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Pulling the Pieces Together at AFRL

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Pulling the Pieces Together at AFRL – Space Vehicles Directorate

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ABSTRACT

The Air Force Research Laboratory (AFRL) is chartered with developing innovative science and technologies to meet the future national security needs of the United States. To this end AFRL is aggressively pursuing the development of Responsive Space enabling technologies.

The Space Vehicles Directorate (AFRL/VS) has made Responsive Space one of its six core thrusts. The objective of the Responsive Space thrust is to develop and demonstrate the technologies that will enable spacecraft with the following attributes:

- Operational within six days of call-up
- Low-cost (<$30M mission costs, including spacecraft, launch and operations)
- Small (Total mass <500 kg)
- Satellite payloads are taskable by theater commanders/forces with direct downlink/ data dissemination into theater assets
- Tasking/data dissemination utilizing existing warfighting equipment & architectures
- Missions tailored for a specific theater
- Rapid, low-cost integration of new technologies and payloads

In order to realize these objectives, AFRL is investing in a robust portfolio of science and technology. These technologies feed into a series of operational experiments with ground-based and space-based test beds. The portfolio direction and progress is continuously assessed and analyzed with extensive modeling and simulation analysis.

Through these focused efforts AFRL is making great progress in achieving this transformational vision. The coming years will bring many more exciting advances.

A VISION FOR THE FUTURE

Given the US military's growing dependence on space-based capabilities and the increasing potential for adversaries to negate these advantages, the joint warfighter must have more flexibility to rapidly augment and/or reconstitute critical space capabilities. In 2001, the Rumsfeld Space Commission recognized this threat to our current space posture by warning:

> *An attack on elements of U.S. space systems during a crisis or conflict should not be considered an improbable act. If the U.S. is to avoid a "Space Pearl Harbor" it needs to take seriously the possibility of an attack on U.S. space systems. The nation's leaders must assure that the vulnerability of the United States is reduced and that the consequences of a surprise attack on U.S. space assets are limited in their effects. [Rumsfeld, 2001].*

The January 2005 U.S. Space Transportation Policy goal is to "ensure the capability to access and use space in support of national and homeland security, civil, scientific, and economic interests." To achieve this goal, the United States Government shall "demonstrate an initial capability for operationally responsive access to and use of space--providing capacity to respond to unexpected loss or degradation of selected capabilities, and/or to provide timely availability of tailored or new capabilities--to support national security requirements." The policy directs "Before 2010, the United States shall demonstrate an initial capability for operationally responsive access to and use of space to support national security requirements."

OSD Space S&T Vector-2

The Department of Defense (DoD) has responded to this challenge by instituting four of DOD-wide Space Science and Technology plans.

These plans, called the *OSD Space Science and Technology (S&T) Vectors*, lay out the strategy for science and technology investments across the DOD necessary to achieve these goals. OSD Space S&T Vector-2, titled "Operationally Responsive, Low-Cost Satellite and Launch Capability", defines end state goals for 2010 as follows:

<u>Satellites</u>

- Spacecraft recurring cost < $20M
- Less than one year development time
- Enable rapid integration of new technologies and payloads (i.e Plug-n-Play capable)
- Payload mass three-times bus mass
- Militarily significant payloads
- Designed for ~ one year mission life

<u>Launch</u>

- Launch from call-up < six days
- Launch costs < $10M

<u>Checkout, Ops, Theater Integration</u>

- On-orbit check-out < four hours
- Theater & global tasking/data dissemination
- Lean ops (i.e., < four people)

FLTC-7 On-Demand Theater Force Projection, Anywhere

These objectives have been captured and extended out to the year 2025 in AFRL's new strategic planning process called Future Long Term Challenges (FLTC's). Eight major FLTC's have been defined across AFRL's ten technical directorates. One of these, FLTC-7 "On-Demand Theater Force Projection Anywhere", includes the OSD Space S&T Vector-2 end state goals for 2010, but also defines end-state goals through 2025. These longer term goals include the further miniaturization of space capabilities that lead to autonomously operating clusters of spacecraft that can reconfigure and morph their capabilities on-orbit. In addition FLTC-7 lays out an S&T Strategy that will someday enable satellites to be rapidly "printed"; further shortening the call-up time and increasing the spacecraft design and flexibility.

