Space Technology 5
Technology Validation Results

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***Abstract*—The Space Technology 5 (ST5) Project is part of NASA's New Millennium Program. ST5 consists of a constellation of three micro-satellites, each micro-sat approximately 25 kg in mass, launched March 22, 2006, on a Pegasus XL rocket. All ST5 components are low mass, low power, and low volume. During the three-month flight demonstration phase, the ST5 team validated the key technologies that will make future low-cost micro-satellite constellations possible, demonstrated operability concepts for future micro-satellite science constellation missions, and demonstrated the research-quality science capabilities of the spacecraft. The ST5 mission was successfully completed in June 2006.**

I. Introduction

The Space Technology 5 (ST5) Project is part of NASA's New Millennium Program. ST5 consists of a constellation of three micro-satellites, each approximately 25 kg in mass. The ST5 mission commenced March 22, 2006, with a Pegasus XL rocket launch, and consisted of 90 days of technology and science validation operations, followed by 10 days of end-of-mission activities. During the flight demonstration phase, the ST5 team validated the key technologies that will make future low-cost micro-satellite constellations possible, demonstrated operability concepts for future micro-satellite science constellation missions, and demonstrated the research-quality science capabilities of the spacecraft.

ST5's advanced technology components include: single-card Command and Data Handling (C&DH) computer, low-voltage power subsystem featuring triple-junction solar cells and a lithium-ion battery, communications subsystem featuring a miniature X-band transponder and an evolved antenna developed using a "genetic" (or "evolved") algorithm, cold gas propulsion subsystem using a single micro-thruster for both delta-V and attitude control, 0.5 V CMOS Ultra Low Power Radiation Tolerant (CULPRiT) logic, Variable Emittance Coating thermal surfaces, miniature magnetometer, miniature spinning sun sensor, and a non-bellows nutation damper.

The three ST5 spacecraft were operated as a constellation, demonstrating "model-based operations" automation and ground communication strategies that will be useful for future missions that plan to deploy multiple spacecraft with minimal ground support personnel (i.e., lights-out operations").

ST5 validated the three primary areas critical to future science constellation missions: formation flying, micro-satellite suitability as a platform for making scientific measurements, and the autonomous response of the micro-satellites to science events.

II. Spacecraft and Component Technologies

The ST5 spacecraft represents a significant design effort to develop a micro-spacecraft with the full subsystem functionality found in larger spacecraft (see Fig. 1). The spacecraft was developed "in-house" by Goddard Space Flight Center (GSFC), with some components developed by outside vendors and industry partners.

Each ST5 spacecraft is octagonal in shape, approximately 25 kg in mass, and approximately 53 cm in diameter (solar panel peak-to-peak) by 48 cm in height (tip of antenna to tip of antenna). The top deck is removable, allowing access to all components during Integration and Test. An integral card-cage provides the structural backbone of the spacecraft, as well as housing the Command and Data Handling and Power System Electronics cards. The card-cage structure is lightweight investment-cast aluminum.

The Command and Data Handling (C&DH) subsystem is a double-sided single card computer that retains all of the functionality found on larger spacecraft while consuming little power (<4 W). It supports all communications activities between the spacecraft and the ground, as well as communications within the spacecraft to all of the components.

The Complementary Metal Oxide Semiconductor Ultra Low Power Radiation Technology (CULPRiT) chip resides on the C&DH board. CULPRiT allows circuits to operate at very low voltage. The technology is capable of significant power reduction over current technology, while achieving radiation and latch-up tolerance. For ST5, the CULPRiT chip was used is a Reed Solomon Encoder. CULPRiT performed flawlessly over the entire mission, transmitting over 330 million telemetry frames with no voltage or current instability, current increases related to radiation, or bit errors. Partners in the CULPRiT development included the Center for Advanced Microelectronics and Biomolecular Research at the University of Idaho, AMI Semiconductor, and Picodyne.

The Electrical Power Subsystem, controlled by a single double-sided power system electronics card, provides electrical services to all components on the spacecraft and battery-charging capability, including over-voltage protection.

