

Roadrunner, a High-Performance Responsive Space Mission

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Abstract: The Roadrunner mission is being conducted by the Air Force Research Laboratory (AFRL) to demonstrate techniques and methodologies to dramatically shorten the development time required for small satellites. The Roadrunner program will demonstrate a 14-month development time from inception to launch readiness, a one-week time from call up to on-orbit readiness, and a 24-hour autonomous on-orbit commissioning. Roadrunner will accomplish these impressive schedule milestones while fielding a suite of experiments centered around a new optical imager capable of sub 1 meter resolution and nearly a dozen complimentary payloads. To accomplish this mission, the Roadrunner spacecraft is built on a bus supplied by Microsat Systems whose original design was qualified for the TechSat-21 program. To meet the tight schedule, Roadrunner makes use of existing designs and hardware from other programs to the maximum extent possible. Additionally, the fully concurrent development of payloads and bus has imposed a “capabilities-driven” approach to design. In this paradigm, interfaces and functionality are determined as a consequence of the capabilities of the existing hardware or designs rather than being specified as a result of requirements derived from basic mission objectives. In this non-traditional approach, the mission experiment plan is being derived as an answer to the question, “What can we do with what we have?”

Introduction



Figure 1 – Roadrunner Mission Patch

Roadrunner is the first AFRL mission to directly address the current Responsive Space efforts, which are aimed at drastically lowering the time to place space assets in theater. The primary objective of the Roadrunner (a.k.a. TACSAT II) mission is to demonstrate the rapid development and rapid deployment of a militarily useful tactical asset. The Roadrunner spacecraft carries a suite of 10 payloads from different organizations and will fly in a 350 km sun synchronous orbit at 10:30 node crossing for optimum imaging. MicroSat Systems, Inc. (MSI) is supplying the spacecraft bus including structure, Attitude Determination and Control Subsystem (ADCS), thermal control and some power components. MSI is also supplying bus systems engineering and assembly, integration and test services.

One of the enablers of this rapid development is the off-the-shelf availability of an MSI bus design from TechSat-21, which was suitable for this mission with fairly minor modifications. The program was also designed to utilize crucial spare flight hardware available from TechSat-21 and MSTI 4. These aspects, combined with rapid payload development efforts are allowing the Roadrunner team to produce an extremely capable system comprising ten payloads at an exceptional pace.

Objectives

To accomplish Roadrunner's primary mission objective, the task is broken into several specific, major objectives as follows:

1. Develop a space vehicle from concept baseline to launch readiness in under 14 months.
2. Deploy a space vehicle from storage to full on-orbit functionality in 7 days including autonomous on-orbit commissioning in under 24 hours.
3. Demonstrate in-field tactical communication, command and control of a satellite.
4. Image targets in the visible wavelengths at a "tactically significant" resolution under 1 m GSD.
5. Geolocate Radio Frequency (RF) targets and image them in the same pass.
6. Demonstrate several additional advanced technology concepts.

Design Approach

These objectives were the basis of the Level 1 and 2 requirements for the mission. From these, the spacecraft (level 3) and subsystem (level 4) requirements were derived. For MSI, these requirements totaled just over

100 items on Roadrunner. For comparison, the TechSat-21 requirements encompassed 2000 items. Reducing requirement count was deliberate step by the Roadrunner team to concentrate efforts on delivering a final product as rapidly as possible while keeping the focus squarely on the most critical elements.

It is also important to note that these basic requirements deliberately do not specify particular spacecraft functional specifications, but rather operational goals. This leaves a great amount of flexibility in the hands of the systems engineering team and the science and operations team to decide how to meet the operational goals with the system that emerges from the development efforts. This allows the development cycle to be considerably shortened by omitting several potential cycles of optimization to meet functional specifications and minimized redesign when certain aspects of the system change during the course of development, such as learning that an instrument will use more power than planned. In this example, rather than resize the power system to meet a specification, the mission operations team replans their activities and the design reference missions to deal with less power being available to the other activities. We term this approach "capabilities driven" and it is a key enabler of the rapid design necessary to meet these objectives.