SCIENCE & TECHNOLOGY GAPS

In 2003 the US Air Force conducted the Responsive Space Lift Analysis of Alternatives. This study examined a variety of alternative methods to rapidly augment or reconstitute space capabilities. These alternatives included (1) Storage of fully integrated spacecraft on the ground combined with responsive space launch, (2) On-orbit storage of spare spacecraft, and (3) On-orbit storage of spare spacecraft combined with on-orbit servicing for life extension or component replacement. The most cost-effective alternative was found to be storage of spacecraft on the ground combined with a responsive launch capability. However, two problems plagued these study results. In the current environment it often takes decades to develop a new space capability and the rapid pace of modern warfighting combined with the rapid rate of technology progression can quickly make a spacecraft obsolete.

At the same time the Office of Force Transformation, lead by Admiral Arthur Cebrowski (ret.) was advocating development of Tactical Satellites. These small, low-cost satellites would be rapidly developed and launched into orbit where they would be directly tasked by the theater warfighter. They would provide timely information directly into the theater of operation. The role of TacSats in operational experimentation supports Admiral Cebrowski's ideals for Operationally Responsive Space (ORS) as stated to the Senate Armed Forces Committee in March 2004:
"At its (ORS) core are (1) the defining of a joint military demand function and (2) the focus on providing joint military capabilities for our operational and tactical level commanders". [Cebrowski, 2004].

To find a technical solution that would enable this vision the Air Force Research Laboratory conducted the Responsive Space Advanced Technology Study (RSATS). This study sought technologies that would enable responsive reconstitution and augmentation of space capabilities and direct support to the tactical warfighter while allowing rapid integration of new technologies and capabilities in a cost-effective manner. This study determined that Plug and Play (PnP) technologies such as Universal Serial Bus (USB), SpaceWire, Firewire, and Ethernet that were developed and widely used by the Information Technology sector could be readily adapted for use in spacecraft. It was hypothesized that this "internet-like" data-bus architecture could provide a low-cost method to rapidly design, integrate, test, launch, and operate a new space capability.

The RSAT Study identified four sets of technologies that must be developed:

- Communications systems that allow tactical tasking and data dissemination
- Miniaturized spacecraft components and payloads (power, propulsion, GN&C, TT&C, and deployable structures/apertures)
- Rapid deployment tools (mission planning tools, rapid assembly and test, and autonomous checkout and operations)
- A modular, plug-n-play spacecraft architecture and components to fit this architecture

S&T PORTFOLIO

AFRL researchers determined the first step in creating a responsive space capability would be to establish a PnP avionics architecture. This framework would form the basis of a rapidly constructible spacecraft system. This framework would then be extensible to accommodate the classic subsystems of a spacecraft (i.e., structural, thermal, power, processing, attitude control, communications), as well as its payload. The tenets of this framework are deceptively simple. They include the concepts of component self-description (through embedded electronic datasheets), self-organization (that is automatic recognition of component-services by the system at large), robustness (dynamical reconstitution of components), and fully exposed testability. This architecture would allow compliant components to connect to a switch-fabric network, analogous to the internet, as suggested in Figure 1. In a manner analogous to the peripherals of a personal computer, new devices could easily be integrated into a spacecraft, allowing rapid tailoring of the spacecraft capabilities prior to launch or rapid, low-cost integration of new technology. In fact, the spacecraft is essentially *defined* by the combination of its component-services. Software applications can easily be developed as aggregations of the simple transactions made available through this PnP mechanism.