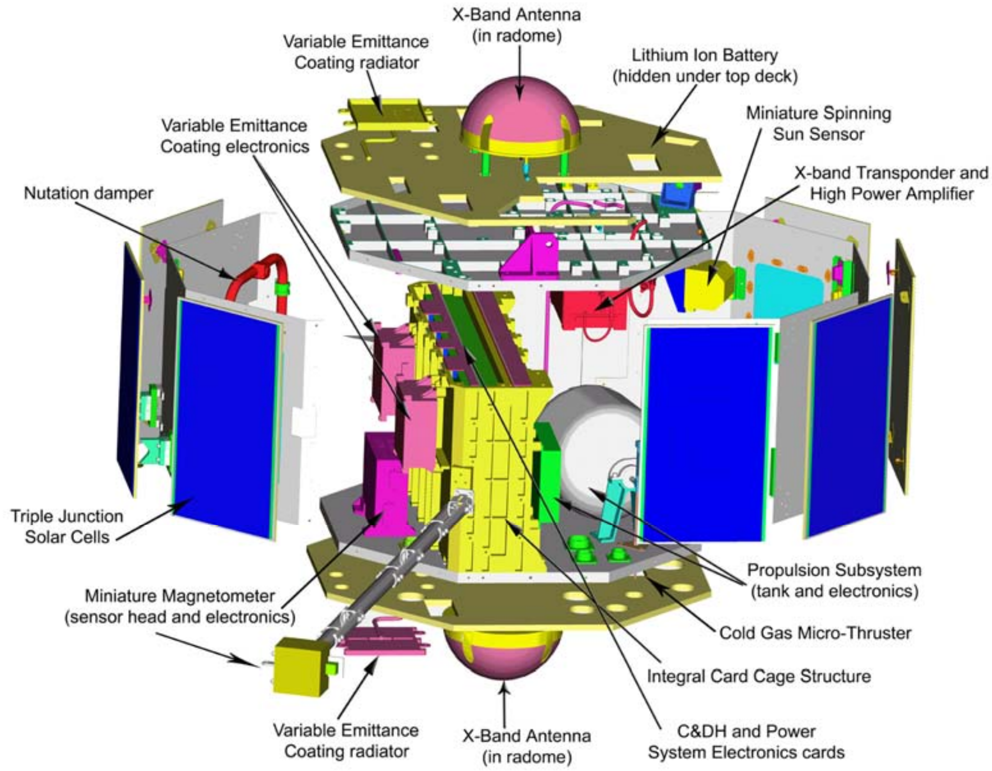

Fig. 1. ST5 Components.

ST5 includes a solar array composed of 8 body-mounted panels with a total power-generating capacity of 25 W (beginning of life) at approximately 10 V. At procurement time, the triple junction ST5 solar cells were the highest efficiency available in the USA, and were available only as research quality cells. The raw cell efficiencies vary from 28.1 to 29.1 percent at 1 sun intensity (without the added complexity of solar concentrators). The ST5 solar cells were procured in partnership with the Air Force Research Laboratory and provided by Emcore.

ST5 energy storage is accomplished using a Lithium-Ion battery with total usable energy storage of 9 A-h (beginning of life) at the maximum operating voltage of 8.4 V. Lithium-Ion represents a dramatic three-fold improvement in energy density over previous batteries. The batteries on all three satellites performed flawlessly over the 90-day mission, with no capacity fade, cell imbalance or voltage decay. ABSL (formerly AEA Technologies) built the ST5 battery.

The spacecraft is designed with a communication subsystem operating at X-band for both ground-to-space (uplink) and space-to-ground (downlink) communications. The communication subsystem employs a new technology X-band transponder, built by AeroAstro, to provide uplink and coherent downlink tracking functionality. Throughout the 90-day mission, the ST5 transponders were used for command, telemetry, and radiometric orbit determination (two-way Doppler).

Two body-mounted antennas, one each on the top and bottom decks, provide nearly 4π steradian coverage with the ground. Each antenna's boresight is mounted co-linear with the spin-axis of the spacecraft. Each ST5 spacecraft houses one quadrifilar helix antenna and one evolved antenna. The evolved antenna is designed using a computer program based on a "genetic" algorithm. The algorithm designs a wire form radiator, "evolving" the design based on a "fitness function" computed from voltage standing wave ratio and gain scores. This evolved antenna design method has the potential for high gain across a wider range of elevation angles and more uniform coverage than conventional designs (a very uniform pattern over the 40-80 degree elevation angles of greatest interest).

