologies to be flight validated include the spacecraft itself, Miniature X-band Communication Transponder, Cold Gas Micro-Thruster, X-band evolved antenna, Variable Emittance Coatings (VECs), Complementary Metal Oxide Semiconductor Ultra Low Power Radiation Tolerant (CULPRiT) chip, and low voltage power subsystem. In addition, we will demonstrate a number of derived technologies included in the ST-5 design: miniature magnetometer, miniature spinning sun sensor, spacecraft deployment mechanism, magnetometer deployment boom, and passive non-bellows nutation damper. The project team has made significant progress in the past year in redesigning the mission, and building and testing the ground system and flight hardware to achieve the mission objectives.

Originally, the ST-5 mission was to be launched as a secondary payload into a Geosynchronous Transfer Orbit (GTO). However, no secondary ride opportunities became available for the ST-5 timeframe. This year, the mission was re-planned for a Pegasus XL dedicated launch into an 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.

[2] IEEEAC paper #1367, Version 4, Updated December 22, 2004

The ST-5 Project had proceeded through Critical Design Review and well into hardware development based on assumptions about the launch vehicle and orbit. In parallel with the mission re-plan, hardware components have completed development and component-level testing, and are being integrated onto the spacecraft. Through component-level testing and spacecraft integration and test, many components can be demonstrated on the ground to begin achieving the validation objectives.

A three-month flight demonstration phase is planned, beginning in March 2006. During this period, we will complete the flight validation objectives. The ground and flight validation of the spacecraft technologies is described in last year's paper [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 (C&DH) and Power System Electronics cards. The spacecraft is spin-stabilized, with a passive nutation damper. The spacecraft thermal control is also 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, shielding of the battery with Metglas ™, and careful wiring of certain components such as the solar arrays to minimize open current loop area.

ST-5 includes a miniature fluxgate magnetometer, which produces high-resolution three-axis magnetic measurements. 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's C&DH provides the sophisticated command and data handling functionality found on larger spacecraft, but in a much 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.

The C&DH card houses the new technology CULPRiT logic. It was developed to operate at low voltage (0.5V supply voltage), while being radiation tolerant. For ST-5,

