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Charles J. Finley

ANSER Space Test Program

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Charles J. Finley, Aerospace
Space Test Program
PO Box 9045 – ABQ/413
Albuquerque, NM 87118-9045
charles.j.finley@aero.org

Abstract

During the 1960's, it became apparent that the Department of Defense (DoD) needed to develop space systems technologies at a rapid rate. Furthermore, the DoD realized that in order to develop and deploy reliable space systems for operational use, they first must test them in space. At that time no organization or funds were readily available to provide timely spaceflight for experiments and demonstrations with military relevance. As a result, the Director of Defense Research and Engineering (DDR&E) wrote a memorandum and created the DoD Space Test Program (STP) in 1966.[1]

The mission of STP is to protect US space superiority by demonstrating the most promising technologies for future operational requirements, thereby reducing the risk of future acquisition efforts. In the 34 years since its inception, STP has flown over 416 scientific experiments on more than 154 missions. The STP "legacy" is far reaching. Each day, the defense community uses some of the data or experience, which originated on an STP experiment, in an operational mission. STP has advanced space technologies in many fields including satellite design, operating systems, knowledge of the space environment, and launch systems. Missions flown by STP were at the forefront of navigation, surveillance, nuclear detection, communication, weather observation and ground radar calibration. Other STP payloads have collected data that furthered the knowledge of the space environment including radiation, composition, and solar effects.

But what can we expect from STP in the future? The answer is, we can expect more of the same. STP is using Space Command's Long Range Plan (LRP) to identify the flavor of the next generation of operational space systems. Everyday, they are planning, manifesting, and launching experiments that will turn Space Command's vision into reality.

Introduction

Space Command's vision for the future of operational space, outlined in their Long Range Plan, guides the Space Test Program. STP's goal is to bring that vision to life and translate ideas and concepts into operational systems. STP is "the primary provider of spaceflight for the entire DoD space research community." They are "DoD's only designated program to demonstrate advanced space systems, designs, and concepts leading to new warfighter support capabilities."[2] In that role, STP shepherds projects that span the full range of development from basic research to advanced technology demonstrations, but they always maintain their focus on investing in space science that will benefit the warfighter.

Predicting the complexion of the Space Force of tomorrow is a formidable task. Space Command draws on their operational experience, just as the scientific community draws on their ingenuity and together they develop a recipe for progress. The current recipe has a definite focus on information – using space systems to gather relevant information and reliably transporting that information to the warfighter in real-time.

The previous decade demonstrated nothing more clearly than the value of information to achieving success. The value of reliable and accurate information is never higher than it is in a military operation. It is in this arena that accurate information can mean the difference between achieving important military objectives and needlessly losing lives.

In their Long Range Plan (LRP), Space Command identifies the missions of the US Space Force through the year 2020 in four areas: Control of Space Capabilities, Global Engagement Capabilities, Full Force Integration Thrusts, and Global Partnership Opportunities.[3] One common theme that spans these areas is the necessity for assured and reliable access to accurate information. Whether the information pertains to the "real time characterization of High Interest Objectives" or preserving "assured communications for command and control", it is an invaluable resource.[3]

Control of Space Capability	Global Engagement Capabilities
• Real Time Characterization of HIOs • Precise Size and Location • Timely Surveillance of HIOs • Reconstitute and Repair Capabilities	• Real-Time Target Characterization and ID • Real-Time Target Set Detection, Surveillance, Monitoring, and Tracking
Full Force Integration Thrusts	**Global Partnership Opportunities**
• Command and Control Support Systems • Communications for Command and Control	• Reconnaissance and Surveillance

Figure 1: Information Oriented LRP Missions of the US Space Force through 2020[3]

The process of getting information to the warfighter in a threatening situation is a complex task that can be broken down into two components. The first component pertains to developing a space system that collects useful information. Such a system must be flexible, affordable, upgradeable, and sustainable. The second component addresses the equally difficult problem of getting the information from the space system to the warfighter. This requires an understanding of the environment in which the space system exists, the environment in which the warfighter exists, and all that stands between the two. Only through this understanding is it possible to take steps to guard friendly assets and assure information remains readily available to friendly forces.