The ST5 transponders and antennas performed flawlessly throughout the mission. This assessment of the transponder and antenna performance is based on automatic gain control, receiver carrier loop stress, transmitter output power, oscillator temperature, received signal strength and bit error rate.

The spacecraft includes a cold gas propulsion system to provide attitude maneuvering capability as well as a limited orbital maneuvering capability. The propulsion subsystem consists of a tank, a single thruster, a fill-and-drain valve, an in-line filter and a pressure transducer. The propellant used for the mission is Gaseous Nitrogen (GN_2).

The propulsion tank, built by Carleton Technologies, has a total volume of 146 cubic inches. It is a composite overwrap (PBO fiber) over a seamless Aluminum 6061-T6 tank, with a maximum expected operating pressure of 2240 psig.

The ST5 micro-thruster was provided by Marotta Scientific Controls. This cold gas micro-thruster is capable of being operated in both pulse and continuous fire modes, to achieve both delta-V and attitude control, and features very low power draw and low leakage rates. The latching solenoid valve design provides an order of magnitude reduction in power consumption compared to thrusters based on continuous duty solenoid valves. The ST5 Cold Gas Micro Thruster far exceeded the original performance goals (Thrust >2.1N @ 2000 psi and 0.1N @ 100 psi and ISP Level > 60 seconds), and performed flawlessly from the beginning of the mission to the end.

The spacecraft is passively spin stabilized, with system momentum about the major principal moment of inertia axis. The initial spin-up of the spacecraft is performed by the spacecraft deployment mechanism.

The ST5 spacecraft employs a passive nutation damping device. The damper is made from titanium and is completely filled with a viscous silicone. The damper design is notable in that it employs very high internal pressures (up to 10,000 psi) and does not use a bellows. The ST5 dampers successfully damped the nutation from the initial spacecraft deployments, as well as maneuvers throughout the mission.

The ST5 thermal-control system is completely passive consisting of painted radiator surfaces and multi-layer insulation.

ST5 demonstrated two thermal control technologies, known as Variable Emittance Coatings (VECs). The Micro Electro-Mechanical Systems Variable Emittance Coatings radiator was developed by the Johns Hopkins University Applied Physics Laboratory (JHUAPL), using multi-layer silicon chip (SUMMiT V) shutters provided by Sandia National Laboratories. The Electro Static Radiator Variable Emittance Coatings radiator was developed by Sensortex, Inc. It consists of a thin film made of a composite metalized polymer. The ST5 VECs serve as a proof-of-concept, with further development required for future missions.

III. Constellation Operations

The ST5 ground system was developed using a rapid assembly method for ground components. The ground system was used to validate an autonomous ground systems operations concept to facilitate constellation operations.

The ST5 ground system incorporates the GSFC Mission Services Evolution Center (GMSEC) common bus architecture to provide a scalable, extensible ground and flight system approach. Through the use of middleware and a generic messaging capability, key functionality can easily be integrated into the GMSEC ground architecture and operated in a “plug-and-play” manner. By meeting standard “socket” specifications, a component on the bus can send and receive messages from other components even if the components were not originally designed to work together. By using GMSEC, components were easily added, deleted, and exchanged to meet changing mission requirements.

The ST5 components on the GMSEC bus were as follows:

- Front-End Data System (FEDS)/Advanced System for Integration and Spacecraft Test (ASIST) – a real-time command and control system, which is used in integration and test, as well as on-orbit operations
- Automated Mission Planning and Scheduling System (AMPS) – a multi-satellite planning and scheduling system together with a scenario scheduler that can perform rapid re-planning and support execution of the plan
- Attitude Determination System (ADS) – performed flight-dynamic functions to determine attitude and generate mission planning products
- SimulinkST5 – An implementation of the Real-time Object Modeling Executive (ROME) built for ST5 as predictive modeling software based on MatLab’s Simulink to model spacecraft systems and predict future conditions
- Criteria Action Table/Advanced Network Services Registry (CAT/ANSR) – a paging system that monitors telemetry and event messages and can alert Flight Operations Team personnel in the event of a lights-out alert
- Smart Sockets – generic middleware which acts as the backbone to the GMSEC bus to allow inter-operability of key components on a messaging level and the rapid reconfiguration of new components onto the bus

The ST5 ground system also incorporates a Model Based Operations (MBO) approach to provide autonomous operations. The ST5 MBO system, SimulinkST5, used Simulink in conjunction with the Advanced Mission Planning and Scheduling (AMPS) system. SimulinkST5 integrated dynamic models of satellite systems and orbit propagation models, thus allowing it to provide anomaly forecasting, dynamic resource allocation, support for short term re-planning and “lights out” operations, and system-level asset allocation.