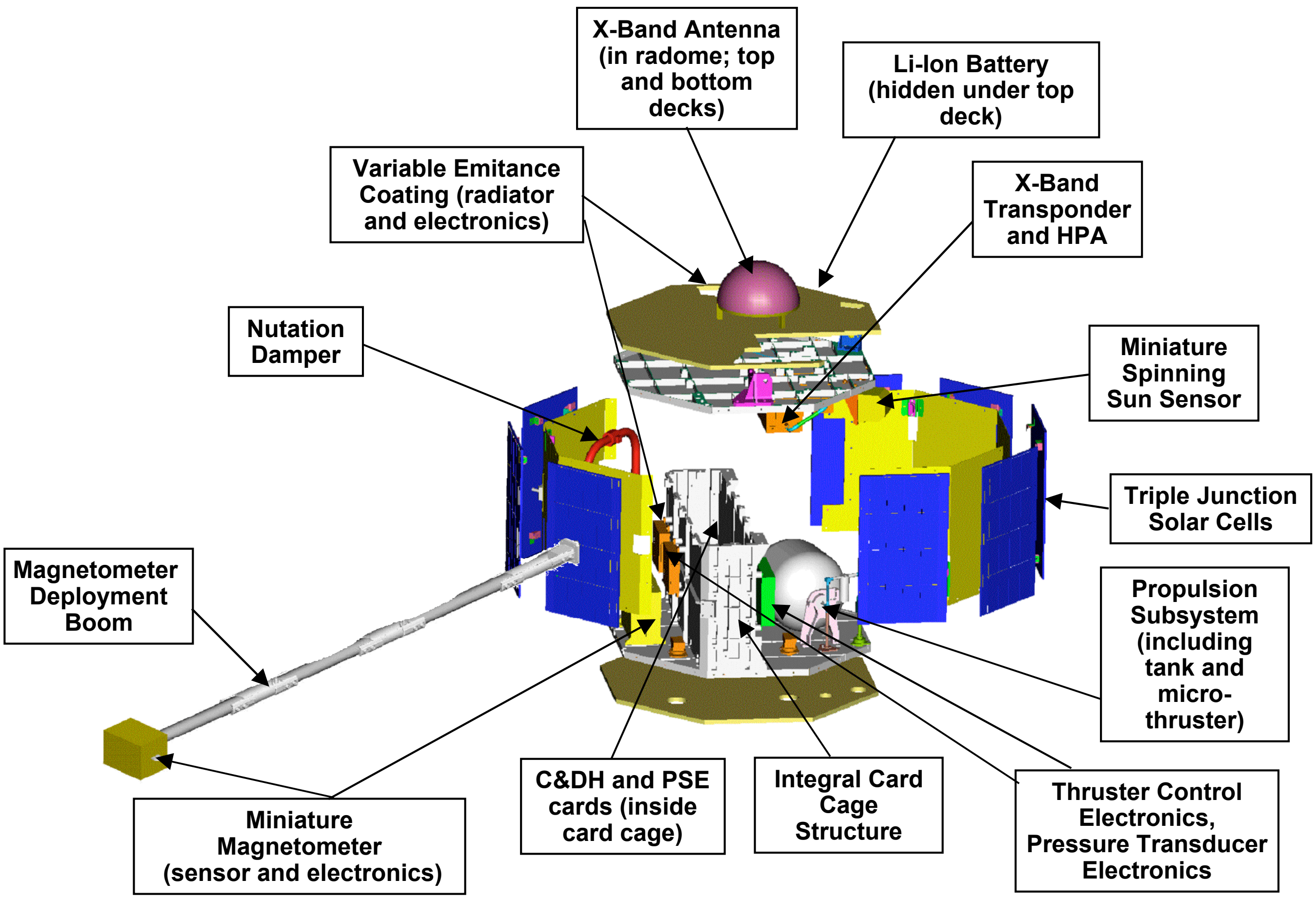


Figure 1— ST-5 Spacecraft Layout. This diagram shows the major components of the ST-5 spacecraft in an "exploded" view.

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.

A 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 ~ 9 Ah. Both the 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 to the various onboard subsystems.

ST-5 is spin stabilized. A deployment mechanism releases each spacecraft from the 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 an ~20 rpm rotation after the magnetometer boom is deployed.

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.

ST-5 communicates with ground stations via an X-band uplink at 1 kbps and downlink at 1 kbps, 100 kbps, or 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 appropriate 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. Two different types of antennas are being developed for ST-5: a quadrifilar helix antenna, and an "evolved" antenna designed with genetic algorithms. One antenna is mounted on each deck (top and bottom) of the ST-5 spacecraft.

A single new technology 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 stored energy in the TCE to close the valve.

A miniature 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 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.

2. MISSION RE-DESIGN

A New Orbit

Originally, the ST-5 mission was to be launched as a secondary payload into GTO. However, no secondary ride opportunities became available for the ST-5 timeframe. Late last year, we were directed to conduct a feasibility study for a Pegasus XL dedicated launch. The preliminary mission re-design was presented to NASA Headquarters and approved in March 2004. Next, the challenge was to produce a mature mission re-design for a delta Critical Design Review a mere four months later. The major drivers for the new orbit design were the Pegasus capabilities, the already-designed and in-construction ST-5 spacecraft and NASA orbital debris guidelines, and cost. We were two years past Critical Design Review, well into building flight hardware, and did not want to change the spacecraft design significantly.

The Pegasus could not achieve the original GTO orbit even for just our three 25 kg spacecraft, and in addition we would be adding payload mass that was required for a new structure (the Pegasus Support Structure, PSS) to attach the spacecraft to the Pegasus upper stage. We had a number of constraints on the new orbit design: the ST-5 power system capabilities (small battery and solar array) could not support eclipses for more than about 10% - 15% of an orbit; the NASA safety standard for orbital debris requires that the spacecraft be able to re-enter within 25 years (significant since the ST-5 spacecraft have no provision for controlled re-entry); and we needed to be able to communicate with our DSN ground stations. To maximize our ability to do operations on-orbit, it was apparent that a sun-synchronous polar orbit (~105.6 degrees inclination) was probably the best choice. We also biased the right ascension of the ascending node (RAAN, the point at which the orbit plane crosses the equator heading north) to compensate for the seasonal variation in the Earth's position relative to the Sun. By doing so the spacecraft would stay in full sun for the entire orbit (a dawn-dusk orbit with the Mean Local Time of the ascending node at approximately 6 A.M.) for the duration of our 90 day mission.