The STP experiments that follow are the defining checkpoints on the roadmap that leads from Space Command's vision to an operational reality. Each complete experiment represents a major step to the eventual system that will likely be part of STP's legacy in 2020.

Mission Part I – Collecting the Information

Historically, engineers have designed large, complex, and highly capable systems to collect weather, geolocation, or reconnaissance data. Recently, however, inspired by the high cost per pound to orbit and substantial improvements in the capabilities of microelectromechanical (MEMS) devices, many satellite designers and operational analysts are favoring microsatellites, designed to work together to function as a single system.

Using a constellation of small satellites to perform a mission previously carried out by a single large satellite has several potential benefits. In a remote sensing capacity, the constellation offers unlimited aperture size and a corresponding improvement in resolution. Furthermore, manufacturers can mass-produce identical satellites, thereby reducing manufacturing costs. From a countermeasures perspective, a constellation of small, distributed satellites would clearly be more difficult to target by an enemy attempting to deny information to the user. The constellation would also be more reliable and give a user the luxury of reconfiguring the constellation to compensate for a weak or failing component. Probably the most significant advantage of this architecture, however, is the inherent adaptability associated with a constellation of microsatellites. By reconfiguring their relative positions, the satellites can potentially perform a number of different missions, from communication to geolocation to remote sensing. The corresponding savings to an organized operational space infrastructure is immense.[4]

On their inaugural Evolved Expendable Launch Vehicle (EELV), STP will fly one of its highest profile missions, TechSat 21. The Air Force Research Laboratory (AFRL) developed TechSat 21 as an advanced technology demonstration of the capability described above. Ideally, the TechSat 21 constellation will evolve into an array of multi-purpose satellites capable of carrying out several different missions (e.g., communications, RF imaging, geolocation, GMTI, and terrain elevation mapping), dependent on their relative positions and orientation of the constellation.[4] The initial STP test of a three-satellite system will concentrate on mastering formation flying, giving the abbreviated constellation the ability to reconfigure from a navigation formation to a communications formation to a synthetic aperture reconnaissance formation.