These systems allowed the operations staff to plan weekly and daily operations for all three vehicles, while managing highly constrained on-board resources with minimal effort. While supporting the mission throughout in “support” mode, these systems were allowed to “control” the ST5 spacecraft with a minimal complement of operations staff to produce and adjust weekly activity plans during the latter third of the mission. This “lights-out” phase of the mission demonstrated that operation of multiple-spacecraft missions can be accomplished via a rapidly configurable GMSEC architecture with minimal ground support personnel.

The ST5 spacecraft also incorporated on-board automation through the use of absolute-time command sequences, relative-time command sequences, and telemetry status monitors, which can be executed while the spacecraft are out of view. The spacecraft monitored themselves for excessive thruster firing, transponder interface problems, command and data handling hang-ups, low battery or voltage conditions, and performed automated failure detection and correction actions to recover. The ST5 spacecraft are capable of autonomously acquiring the Sun when commanded by the ground or when onboard fault conditions (based on Sun angle) are met.

IV. Research-Quality Science Demonstration

One of the primary goals of the ST5 mission was to demonstrate the research-quality science measurement capabilities of the micro-sats, and the scientific usefulness of synthesizing higher-order measurements from collective measurements taken by a constellation of spacecraft. ST5 validated the three primary areas critical to future constellation missions: formation flying, micro-satellite suitability as a platform for making scientific measurements, and the autonomous response of the micro-satellites to science events. Each ST5 spacecraft deployed a precision magnetometer, a representative science instrument. The spacecraft have a low magnetic signature to avoid interference with the magnetometer. They are able to detect and respond autonomously to science-events, and to dynamically change data recording rates in response to significant changes in the magnetic field.

The ST5 science team used the coordinated collection of magnetometer measurements taken by the three micro-satellites flying in formation over the Earth's auroral ovals in low Earth orbit to study the electric current systems in the region. 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 above approximately 60–65 degrees magnetic latitude, they expand to middle latitudes in response to intense solar events (e.g., coronal mass ejections). On the night-side of the Earth, the auroral oval connects to the plasma sheet where dynamic processes release as much as $10^{10\text{-}12}$ W during geomagnetic storms and substorms, most of which is eventually transferred to the Earth's ionosphere and upper atmosphere. 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" or "FACs" because they are guided by and follow the geomagnetic lines of force. This is the science behind the beautiful aurora that we see in the northern or southern skies (see Fig. 2).

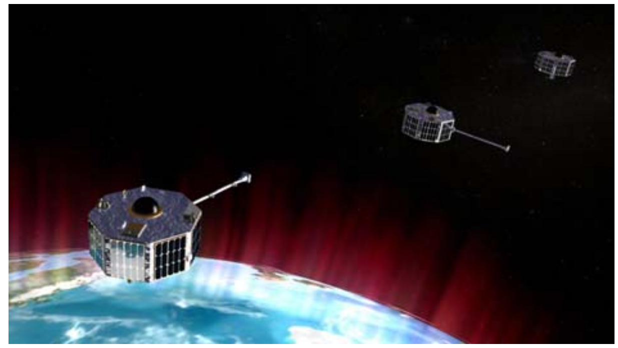

Fig. 2. ST5 spacecraft formation flying through the auroral region.

ST5 provided the first simultaneous, multi-point measurements of the magnetic field associated with the auroral current sheet. The technique to obtain the current density by directly measuring the gradient of the magnetic field is called gradiometer analysis. It requires two-point measurements of the magnetic field by two spacecraft simultaneously, and the spacing of the two spacecraft has to be smaller than the thickness of the current sheet (so that the both spacecraft can be within the current sheet at the same time). The thickness of the auroral current sheet is typically approximately 500–1000 km. ST5 data provided many opportunities for gradiometer analysis of the current density.