We could also choose either a circular or elliptical orbit. We worked with our counterparts at Orbital Sciences Corporation and the NASA Kennedy Space Center to get first-order performance estimates of the Pegasus XL with our estimated total mass of 150 kg (including the PSS). By their calculations the largest circular orbit that could be achieved was slightly less than 1000 km, and the ranges of elliptical orbits spanned from a moderate-eccentricity 300 km x 4500 km to a low-eccentricity near-circular orbit. The elliptical orbits also have the added complications (from a mission design standpoint) that the initial argument of perigee (AOP) is set by the burnout of the upper stage rocket motor, so the launch site and launch range restrictions affect the range of possible AOP that can be achieved. Also, elliptical orbits have the "feature" that the line of apsides (an imaginary line drawn between the arguments of perigee and apogee) will precess, so the perigee and apogee will "walk" around the orbit, having the net effect of changing the ground station pass times and lengths throughout the mission. In the end we selected the 300 km x 4500 km elliptical orbit based on our need for Deep Space Network (DSN) X-band support and the requirement for uncontrolled re-entry of the ST-5 spacecraft within 25 years. In a low circular orbit the spacecraft would not be able to communicate with DSN due to both excessive slew rates on the DSN 34m Beam Wave Guide (BWG) antennas and pass lengths too short to downlink all our data. In a high circular orbit, the spacecraft would not re-enter within the required 25 years. In the elliptical orbit, we can maximize apogee, and the re-entry requirement drives the selected perigee. We used the strategy of setting the apogee high enough (4500 km) that our spacecraft stays in the sun for the entire orbit and we calculated the maximum allowable perigee (300 km) that will result in re-entry within 25 years. We wanted to stay above 250 km perigee as the atmospheric density begins rising rapidly (exponentially) and results in large drag/perturbation torques on the spacecraft as it passes near perigee.

We considered two major constellation formations for the elliptical orbit, again with the same design drivers. The first option was a triangular formation ("the triangle") with two spacecraft in a single orbit plane and the third spacecraft slightly (perhaps 1 – 3 degrees) out of plane. The triangle was highly desirable from a scientific standpoint to facilitate a curl-B measurement of the Earth's magnetic fields; however, the plane change for the third spacecraft would have required the launch vehicle to have a re-startable upper stage. Pegasus XL missions can use the Hydrazine Auxiliary Propulsion System (HAPS), but for our mission the HAPS would have limited our maximum apogee, driving it down to ~2500 km. Our analysis showed that a lower apogee orbit could result in significant earth shadow eclipses within the life of our mission—eclipses that our power system couldn't handle. Thus we chose the "string of pearls" constellation formation with all three spacecraft flying line astern.

Since the longest communications passes occur when the ground station is in view of the spacecraft near apogee, we looked at various means to get the apogee to occur over the northern hemisphere where two (Goldstone, California USA, and Madrid, Spain) of the three DSN stations are (the third DSN station is in Canberra, Australia.) The standard 3-stage Pegasus launch out of Vandenberg is towards the south and places the argument of perigee at approximately 160 degrees, hence the argument of apogee is at 20 degrees, or just above the equator. For our 300 x 4500 km orbit the line of apsides (and therefore the arguments of perigee and apogee) rotates clockwise at about 1.2 degrees per day viewed from the Sun. Therefore our apogee would spend most of its time in the southern hemisphere during the initial 90 day mission. To get the apogee to occur in the northern hemisphere would have required either changing the launch site (too expensive), or using the HAPS, which was both expensive and decreased the achievable apogee below what was acceptable. So, we opted for the standard Pegasus launch out of Vandenberg and knew we would have to consider some other options to guarantee sufficient downlink time.

The new orbit has only a small effect on the technology validation strategy. There is a lower total dose of radiation over the 3-month mission life, affecting the validation of the CULPRiT chip.

Significant analysis was also required to determine the spacecraft deployment strategy from the Pegasus launch vehicle. The goals are to deploy the spacecraft so that they do not collide upon initial deployment or upon subsequent close approach, and to have the spacecraft begin passively separating from each other toward the first constellation configuration. The Pegasus battery constrains how long the spacecraft can stay on the launch vehicle. It is also desirable to deploy the spacecraft as quickly as possible from a thermal perspective to minimize how long spacecraft components are exposed to hot or cold extremes after the fairing is removed. However, the initial separation distance of the spacecraft is limited by the force of the pinpuller on the deployment structure and forces between the spacecraft and the launch vehicle. So the time between deployments must be long enough to avoid collision risk between the ST-5 spacecraft. The deployment order and timing have been determined by analysis and are illustrated in figure 2.