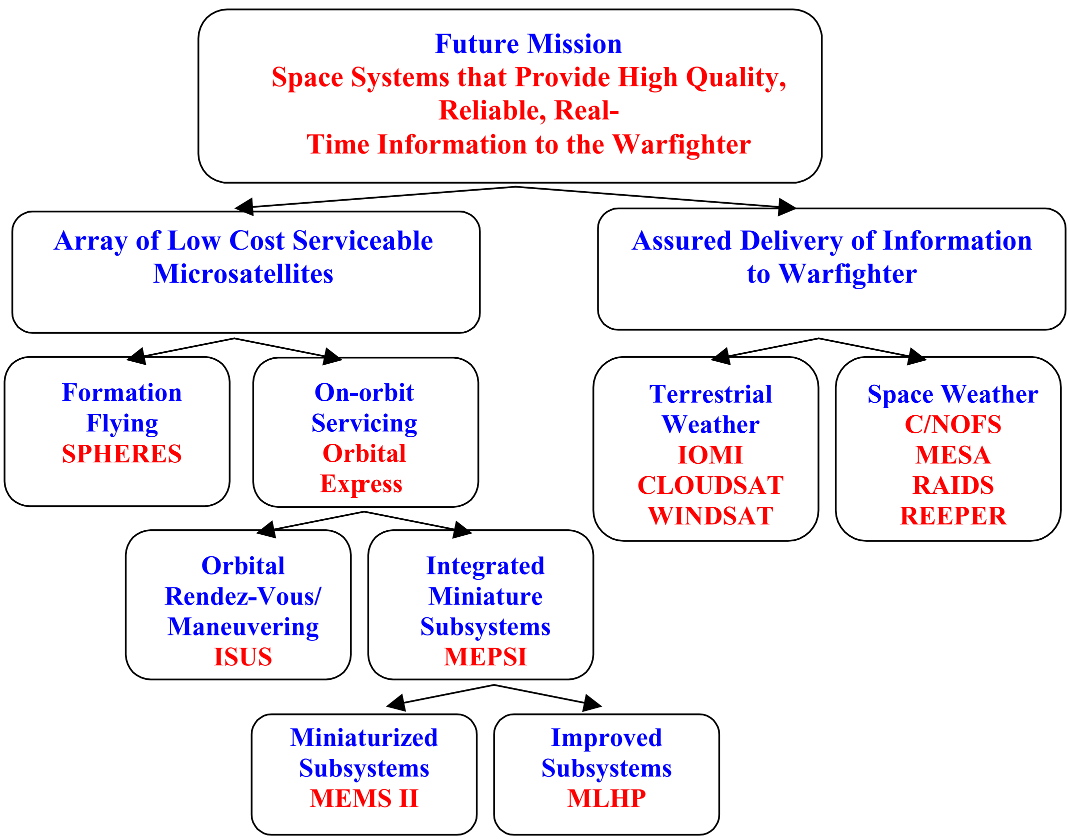

Figure 2: Roadmap of STP Experiments

TechSat 21 is clearly a technology leap capable of significantly benefiting our future US Space architecture, but hand-in-hand with such an ambitious experiment comes a corresponding high risk of failure. Fortunately, built into STP is an ability to mitigate risk by drawing on their extensive library of related experiments. These experiments have graduated levels of risk and return, but each represents a smaller technology step that contributes to the body of knowledge and experience that will make TechSat 21 a success. Figure 2 is the kind of roadmap STP uses to advance operational space systems towards their long-range vision.

The Rendez-Vous

Before deploying free-flying satellites that maneuver in formation and demonstrate how different relative positions can optimize them for different missions in TechSat 21, STP will fly SPHERES. SPHERES focuses only on the complicated problem of formation flying microsats in zero gravity. SPHERES satellites will float in the zero gravity environment of the International Space Station (ISS) and give astronauts the opportunity to carry out real time interactive experiments designed at optimizing the way satellites fly in and reconfigure their formations.[5] Astronauts and ground personnel will perform experiments to investigate autonomous formation control, precise position knowledge and timing synchronization, micro-propulsion, and how to best trade time or fuel when reconfiguring to carry out different missions. Using SPHERES, system developers will build a database of experience on how to best reconfigure a formation of satellites. TechSat 21 will benefit from SPHERES and other STP experiments designed to exploit formation flying (e.g., CLOUDSAT and NANOSAT) and lead eventually to a full constellation of operational LEO satellites with worldwide coverage.

Just as SPHERES will teach us the mechanics of formation flying a constellation of satellites in space, STP plans to fly one of the Defense Advanced Projects Agency's (DARPA) experiments, Orbital Express, to solve the other half of TechSat 21's problem. Orbital Express will demonstrate how two satellites can work together autonomously in an operational scenario.

Orbital Express will integrate miniaturized subsystems into a technology demonstration where a servicing satellite completes a rendez-vous with another spacecraft in an operational scenario.[6] Although DARPA has yet to choose the target mission, preliminary studies by three independent teams of contractors identified candidate missions for Orbital Express. They targeted their efforts at identifying the kind of mission that stands the most to gain from servicing companion satellites and came up with some interesting potential applications. Generally, however, their data suggests a servicing constellation, like Orbital Express, best supports missions that are highly complex and expensive, or involve many components. Likely candidates for the demonstration may therefore be a space-based radar or laser array.

The Orbital Express satellite will be a servicing vehicle, capable of refueling the satellites in a constellation, thereby removing the fuel constraint, which previously limited the constellation's ability to reconfigure. The constellation might then have the flexibility to alter its orbit to avoid threats for a specific time over target, to put perigee over target for improved resolution, or to put apogee over target for longer time on target. Furthermore, the servicing satellites could inspect, repair, or upgrade the constellation on orbit.

The problem of completing an active servicing of one spacecraft by another in an operational setting, however, is still a significant one. It is wise, therefore, to mitigate the risk further by first completing a more manageable experiment. Again, STP looks to its extensive database of experiments to identify one that focuses on a smaller part of Orbital Express's problem. They come up with ISUS.