To minimize the documentation burden and allow the engineers to work as fast as possible on finishing the design, a number of compromises are made. First, documentation is limited to the critical items only: requirements, ICD's, drawings, schematics, block diagrams, test plans/procedures, and systems resource budgets (mass, power, data, etc.).

As a particular example of this minimization, rather than run most changes through a formal change control board, the line engineers are empowered to make changes to their own areas of expertise without needing outside pre-approval as long as their changes don't overstep boundaries into another subsystem. If changes do cross boundaries the systems lead and the leads of the affected areas have to be involved in approving the change. Change documentation is also shortened to a simple spreadsheet log of changes for most items, although formal change paperwork is still used for the more involved, systemic issues or those that require contract modifications to accommodate.

Throughout the design process, the MSI programs employ small, focused teams which cross several organizational boundaries to make truly integrated product development teams. These teams work without regard to organizational origin in their day-to-day activities and are empowered to make decisions in real time. To do this, the team needs to communicate effectively with each member directly rather than work through intermediaries and representatives. Communication is kept informal via e-mail and impromptu teleconferences rather than organized into meeting after meeting.

Bus Description

The Roadrunner spacecraft is built on a bus supplied by Microsat Systems whose original design was qualified for the TechSat-21 program. Broad Reach Engineering is providing the avionics system which has heritage from both the TechSat-21 program and the XSS-11 program. The Roadrunner bus is a 3-axis stabilized platform capable of providing pointing accuracy of better than 0.15 deg

with an avionics suite built around the BAE Rad 750 and a cPCI backplane. The high performance composite bus structure comprises only 13% of the spacecraft mass and is compatible with either Space X Falcon or OSC Minotaur launch environments and envelopes.

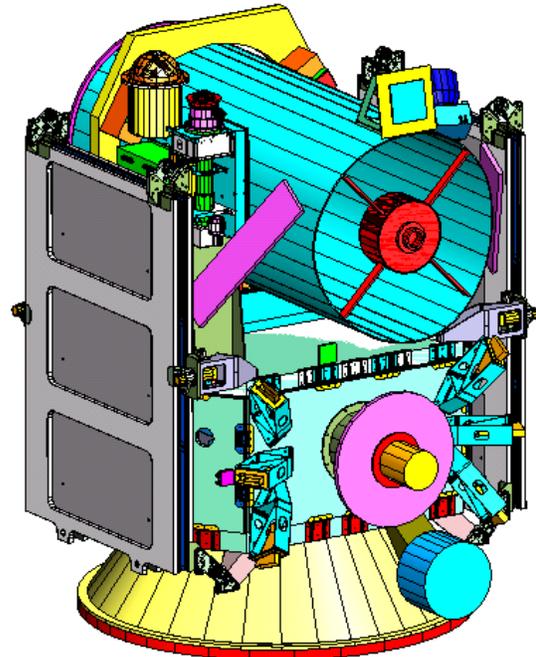


Figure 2 – Roadrunner in Stowed Configuration

The Roadrunner primary structure is made of composite facesheet panels over an aluminum honeycomb core. The basic configuration is an irregular octagon with a “payload” and “separation” deck to completely enclose the core bus avionics. This form factor is a legacy of the TechSat-21 requirement to fit within the EELV Secondary Payload Adapter envelope. The launch vehicle adapter is made of cast aluminum and is machined to the final configuration. The separation system was moved to below the adapter, which stays attached to the bus after separation. This was done to provide the stiffest interface possible to the launch vehicle. Even at more than twice the original spacecraft design

mass of TechSat-21, the structure is limited by stiffness requirements of Falcon rather than strength to handle launch loads on Roadrunner's 410 kg.

The Roadrunner ADCS actuator suite consists of three Dynacon MW-1000 reaction wheels (a growth version of their successful MW-200 design) and three Microcosm/Zarm MT-15-1 torque rods. The Goodrich/OCA star camera acts as the center of the high precision attitude determination system. An LN-200 IMU, Goodrich analog sun sensors, and a Billingsley TFM100S magnetometer complete the sensor suite. The Systron-Donner rate sensors inside the Dynacon wheels afford the only true redundancy of the bus design. All other elements are single string. ADCS system design, analysis, and software are provided by Advanced Solutions, Inc. (ASI).