Revised Science Demonstration Strategy

The fundamental measurement strategy of all micro-satellite constellation missions is to synthesize higher order physical quantities from the collective measurements made by the individual satellite elements**.** The ST-5 mission will provide validation for this measurement concept using three micro-satellites. Specifically, the measurement concept validation will use the natural environment of low Earth orbit to validate the 3 primary areas critical to future constellation missions: formation flying, ST-5's suitability as a platform for making scientific measurements, and the autonomous response of the ST-5 spacecraft to science events.

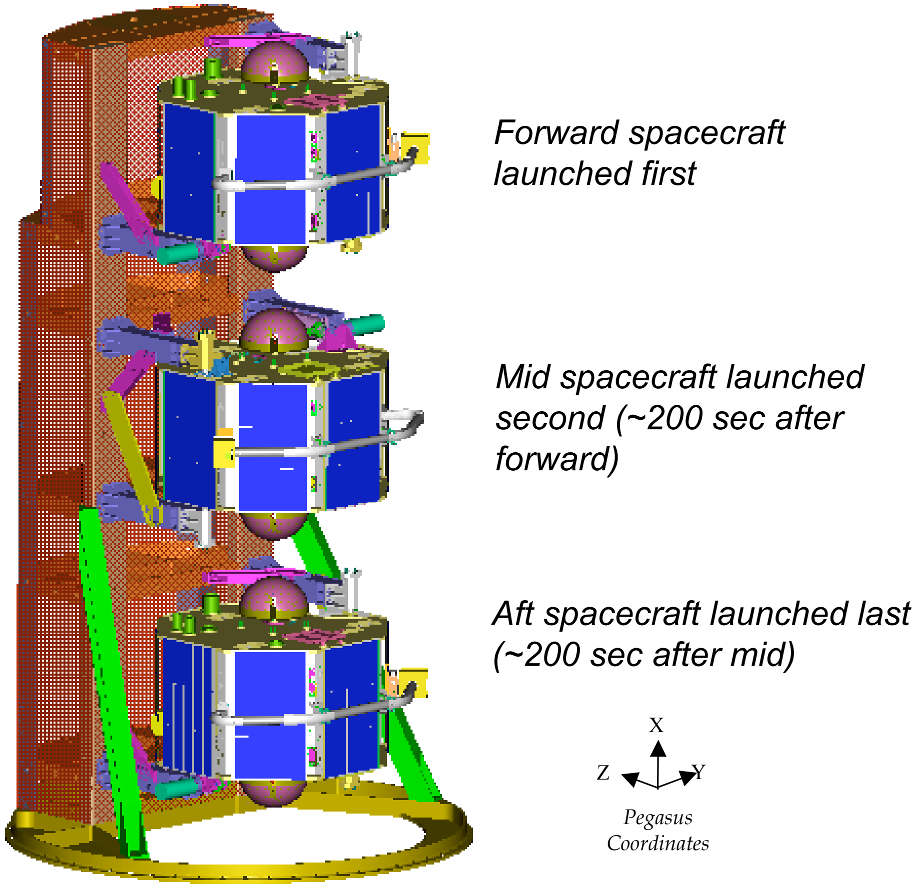


Figure 2— Three ST-5 Spacecraft shown mounted on Pegasus Support Structure. Spacecraft are deployed in the order shown.

ST-5 will validate the constellation measurement concept through the coordinated collection and analysis of magnetometer measurements taken by the three spacecraft formation flying over the Earth's auroral ovals in low Earth orbit. The auroral ovals are annular regions a few degrees of latitude in width that encircle the north and south magnetic poles of the Earth. Typically found at ~ 60 - 65 degrees latitude, they expand to middle latitudes in response to intense solar events (e.g., coronal mass ejections). These regions are unique because they constitute magnetic "footprints" of the external boundaries of the geomagnetic field where solar wind energy enters the system on the dayside and the flanks. On the night side, the auroral oval connects to the plasma sheet where dynamic processes release as much as 10^{10} - 10^{12} W during geomagnetic storms and substorms, most of which is eventually transferred to the Earth's ionosphere. The primary mechanism for this transfer of energy to the ionosphere and upper atmosphere is the formation of intense electric currents that flow along the geomagnetic lines of force emanating from the auroral ovals. These currents are termed "field aligned currents" because they are guided by and follow the geomagnetic lines of force. In this manner, ST-5 will study the science behind the beautiful auroras that have captivated human civilizations for millennia.