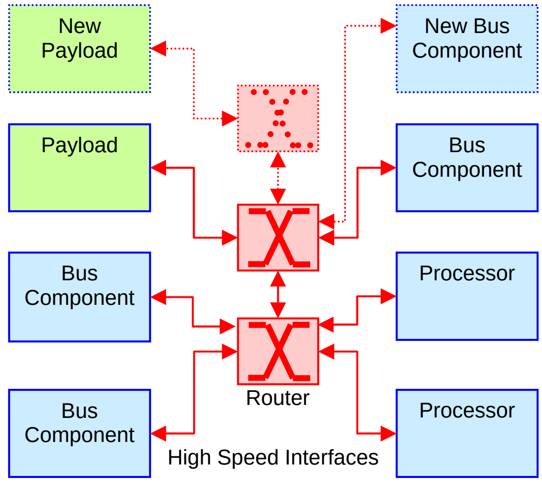

Figure 1: Plug-n-Play Avionics Architecture

PnP Avionics

In late 2004 AFRL received approval for a committee on standards (CoS) by the American Institute for Aeronautics and Astronautics (AIAA), a US national level standards development organization. This CoS included representatives from government, industry, and academia. The working group developed a series of standards, christened "Spacecraft Plug-n-Play Avionics" (SPA) to describe a spacecraft architecture based on standard interfaces to connect modular components or subsystems. These standards are based on commonly used standards in the Information Technology (IT) industry. The standards have initially focussed on interface definitions for low-data-rate components, "SPA-U" (based on USB 1.1 standard), and high -data-rate components SPA-S (based on the European Spacewire standard).

Provisions for other SPA-*x* standards can be readily made, so long as certain principles are followed. ASPA guidebook is in preparation to assist in the definition of future SPA standards. Any SPA standard, for example, must support data transport, power delivery, time synchronization, single point ground connection, and mimimal "hooks" for self-description. While they are excellent standards for data transport, neither USB nor Spacewire provide all of these features. To make them into SPA standards, the CoS focused on minimally-invasive approaches. The CoS tended to overlay features as opposed to modifying the inner workings of proven standards. Instead, sensible extensions were proposed:

- Connectors with enhanced robustness
- The addition of a separate 28V power delivery
- Use of a distinguished single point ground conductor
- Addition of a one pulse per second (1PPS) signal for system-wide time synchronization
- Provision for an electronic datasheet
- The optional inclusion of a special test bypass interface to support test/debug and hardware-in-the-loop integration

Ultimately these standards allow a spacecraft avionics architecture with distributed computer processors and sensors connected as shown in Figure 2.

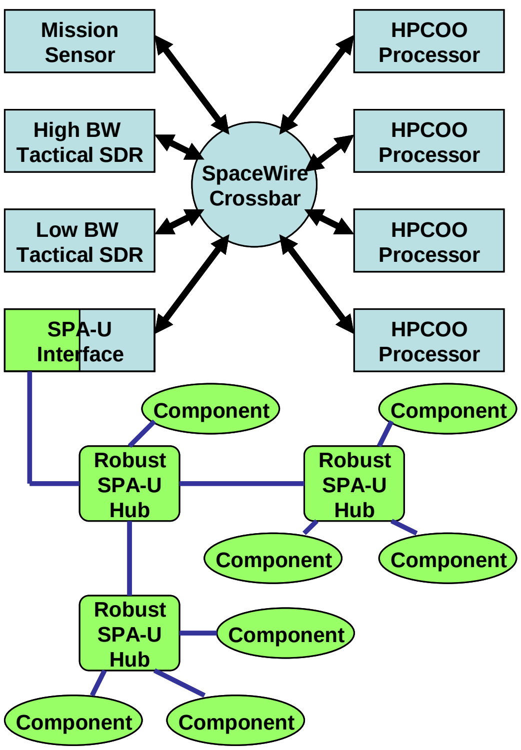

Figure 2: Distributed Avionics Architecture Based on Plug-n-Play Standards

To accelerate implementing this PnP architecture, an interface module was defined for existing spacecraft components. These interface modules are called Applique Sensor Interface Modules (ASIMs). This evokes a "peel-and-stick" paradigm; permitting legacy devices to rapidly integrate into a PnP network. In essence, the ASIM is a smart interface chip (or multichip module). They are analogous to a USB interface chip in a personal computer. Just as USB chips permit the rapid integration of a mouse or keyboard into a personal computer, the ASIM permits ordinary legacy spacecraft components (such as a reaction wheel, thermometer, or camera) to be rapidly integrated into a spacecraft vehicle. The ASIM electronically stores specific information about the device (using XML) in a small nonvolatile memory. This information becomes an XML Transducer Electronic Data-sheet (or xTEDS). The ASIM passes xTEDS information to the spacecraft system upon request as devices are plugged into the network. For example, a component might state in effect facts such as "I am a reaction wheel" or "I have these mass properties…" or "I need 10W power in *x* mode" etc… These primitive pieces of information constitute an "ontology" or vocabulary, and the whole of the responsive spacecraft is based on compositions drawn from the transactions possible with this ontology. In other words, this enables software applications to be "PnP aware".