Because the ADCS suite was largely inherited from the TechSat-21 and MSTI 4 excess flight hardware, the system is not optimized for this particular mission. As a consequence, the slew rates for Roadrunner are considerably slower than would normally be the case for a LEO imager. The Roadrunner Mission Operations team at AFRL plans to compensate for this limited capability by intelligently planning operations to accommodate the system limitations and in some cases is considering pre-biasing the momentum management system to greatly extend the system performance for a restricted set of operations.

The bus power system is based on a direct energy transfer topology, which delivers unregulated 28V switched power to the loads. This means that the main solar arrays (and the experimental arrays) are tied directly to the battery via a set of FET's and

the loads are similarly directly connected to the battery. The battery is a 30 Amp-hour Lithium-Ion unit from Yardney which is almost identical to the one delivered for XSS-11. Due to the battery chemistry, the bus typically operates between 31 and 34 volts for the majority of the time. The main arrays are triple junction GaAs panels from the MSTI 4 program, which are supported on an MSI composite panel framework which carries the structural loads and deploys them. The main array generates up to 550 Watts.

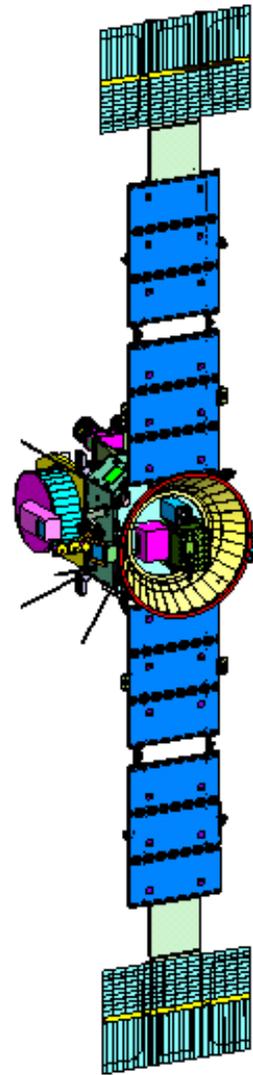


Figure 3 – Solar Array Configuration

The C&DH system and the EPS system are contained in the Integrated Avionics Unit

(IAU) from Broad Reach Engineering. This is an evolution from both the TechSat-21 and XSS-11 programs with some specific card changes made to accommodate the particular experiment suite of Roadrunner. The heart of the C&DH system is the BAE Rad 750, a Power PC-based space computer. Broad Reach also supplies the bus flight software and integrates the ADCS software from ASI and the experimental software. MSI provides fault protection and safe mode command scripts, which initialize the vehicle on separation.

Bus communication is primarily provided by a Mini-SGLS system left over from MSTI 4. The system is a fairly standard implementation with 2 pairs of patch antennas for full sphere coverage and the required encryption and decryption equipment. An auxiliary command uplink and downlink of bus data is also available via the CDL experimental system. Due to large data volumes, some experimental data such as the three color channels from the imager, are only able to be downlinked via the CDL.

Thermal control is provided by a largely passive design under the direction of MSI's thermal analysis. Interior boxes radiate their heat to neighbors via custom coatings (mostly tape) and conduct heat through the structural panels to the exterior. The launch vehicle adapter also serves as a radiating surface. Exterior components are generally designed to passively maintain temperatures in the operating range by judicious use of thermal blankets and second surface reflector tape. Tape was chosen over paint because the taping process can be done in a few days without sending hardware to specialty paint shops, thus saving two weeks in the schedule. Minco kapton tape heaters are used in select areas to keep components above their cold limits in certain modes.

Roadrunner Payloads

The centerpiece of the Roadrunner mission is a visible wavelength imager. This imager is being developed by AFRL in conjunction with SAIC and Nova Biometrics to deliver less than 1 meter ground sample distance resolution. The imager produces three color bands and one panchromatic channel of data across a 6144 pixel wide swath. The imager optics are built upon a commercial, off the shelf 20-inch aperture telescope by RC Optical Systems and shown below in figure 4.