Although individual spacecraft have studied the auroral field aligned current phenomenon before, ST-5 will be the first mission to provide simultaneous multipoint measurements across a field aligned current sheet. The ST-5 measurement concept requires that the 3 spacecraft execute and maintain pre-determined formations. For each formation, the separations must be achieved in specified periods of time. Separations of tens of kilometers to several hundred kilometers are required in order to meet the constellation validation requirements.

Formation #1: Spacecraft separations will evolve to achieve separations of spacecraft 1 to 2 and spacecraft 2 to 3 of approximately 25 km and 75 km by Day 30. Initial constellation performance assessments and measurement concept validations are to be performed and field-aligned current motion, thickness, current density and temporal stability determinations made during this interval.

Formation #2: Spacecraft separations will evolve to achieve separations of spacecraft 1 to 2 and spacecraft 2 to 3 of approximately 50 km and 100 km by Day 60. Further constellation performance assessments will be conducted, measurement concept validations will be performed, and field-aligned current motion, thickness, current density and temporal stability determinations made over these new spatial scale lengths. ST-5's field aligned current measurements will be verified using independent data from the International Geomagnetic Reference Field, as well as scientific and operational spacecraft such as Oersted, CHAMP, DMSP, and Iridium. The ST-5 constellation formations are shown in Figure 3.

Planning for a possible third constellation formation based on the science data results from the first two formations will occur towards the end of the 90 day mission, but it is likely that any third constellation maneuver would occur during a potential post-90-day extended operations, assuming that there were funding for an extended ST-5 mission.

The new orbit did affect the validation strategy to demonstrate the research-quality science capability of the ST-5 spacecraft. Due to high magnetic fields in the new orbit, the magnetic cleanliness of the spacecraft can be verified on-orbit only to 10 nT vs. 1 nT for the GTO orbit.

Refined Constellation Operations Concepts

The ST-5 spacecraft will be operated as a constellation, demonstrating concepts for autonomous constellation management and operations. The spacecraft and ground system provide evolvable steps along the road to future constellation missions.

The original ground system concept for ST-5 has been modified to support an integrated constellation approach, as opposed to stand-alone tools. Goddard has developed the 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. The heritage components have been extended with generic constellation support requirements, and the new components are designed with spacecraft constellation support in mind.

ST-5 ground operations are automated through the use of several components. 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 Advanced Mission Planning and Scheduling (AMPS) system is a multi-satellite planning and scheduling system that allows for near real-time autonomous replanning when the model detects constraint violations.

Part of the job of the mission controllers and the ground system is made easier by Fault Detection and Correction (FDC) mechanisms in hardware and software onboard the spacecraft. 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. The spacecraft are capable of surviving without ground contact for weeks if necessary if ground contact is lost for some reason.

We anticipate that the key contributions from ST-5 will be the demonstration of model-based operations and the plug-and-play ground system approach. Whereas previous attempts at model-based operations involved significant staffing to maintain the models, ST-5's models will be self-updating.

Communications Strategy

As described earlier, the ST-5 orbit is an elliptical 4500km by 300km polar orbit, with an argument of perigee at 160 degrees, with the apogee initially just north of the equator and rotating into the southern hemsiphere at about 1. 2 degree per day. Since the longest communications passes occur when the spacecraft is at or near apogee, this means that the visibility is greatest for southern latitude ground stations.

For the previous GTO orbit, we already had an agreement in place that ST-5 would use the Deep Space Network (DSN) for space-to-ground communications. We had already demonstrated the ST-5 prototype transponder's compatibility with DSN. However, in the new orbit, the best visibility would be at the Canberra DSN station, which has only one antenna that can support ST-5. The DSN operations concept is optimized for long, infrequent passes needed by planetary missions, so it is difficult to schedule DSN for the more frequent, shorter passes that ST-5 needs in the new orbit.