SPA-U networks are composed of hosts, hubs, and endpoints, each supporting the SPA-U standard. Endpoints are implemented within the ASIMs, and the network has one or more SPA-U hosts. The networks are expanded through the use of hubs. SPA-U hubs are called "robust" because they are capable of dynamically re-orienting upstream (to host) and downstream (to endpoint) connections, based on disruptions to network topology. The SPA-U hubs are also devices, as they contain a single ASIM. In addition to managing the USB data transport connections, robust hubs also distribute power and synchronization signals.

PnP Software and the Satellite Data Model

To utilize the information that is available in this "internet-like" architecture, an intelligent PnP software architecture was developed. The *Satellite Data Model* (SDM) is a side-ware (the term side-ware highlights the SDM support in the discovery and data organization processes but does not burden data messages as middle-ware often does) providing the ability for components to share data and resources without being first programmed to know the physical parameters of the other components. The SDM does this by exploiting the xTEDS of networked SPA components. SDM allows components to register their own xTEDS, to post their data on the network, to read data from other SPA components, and to post data requests to the network to be carried out by other components on the network.

In December 2005, all of these technologies were combined together in the first ever demonstration of a modular, PnP spacecraft architecture in AFRL's Responsive Space Testbed. This ground-based demonstration proved that a PnP spacecraft architecture was feasible.

Responsive Space Test-bed (RST)

In 2005, AFRL/VS built a dedicated laboratory to develop and demonstrate the technologies necessary for a six-day call-up spacecraft. This *Responsive Space Test-bed* is divided into three experimental "cells" capable of supporting a number of simultaneous projects:

- Responsive Satellite Cell
- Responsive Technology Cell
- Flat-Sat Cell

Figure 3: Demonstrator Bus in the Responsive Satellite Cell

The *Responsive Satellite Cell* combines together all of the technologies necessary to demonstrate in real-time the chain of events from call-up of a new spacecraft capability to launch. This includes a spacecraft software design tool referred to as the *Satellite Design Tool* (SDT), a first-generation PnP satellite bus (demonstrator bus), a self-organizing ground control station, a six degree-of-freedom spacecraft dynamics simulator (including an orbit propagator), and a hardware-in-the-loop system (HWILS). The HWILS integrates into the test bypass interface connections on SPA-U components. The SDT, although still in development, demonstrates the concept of "satellite design automation". It implements rapid satellite design as a push-button tool flow; guiding the user to specify the critical characteristics of a spacecraft mission. SDT uses high-level "software wizards" to effectively capture the mission specifications in a process referred to as "mission capture". From these simple inputs, SDT analyzes and helps the user develop the specification of a suitable spacecraft orbit. This basic information leads directly to a number of critical parameters, including available spacecraft mass, the power profile available in that orbit, radiation environmental data, etc. Other expert wizards provide a rapid and interactive generation of a "buildable" spacecraft design based on available (and rapidly acquirable) PnP components. Following this step, SDT then generates a bill of materials, a set of configuration files/links, and other useful information, such as a set of assembly instructions for the spacecraft.

The first generation demonstrator bus is made of machined aluminum ortho-grid panels. Distributed throughout the panels are prefabricated wiring harness sections that connect up to forty eight PnP (e.g. SPA-U) ports. The user can simply install components on the demonstrator bus in the locations prescribed by the SDT assembly instructions. The user can also relocate components if feasible alternatives or changes are required.

Figure 4: Satellite Design Toolkit and Satellite Ground Control Station

During the process of live assembly, as the user installs SPA-U components on the demonstrator bus, the spacecraft software (powered by SDM sideware, presently running on a real-time Linux kernel) reads the xTEDS information. A specially defined telemetry downlink application passes the xTEDS to ground control software. From *only* the xTEDS, the ground console interfaces are dynamically created as a by-product of the spacecraft assembly process. Presently, this automatically generated ground console is layered onto a commercial system, adapted from the software used in the Tacsat 2 mission. The spacecraft can then be flown in simulation through SDT's six-DOF flight simulator. Signals from the simulator are tightly coupled to the HWILS, providing an effective means of test and debug of the entire spacecraft. The test-bed currently runs preliminary versions of the associated software, and parts of the basic framework are still in development. Over time, this capability will be expanded and enhanced to permit higher-speed component connections, hierarchical console generation, and in principle the ability to single step the spacecraft through a time sequence of events.