The objective of the ISUS experiment is to demonstrate how its Solar Orbit Transfer Vehicle (SOTV) can rendez-vous with another satellite and significantly adjust its orbit. SOTV will be able to tow a spacecraft from a basing orbit to any orbit of interest from Low Earth Orbit (LEO) to Geosynchronous (GEO) orbit using an innovative solar propulsion system that uses concentrated sunlight to heat a propellant to high temperatures. SOTV's propulsion subsystem potentially delivers an I_{sp} of 800 seconds, nearly twice that of current upper stages.[7]

The Microsatellite

Before understanding how a constellation of microsatellites can work together to perform a single mission, or even understanding how one microsatellite can rendez-vous with another for servicing purposes, developers must thoroughly understand microsatellites themselves and the MEMs technologies that comprise them.

The largest impediment to getting highly capable systems into space is the high cost per pound to orbit. Rather than depend on a next generation of inexpensive launch vehicles that might offer engineers the luxury to make systems bigger, STP invests heavily in miniaturized spacecraft technologies that make subsystems and payloads smaller. DARPA's MicroElectroMechanical Systems for Space Applications II (MEMS II) and the joint DARPA/AFRL Microelectromechanical-Based Autonomous On-Orbit Satellite Inspection Experiment (MEPSI) are two STP experiments set to demonstrate that one need not sacrifice capability to decrease system size and weight.

More ambitious than MEMS II, MEPSI is a free-flyer experiment that demonstrates the capability to store a miniature (1kg) inspector satellite and release it upon command to conduct surveillance of the host vehicle for independent situational awareness.[8] MEPSI integrates MEM based subsystems (RF data transceiver, 3-axis inertial sensor, micro-propulsion, magnetometer, imager, range finder, data storage, health monitoring, processing, and power generation subsystems) into radical new low power, autonomous, space systems in support of critical satellite operations.

MEMS II, on the other hand, does not attempt to combine its subsystems into a package or test it in an operational scenario. It will fly on the ISS Express Rack, rather than as a free-flying satellite, and collect data on the performance of microgyro systems, microsensor arrays, micropropulsion subsystems, nanoscale RF resonators, and microcommunication and networking systems.[9] It is, therefore, an attractive candidate for STP to use as a building block to its more ambitious experiments.

MEMS II's objectives are tied directly to Space Command's Long Range Plan, which identifies three critical capabilities for protection of space assets where microtechnology can make significant contributions: (1) Distributed microsensor systems on spacecraft can be a key element in detecting and analyzing onboard anomolies as they occur. This knowledge is essential to the mitigation and rapid correction of threatening events. (2) The rapid reconstituting and/or repair of space assets can be accomplished with the aid of inspector or robotic nanosatellites hosted on larger spacecraft. (3) Finally, some missions (weather observation, nuclear detection) could potentially be rapidly reconstituted with minimal launch requirements by deploying constellations of kilogram class satellites.[3] MEMS II is designed to evaluate components that are essential to the eventual realization of these capabilities through space applications of microtechnology.

These microengineered ensembles of sensors and actuators, with their low cost, weight, volume and power, are poised to revolutionize military space missions of the future, enabling lower cost, more rapid development cycles, and the realization of new space architectures and missions. Once mature, this technology will create mass producible subminiature satellites and use them in distributed space-based systems, for communications, surveillance, and space control missions.

Part II – Delivering the Information

STP recognizes that even if engineers develop a next generation of space systems capable of collecting very high quality information, the systems are useless if they can't deliver the information to the user in a timely and reliable fashion. Therefore, STP will fly a series of experiments targeted at characterizing the near-earth space and atmospheric environment. This is the environment in which our space systems must exist and this is the environment through which our information must pass to get to the warfighter in the field.