Outside DSN, there was no existing ground station that could support ST-5's X-band uplink without modification. The NASA McMurdo Ground Network station in Antarctica provides the best visibility for ST-5 over its 90-day mission life. However, McMurdo at the time did not have the capability to communicate on the X-band frequencies that ST-5 uses. Figure 2 shows the visibility at several different ground stations. In the figure, the visibility times at the various ground stations are represented by the "height" of the bars, and the overall height of the graph on any day is the sum of all the available contact times at the various ground stations. It is apparent from looking at Figure 2 that the southern latitude stations (McMurdo and Canberra) have good visibility during the mission, and that the northern DSN station and the GN station at NASA-Wallops Flight Facility (in Virginia, USA) have very little coverage at the beginning and end of the mission, and almost none during the middle of the mission. Because of the superior visibility there, we are upgrading the McMurdo ground station to support ST-5. This is a very intense activity, because McMurdo is accessible only during certain months of the year (the Antarctic summer, October through February.)

Our plan is to use DSN primarily for tracking and uplink, and McMurdo primarily for data downlink.

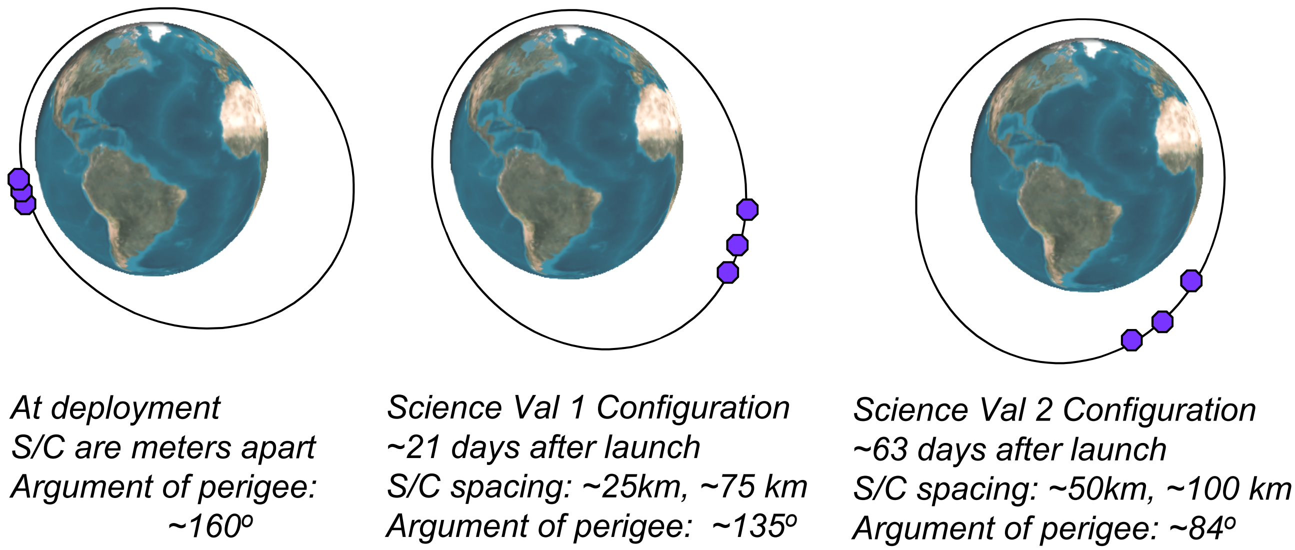


Figure 3 – ST-5 Constellation Formations. These constellation formations allow simultaneous measurement of the earth's magnetic field across auroral sheets.