The *Responsive Technology Cell* allows new PnP technologies to be explored. This cell is where the basic mechanisms of the PnP infrastructure are cultivated before they are transferred into the Responsive Satellite Cell. For example, in 2006 the Responsive Technology Cell will include a demonstration of an Adaptive Wiring Manifold (AWM) that could eliminate the need to create custom spacecraft wiring harnesses. A PnP thermal management experiment and PnP power system will also be built in this test cell in 2006. In the future, this cell could be used to explore multi-gigabit, ultra-low power, and wireless spacecraft architectures.

The *Flat-Sat Cell* is a cleanroom laboratory where spacecraft flight hardware can be checked out and integrated into a spacecraft Engineering Unit prior to integration on the actual flight spacecraft. This permits the high-TRL (technology readiness level) implementations of SPA and related technologies to be developed and integrated. All three of the RST test-bed cells are interconnected and can share the common laboratory facilities such as the six-degree of freedom flight simulator and HWILS. This interconnection will allow spacecraft components to be integrated into the Flat-Sat Cell and then flown through a virtual spacecraft mission prior to final integration. Ultimately the Flat-Sat Cell will be utilized for checkout and integration of the TacSat-3 spacecraft and future TacSat spacecraft.

Extending Plug-n-Play

In 2006 the Space Vehicles directorate is expanding its focus on plug-n-play modularity from the avionics and software backbones to encompass the development of structural technologies that will enable rapid assembly of a spacecraft structure. This focus includes technologies that will allow a spacecraft structure to be easily integrated together and thermal technologies that will enable a modular, plug-n-play approach to the management of thermal energy generated on the spacecraft. Researchers are also working on techniques for dynamic, rapid mass balancing of the spacecraft.

AFRL/VS is collaborating with spacecraft component suppliers to develop spacecraft Plug-n-Play spacecraft components that are more mass, volume, and power efficient. In 2006, AFRL/VS awarded more than $17M in Small Business Innovative Research (SBIR) contracts for development a number of commodity spacecraft components, including star trackers, reaction wheels, Inertial Measurement Units (IMU's), Thin Film Solar Arrays, Electric Hall-Effect Thrusters, and simple scalar instruments. These components are being developed to fit into the SPA architecture and to provide increased spacecraft capability in a small satellite. In time, a growing PnP catalog will be created, in which a "SPA inside" logo might suggest a "universe" of freely interchangeable and interoperable PnP elements, from which entire systems can be constructed.

In 2006 AFRL/VS will continue to develop spacecraft autonomous systems that will enable rapid integration and test, short on-orbit checkout times, and lean spacecraft operations. The ultimate goal is to develop a "lights-out ground operations and to perform on-orbit operations autonomously. This will enable the spacecraft to respond to evolving contingencies or scenarios where reliance on the ground would be detrimental to mission success. Satellites of the future must be capable of detecting and mitigating anomalous events or reacting to trigger conditions by having an inherent ability to plan and subsequently reconfigure themselves, or in certain cases alter mission objectives. AFRL/VS is investing in the technologies necessary to achieve this goal. This includes autonomous fault detection, isolation, and resolution, on-board data processing and sensor re-tasking, optimized mission and data downlink planning, and collaborative decision making across multiple spacecraft

OPERATIONAL EXPERIMENTATION

During his time as head of the Office of Force Transformation Admiral Cebrowski was an early proponent of the use of Operational Experimentation to develop transformational warfighting capabilities. In keeping with this vision the Space Vehicles directorate in collaboration with other DOD Partners (DARPA, AFSPC, SMC, ONR, NRL, OFT, USSTRATCOM, et al.) has embarked on an aggressive series of Tactical Satellite (or TacSat) experiments. The goal of these experiments is to mature and focus the S&T Investments and allow operator feedback into the S&T process.