Fig. 3 is an example of the gradiometer analysis using the magnetic field data from two of the ST5 spacecraft (known as 094 and 224) on March 31, 2006. The magnetic field data were taken near the dawn at approximately 500 km altitude in the northern hemisphere. The current density determined by gradiometer analysis using simultaneous two-point magnetic field data from the two ST5 spacecraft is shown in the black trace. The gradiometer analysis result shows clearly two current sheet structures with currents flowing in opposite directions: the region 1 current (R1) flowing downward (positive current density J) and the region 2 current (R2) flowing upward (negative current density J). The current sheet thickness (in km) and the total integrated current intensity (in mA/m) are also shown for each current sheet in Fig. 3. In comparison, the current density determined using single spacecraft data and by assuming a stationary current sheet is shown in red. The fluctuations in the red trace are mainly caused by temporal variations of small scale structures embedded within the large scale current sheet and do not represent the true current density profile within the current sheet.

The ST5 spacecraft also observed lithospheric magnetic fields, also known as crustal magnetic fields, due to the magnetization of Earth's crust or magnetic minerals. Since they are much weaker than the gradients produced by auroral currents, they are seen only when the spacecraft are away from the auroral current region.

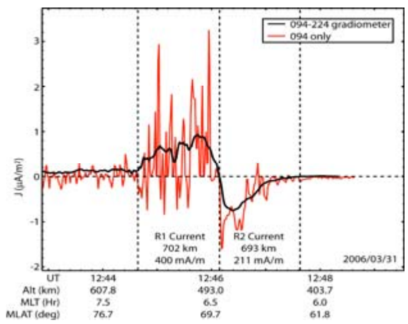

Fig. 3. Gradiometer analysis of field-aligned current density.

Using simultaneous two-point measurements in determining the magnetic field gradients effectively removes temporal effects by sampling the magnetic field at the same time. Fig. 4 shows the low altitude (<400 km) magnetic field gradients (in nT/m) measured by ST5 spacecraft 094 and 224 between March 28 and June 2, 2006 [1]. The gradients are calculated by first removing the Earth's internal magnetic field (International Geomagnetic Reference Field (IGRF) model) from the magnetic field strength measured by spacecraft 094 and 224 individually, and then calculating the difference between the 094 and 224 measurements. Spacecraft separation averaged 400 km (Range: 100–600 km). The "modeled gradient" show the gradients predicted from the Comprehensive (CM4) field model, a model derived using data from satellite mapping missions (Orsted, CHAMP, Magsat, and POGO), and ground-based observatories. The gradients from ST5 data exhibit correlations of between 0.5 and 0.94 with the CM4 model. ST5 provided the first simultaneous two-point measurements of lithospheric magnetic field gradients.

ST5's sun-synchronized polar orbit in the dawn-dusk meridian plane and 106 degree inclination angle provided many unique opportunities for the spacecraft to skim through the dayside subauroral region in the east-west direction. The subauroral region is the circular band just below the auroral oval in latitudes. Other similar polar orbiting spacecraft have crossed through the dayside subauroral region in the north-south direction when their orbits were in the noon-midnight meridian plane. When their orbits were in the dawn-dusk meridian plane, they did not have the access to the subauroral region because their inclination angles were too close to 90 degrees. ST5 observed a new class of magnetic pulsations (also called waves) that have never been reported before. The magnetic pulsations appear to occur only in a very narrow region latitudinally (approximately 100 km in north-south direction, or approximately 1 degree in latitude), but in a much extended region longitudinally. (This is why these signatures cannot be resolved when crossing the region in north-south direction.) The three ST5 spacecraft always observed these pulsations in the same region, even when 155 was up to 10 minutes ahead of the two trailing spacecraft along the orbit.

The periods of the pulsations are in the range from approximately 10 to 20 seconds. The amplitudes are in the range of approximately 5 to 40 nT. Highly sensitive magnetic field measurements are required to resolve such small amplitude features since the background magnetic field is in the range approximately 20,000 to 40,000 nT. Fig. 5 shows an example of these pulsations. The pulsations are observed by the leading spacecraft 155 first, followed by mid-spacecraft 094 about 5 minutes later, and lastly by the trailing spacecraft 224 after another approximate 1 minute. The wave forms at the three spacecraft are highly coherent. Fig. 6 shows the high- pass filtered data in the coordinate system ordered by the background magnetic field.