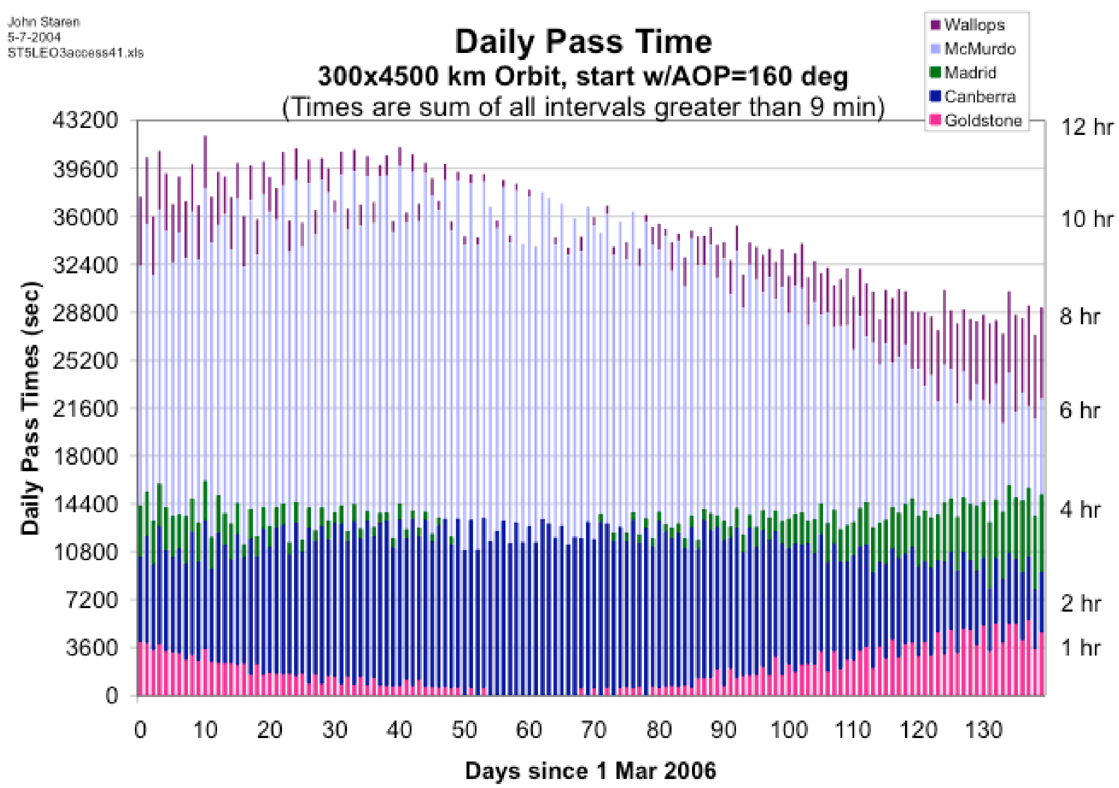


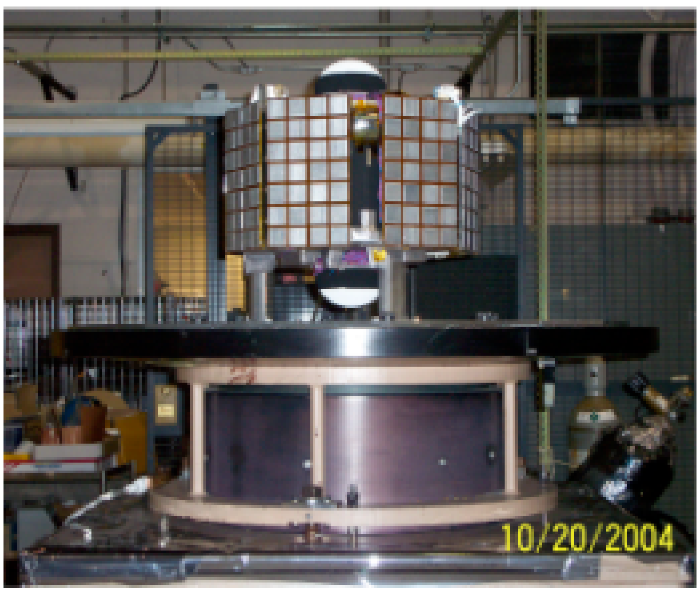
Figure 4 – Ground Station Visibility for ST-5. Because the ST-5 apogee precesses through the southern hemisphere over the 90-day mission, visibility is greatest at southern latitude sites. McMurdo has the best visibility, followed by Canberra.

Spacecraft Antennas

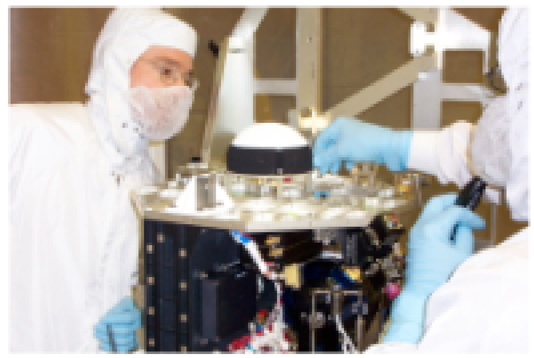
ST-5 will fly two different types of X-band antennas, a Quadrifilar Helix (QFH) and an “Evolved” antenna. The QFH antenna was originally designed for our previous GTO orbit. It is optimized for mid-elevation gain, and has a sharp dip in the gain curve at zenith. This characteristic made the QFH less desirable for a polar orbit. Fortunately since our alititude is lower and DSN have a tremendous effective isotropic radiated power (EIRP) we still have large link margins to the DSN stations with the QFH antenna. However, the QFH on ST-5 would not provide acceptable performance with the smaller 10m dish at McMurdo.