TacSat-2

TacSat-2 is the first TacSat experiment conducted by AFRL/VS. This ~390 kg spacecraft will carry into a Low Earth Orbit (LEO) a Specific Emitter Identification (SEI) Payload developed by the Naval Research Laboratory and a visible imager that will provide approximately one meter resolution panchromatic, and three-color imagery. TacSat-2 will enable tactical tasking and data dissemination through the use of an onboard Common Data Link (CDL) radio. This 274 Mbps link will enable the spacecraft to communicate with existing US Army MIST (Modular Interoperable Surface Terminal) ground stations. TacSat-2 will allow the user to experiment with rapid tasking of the SEI and imager payloads and downlink of the requested data in the same orbit pass.

Figure 5: TacSat-2 Spacecraft

TacSat-2 also includes spacecraft autonomy experiments and an experimental on-board scheduling system. The On-Orbit Checkout Experiment (OOCE) will experiment with an autonomous, four-hour on-orbit checkout algorithm. TacSat-2 also includes an Autonomous Tasking Experiment (ATE) that will allow the spacecraft to accept high level taskings to image targets. It will also allow the spacecraft to autonomously generate and execute the sequence of activities necessary to achieve those objectives..

TacSat-2 is nearing completion. The integration and test phase of TacSat-2 is scheduled to be completed on 30 June 2006. At that time the spacecraft will be placed into storage until Spring 2007 when the launch vehicle is ready for the spacecraft integration. During the launch campaign the team will conduct a Rapid Call-Up Experiment. The goal of this experiment will be to document the spacecraft launch campaign and determine the steps necessary to conduct a six-day launch campaign.

TacSat-3

The TacSat-3 Program was initiated at AFRL/VS in October 2005. This spacecraft consist of a first generation, low-cost, modular bus (developed with funding from the Office of Force Transformation), a low-cost Hyperspectral Imager developed by AFRL/VS, and a data exfiltration payload provided by the Office of Naval Research. TacSat-3 will provide the tactical warfighter the opportunity to experiment with direct tasking and data downlink of a hyperspectral sensor.

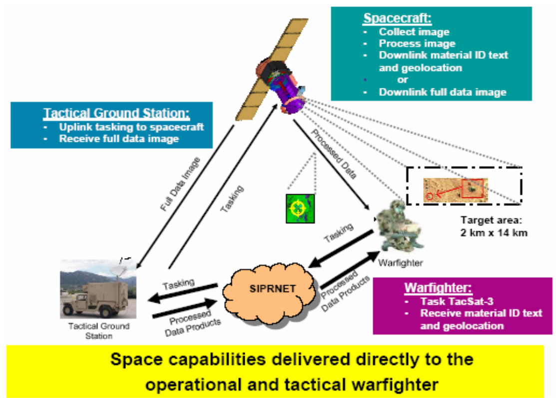

Figure 6: TacSat-3 Will Experiment with Tactical Tasking and Data Downlink of a Hyperspectral Sensor

The TacSat-3 Hyperspectral sensor includes a co-aligned panchromatic imager and an onboard processor. This combination will enable the tactical user to request a hyperspectral analysis of a given region for specific objects. The imager will collect the full hyperspectral data cube of the region plus a panchromatic image of the area. The on-board processor will analyze the region for objects of interest and will then geo-rectify the location of these objects with the panchromatic image. The tactical user will then be provided with a panchromatic image of the region with icons on the image that represent locations of the objects of interest.

The TacSat-3 spacecraft carry a second generation CDL radio. This will enable tasking of the spacecraft from a tactical theater and dissemination of the spacecraft directly to the tactical theater. The spacecraft will have a parallel CONUS-based tasking and data dissemination ability. This will allow the user to experiment with multiple methods for tasking the spacecraft and downloading the collected data.

Design constraints established for the TacSat-3 program include a total program cost less than $50M. This includes the spacecraft, launch, and one year of operations. The spacecraft must mass less than 400 kilograms so that it can be launched on a low cost, responsive, launch vehicle. The program goal is a build time for payload and modular bus of less than 18 months. TacSat-3 is currently scheduled for launch Fall 2007. [Davis, 2006]

MODELING SIMULATION AND ANALYSIS

On-orbit experimentation is often a critical step to transition new technologies into operational systems. However, these technologies will not survive the DoD Acquisition process if they do not provide a cost-effective military benefit. Military benefit must be illustrated beyond the specific system's technical contributions. It must be evaluated in terms of the synergy the system engenders across multiple mission areas and its contributions across a full range of military operations. When this is accomplished, decision makers can make better informed and more effective technology investment decisions.