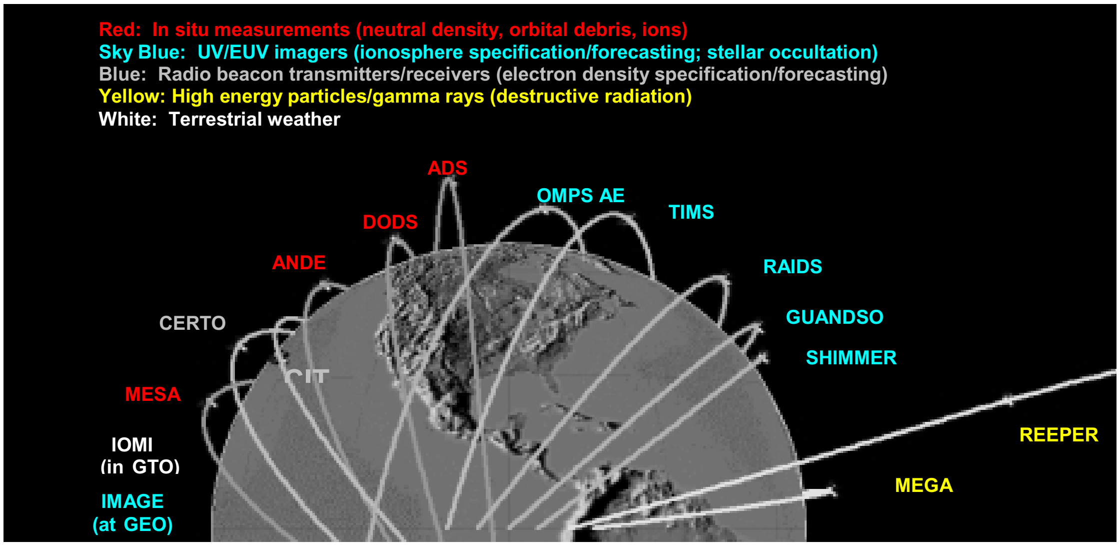

Figure 3: Orbits for Year 2000 STP Space and Terrestrial Weather Experiments[10]

Experiment	Domain	Phenomena	SWx Concept
IOMI	Troposphere	Surface Weather	Meteorology
CITRIS	Ionosphere	Electron density	NPOESS, SBIRS-LO piggy-back
CERTO*	Ionosphere	Electron density	NPOESS, SBIRS-LO piggy-back
TIMS	Ionosphere	e^-/Ion/neutral	NPOESS
RAIDS	Ionosphere	e^-/Ion/neutral	NPOESS
IMAGE	Ionosphere	e^-/ Ion	GEO, HEO
SHIMMER	Ionosphere	OH density	NPOESS
OMPS AE	Ionosphere	Ozone Mapper	Improved models
MESA	Ionosphere	Scintillation	Improved models
GUANDSO	Thermosphere	Neutral density	Improved models
ADS	Thermosphere	Neutral density	Improved models
ANDE	Thermosphere	Neutral density	Improved models
DODS	Thermosphere	Orbital Debris	Improved models
MEGA	Magnetosphere	Gamma ray flux	Improved models
REEPER	Magnetosphere	Particle fluxes	Improved models/
*Piggy-back on many Satellites			

Figure 4: Purpose of Year 2000 Space and Terrestrial Weather Experiments[10]

Space Weather

Historically, some of the most significant contributions from STP have come in the arena of space weather. The current STP experiments are no exception. "Space Weather refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power distribution grids, leading to a variety of socio-economic losses."[11] Figure 3 summarizes current year STP experiments geared towards tackling space weather challenges and the accompanying chart (Figure 4) identifies the phenomena each will study and the operational tool or system to which it will contribute.

As we move into an era when military operations are characterized by precise interaction among complementary assets, reliable communication emerges as an essential element of success. Two of STP's efforts, C/NOFS and MESA, attempt to develop a capability to forecast impending communication disturbances, much as we currently forecast adverse weather.

These disturbances are caused by the poorly understood phenomenon of scintillation. Scintillation is a local disturbance of the Ionosphere that results from an instability as it "relaxes" from daytime active levels. It is difficult to predict when or where scintillation will occur, but once detected, it is fairly easy to track and to project areas it will impact. It is analogous to following a terrestrial severe-weather front.