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.

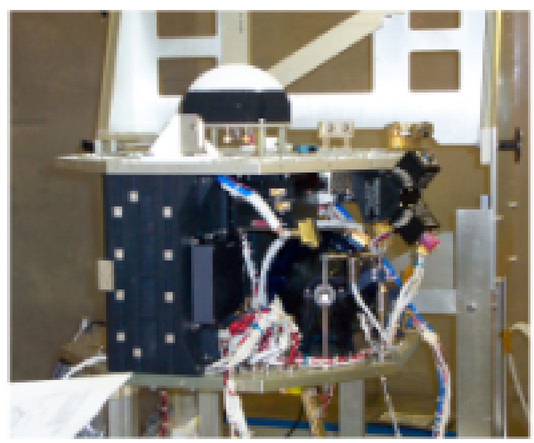
Previously, we had planned to use the evolved antenna as a backup and technology demonstration on 1 or 2 spacecraft. It was to be coupled at approximately -10 to –20dB from the primary QFH antenna. However, due to the new orbit, both antennas have equal visibility to the ground stations. Because the evolved antennas had not been built yet, and



Spacecraft at Mass Properties
(shown with solar array mass dummies)



Mounting the Antenna



Inside the Spacecraft

Figure 5— ST-5 Spacecraft #1 in Integration & Test

could be re-designed quickly, we made the decision to optimize their design for the new orbit, to build enough to fly on all three spacecraft, and to couple the top and bottom deck antennas equally. The evolved antennas are being developed on a schedule to accompany the second and third ST-5 spacecraft through the full spacecraft environmental test flow, and we plan to retrofit an evolved antenna onto the first spacecraft later in its testing flow.

3. Spacecraft Development and Test Progress

Although we were able to minimize the changes to the spacecraft, there were some design changes due to the new orbit. The low-earth orbit has a higher magnetic field than the GTO orbit, so the magnetometer dynamic ranges were changed. Flight software science data processing algorithms were modified to align with the new science validation strategy. Minor adjustments were made to radiator sizes and coatings to account for the more benign thermal environment.

To date, all of the flight hardware for the first spacecraft has been delivered except the magnetometer boom and evolved antenna. These will be retrofitted onto the spacecraft later in the integration and test flow. The spacecraft has been electrically and mechanically integrated (see Figure 3), and some functional testing has been completed. Environmental testing, consisting of electromagnetic interference, electromagnetic compatibility, random vibration, shock, thermal vacuum, thermal balance, mass properties, and magnetics will be conducted during the fall of 2004.

4. Conclusion

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.

The project team has successfully re-planned the mission for the new orbit. The re-plan allows the mission to achieve the same high-level validation objectives with a different launch vehicle. The new mission design involves a revised science validation strategy, a new orbit and different communication strategy, while minimizing changes to the ST-5 spacecraft itself. The constellation operations concepts have also been refined. The mission design changes are described in Table 1. Most flight components have been delivered, and the first spacecraft is in integration and test.

Table 1, Summary of Requirements Validation Strategy Changes

ST-5 Project Top-Level Requirement	New Mission (Sun – synchronous Polar Orbit) Changes to Validation Strategy
Design, develop, integrate, test and operate three full service spacecraft, each with a mass less than 25 kg, through the use of breakthrough technologies.	New mission develops, builds and tests three 25-kg spacecraft and validates the same technologies. There is a lower total dose of radiation over the 3-month mission life, affecting the validation of the CULPRiT chip.
Demonstrate the ability to achieve accurate, research-quality scientific measurements using a constellation of 3 nano-satellites, each with a mass less than 25 kg.	ST-5 will validate the constellation measurement concept through the coordinated collection and analysis of magnetometer measurements taken by the three spacecraft formation flying over the Earth's auroral ovals in low Earth orbit. Due to high magnetic fields in the new orbit, the magnetic cleanliness of the spacecraft can be verified on-orbit only to 10 nT vs. 1 nT.
Execute the design, development, test and operation of multiple spacecraft to act as a single constellation rather than as individual elements.	Ground system concept for ST-5 has been modified to support an integrated constellation approach, as opposed to stand-alone tools

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[3] New Millennium Program Web Site http://nmp.jpl.nasa.gov/

BIOGRAPHY

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.

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.

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 Scientist for Magnetospheric Physics at NASA Headquarters.