AFRL/VS has developed a technology focused Modeling Simulation and Anlysis (MS&A) capability to provide an initial assessment of a new technologies potential military benefit. This MS&A begins with the physics and engineering levels models and carries them through a system design and into a mission or campaign level analysis. This requires putting the technology or system into a simulated operational context, developing modes of employment, and evaluating the performance over an appropriate range of mission scenarios or vignettes.

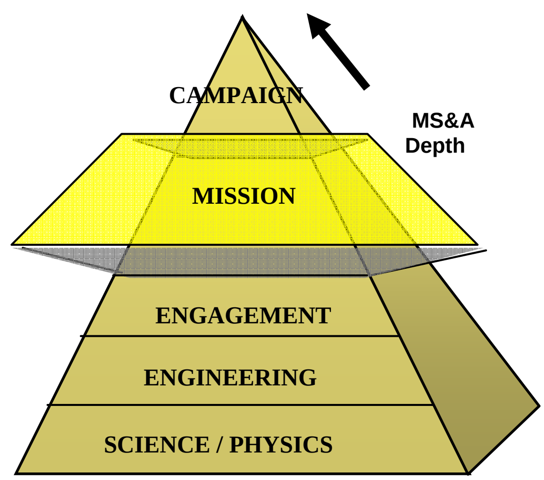

Figure 7: Modeling, Simulation and Analysis (MS&A) Framework

The goal at the engineering level is to model technology performance of components and integrated systems and to conduct technology trades. These trades feed back into technology development programs as research and development requirements. They also help guide the development of future operational experiments as mission capabilities that should be tested.

Recent MS&A efforts include an analysis of the TacSat series of Operationally Responsive Space (ORS) experimentation satellites. AFRL/VS assessed the utility of TacSat-2 and TacSat-3 payloads using modeling, simulation, and analysis (MS&A) techniques at the engineering, engagement, and mission levels. The results of these studies addressed the utility of the experimental spacecraft, as well as the potential performance benefit of an "objective system" that would fly an advanced version of these technologies.

This analysis showed that Tactical Satellites can provide useful and timely information to the warfighter in certain scenarios. The unpredictability of overflight time, combined with the capabilities of new and innovative sensors, were shown to effectively counter current enemy CC&D measures. Once operational these TacSats should become a key instrument of ISR collection and dissemination. This will present field commanders with a significant advantage [Murphey, 2006].

AFRL/VS is currently conducting a mission level analysis of a TacSat spacecraft that operates in a theater inclined, Highly Elliptical Orbit (HEO) with a UHF communications transponder payload. This is similar to operational experiment currently being conducted by the Naval Research Laboratory's TacSat-4 spacecraft. This analysis will assess the potential warfighting benefit of this capability. This study will be completed in mid-2006.

CONCLUSION

The Air Force Research Laboratory (AFRL) is chartered with developing new science and technologies to meet the future national security needs of the United States. The US has determined that assured access to space is critical to it's future national security. To that end the January 2005 U.S. Space Policy Directive states "Before 2010, the United States shall demonstrate an initial capability for operationally responsive access to and use of space to support national security requirements." In concert with the larger DoD Space Enterprise, AFRL has developed an innovative and aggressive vision for the future. This vision will provide the Tactical warfighter with a space-craft that can be rapidly tailored with new technologies to meet specific mission requirements, placed into orbit in less than six days, tasked directly from a tactical theater, and that can provide information directly back into the tactical theater.

To achieve this vision AFRL is aggressively pursuing the development of responsive space technologies and spacecraft. This includes a robust portfolio of Plug-n-Play hardware and software technologies, spacecraft components with increased performance that are smaller, lighter weight, and less costly. These technology developments feed into a series of operational experiments on ground-based and space-based test beds. The portfolio direction and progress is continuously analyzed with extensive modeling and simulation analysis.

Through these focused efforts AFRL is making great progress in achieving this transformational vision. The coming years will bring many more exciting advances.

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