The effect of scintillation is significant. Disturbances in the Ionosphere degrade or prevent transmissions, particularly in HF, UHF, and L-band, for limited periods. Therefore, during periods when scintillation is strong, operators cannot communicate on HF or UHF, surveillance radars cannot detect and track targets, emitters cannot be located accurately, and GPS receivers can potentially lose their signal.[12]

For each of these informational disturbances, there is an operational work around. Experienced communications personnel can change frequency or data rate (EHF, SHF, X- and K-bands not affected), change satellite relay (look for a gap in scintillation bands), delay sending messages for a few hours, or employ redundant navigation systems. However, without the ability to forecast periods of scintillation, operators cannot determine when to implement work-around procedures. Ideally, C/NOFS and MESA will lead to an operational planning tool, much like a weather forecast, that tells planners the best time to complete a military operation.

Terrestrial Weather

Atmospheric effects disrupt the operator's ability to deliver information even more frequently than ionospheric effects do. Although the US currently has a formidable constellation of assets dedicated to predicting potentially harmful atmospheric effects, coverage gaps exist over some of the most historically volatile regions that could potentially make military forces vulnerable in future conflicts. Because of IOMI's dual role as both an experiment and an operational system devoted to covering one such gap, it is STP's highest priority mission for 2000. IOMI will not only serve as a flight test for a revolutionary small, lightweight, high spectral resolution, infrared Fourier Transform spectrometer and visible imager, but it will take on an operational mission once its scientific mission is complete. From its geosynchronous position, parked above the Indian Ocean, Naval forces will use its temperature, water vapor, and CO_2 and O_2 profiles for weather nowcasting, ship routing, projection of in-route winds, and potential avoidance of nuclear, chemical, and biological weapons.[13] Operational forces will benefit from this STP payload almost immediately after its launch.

IOMI is essential to filling a gap in current weather forecasting capabilities, but WindSat is essential in developing the next generation of space-based weather systems. The National Polar-orbiting Operational Environmental Satellite System (NPOESS) merges Department of Defense (DoD) and Department of Commerce (DOC) meteorological satellite systems into a single national asset. NPOESS will provide national, operational, polar-orbiting, environmental remote sensing. WindSat will contribute by transitioning passive microwave polarimetric radiometry technology for use in the development and production of the NPOESS Conical Microwave Imager and Sounder (CMIS).[14]

Finally, STP will launch CloudSat as part of NASA's Earth System Science Pathfinder (ESSP) program. CloudSat is a mission dedicated to studying the effects of clouds on climate and weather. It will use a millimeter-wavelength radar and an infrared spectrometer to measure the altitude and properties of clouds.[15] This new information will provide the first global measurements of cloud properties to help scientists compile a database of cloud measurements to improve how clouds are represented in global climate and numerical weather prediction models.

Conclusion

US Space Command has the unenviable task of attempting to plan for a future that is uncertain. As planners and developers remain focused on their goal of supplying the warfighter with the tools and information they need to remain effective on tomorrow's battlefield, long space system acquisition cycles complicate the planning task. Acquisition cycles span changing administrations, with the associated variable funding constraints, and counter the efforts of planners to react to the changing needs of their customer -- the warfighter.

Testing is a key component of the acquisition cycle. The experiments STP flies have the potential to significantly impact the complexion of future US operational space systems. These experiments represent Space Command's developmental tests of the technologies in which they plan to invest and the data from the experiments can mean the difference between investing in the next great success story, as it was in the case of GPS, or wasting limited funds on a system doomed to failure. STP mitigates the risk inherent to acquiring new space systems in much the same way current developmental test organizations mitigate the risk associated with new aircraft acquisitions.

The experiments STP plans to fly in the next five years have direct ties to the operational systems that will follow. They will supply the warfighter with information to remain situationally aware and ready to react with precision on short notice. In twenty years, the US Space Force will have the luxury of calling upon systems of unprecedented capability in their time of need and, if the warfighter of tomorrow takes time to reflect upon who brought US Space into the future, he will discover it is the current members of the Space Test Program that deserve his gratitude.

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