The data from 155 and 224 have been time-shifted to line up with the 094 data. There are high correlations among the signals at the three spacecraft. The likely cause for these pulsations is a thin east-west layer of pulsating aurora (quasi-periodical variations of auroral intensity), but must be verified by other coordinated observations. This is an example of ST5 multi-point measurements have enabled new science.

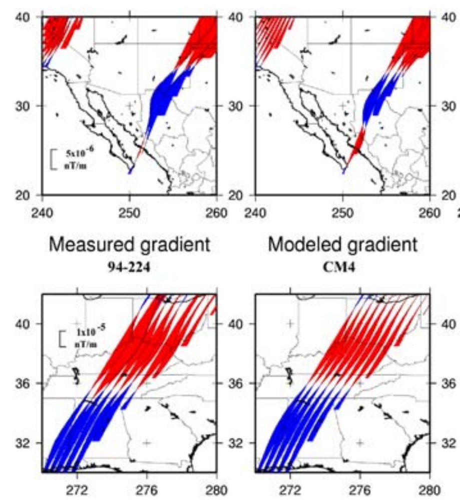

Fig. 4. Measured magnetci field strengt residuals and gradients, compared with CM4 field model.

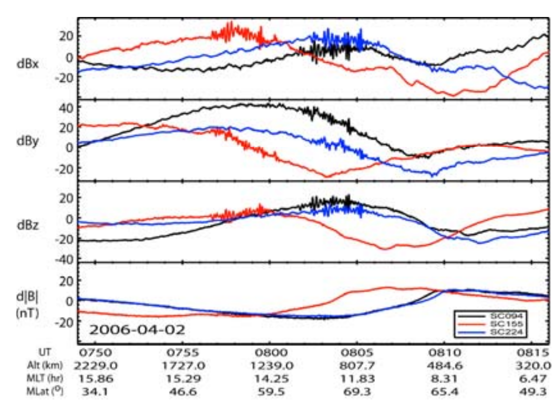

Fig. 5. Example of magnetic pulsations observed by ST5 in dayside subauroral region.

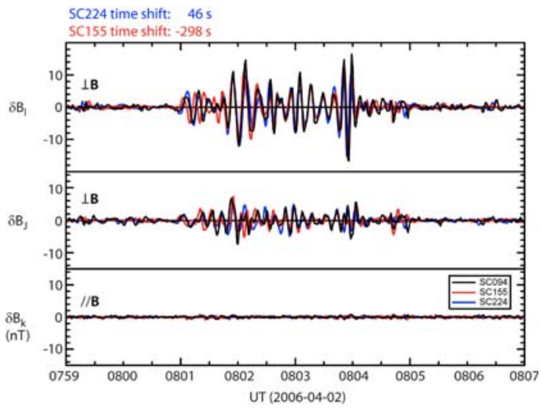

Fig. 6. High-pass filtered pulsations.

V. Technology Infusion

Several constellations of small spacecraft are currently under study or in formulation, particularly for NASA's Heliophysics science program. ST5 component and system-level validation provides risk and cost reduction for these future constellations of small spacecraft. Additionally, infusion of various ST5 components and technologies enables any space mission to reduce overall mass, volume, power, cost and risk. ST5 technologies are already being infused into future missions, such as:

- Sun sensor: Time History of Events and Macroscale Interactions during Substorms (THEMIS)
- Propulsion tank: DAWN
- Magnetometer boom: Geospace Electrodynamic Connections (GEC), Magnetospheric MultiScale (MMS) mission
- Spacecraft bus: Magnetosphere Constellation (MagCon) and/or a potential MIDEX mission proposal
- Lithium-Ion battery: THEMIS, Solar Dynamics Observatory (SDO), Lunar Reconnaissance Orbiter (LRO)
- Triple-junction solar cells: Messenger
- Miniature Magnetometer: MMS, and included in proposals for Solar Terrestrial Probes, Living with a Star and Explorer missions
- Ground system automation components: Gamma Ray Large Area Space Telescope (GLAST), Terra SDO, and Space Operations Institute
- Model-based operations tool (SimulinkST5): will be further developed under the Advanced Information Systems Technology (AIST) Program

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[2] C. Carlisle, E. Webb, et al., *ST5 Project Technology Validation Report*, New Millennium Program document ST5-495-586 (export-controlled document available to U.S. persons who sign a Non-Disclosure Agreement).