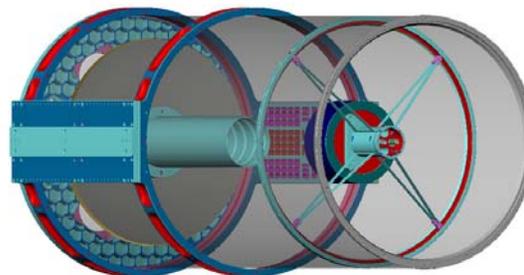


Figure 4 - RCOS 20-Inch Telescope Design

The Target Indicator Experiment (TIE) payload locates targets based on RF signatures in conjunction with P3 aircraft. A version of this experiment is flying as TacSat-1. This payload uses a total of 11 antennas whose FOV constraints play a significant role in the overall configuration of the spacecraft.

The Common Data Link (CDL) payload is an experimental communication system compatible with terrestrial CDL, which is currently used to operate military unmanned aerial vehicles including Global Hawk and Predator. This system will enable downlinking of data at 274 Mbits/second, a key capability for future TacSat missions and a central demonstration of the high

performance possible in modern microsattellites. This payload is a modified unit that was originally a production line system intended for aerial use. CDL will allow in-theater commanders to directly task Roadrunner for images and allow them to receive the requested data in near real-time on the same satellite pass.

The Roadrunner On-orbit Processing Experiment (ROPE) is an array of on-orbit reprogrammable FPGA's designed to process imager data into standard military imaging formats, use high level algorithms to identify likely targets from the imaging data, and to compress the resulting data streams and generate JPEG's for instant access on the ground. ROPE is being developed by AFRL at Kirtland AFB.

The Hall Effect Thruster (HET) payload is based on the Busek Tandem Hall Thruster, model # BHT-200-X3. This next generation ion engine provided by AFRL at Edwards AFB has variable Isp (up to 1600s), variable thrust levels, and variable power usage. These flexible features make the system highly adaptable to changing mission requirements and future TacSat needs. An EM under test is shown in figure 5 below.

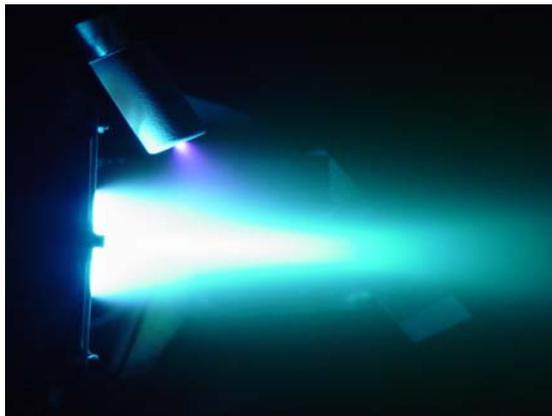


Figure 5 – The Hall Effect Thruster is a state-of-the-art high performance electric propulsion system

The Integrated GPS On-orbit Receiver (IGOR) payload has been developed by Broad Reach Engineering from the JPL BlackJack receiver designs to conduct ionospheric reflection and transmission experiments. In addition, IGOR provides the spacecraft with an extremely precise navigation solution, enabling high precision imaging operations.

The Atmospheric Density Specification (ADS) payload consists of two complementary experiments for characterizing the neutral wind of the upper atmosphere: the Anemometer Cross-track Measurement Experiment (ACME) and the Absolute Density Mass Spectrometer (ADMS). ACME measures the cross-track velocity component of the very rarified atmosphere at the Roadrunner altitude (350 km) and requires precise pointing knowledge to remove the spacecraft in-track velocity component from its measurement. ADMS measures the atomic mass of the species present in the wind from 1 to 50. This coordinated ADS payload provides unprecedented high-accuracy measurements of inputs critical for understanding the dynamic processes that affect the variability of the upper atmosphere. ADMS is being developed by AFRL/VSBX at Hanscom, AFB and ACME is being developed by the University of Texas, Dallas.

The Miniaturized Vibration Isolation System (MVIS) is an experimental apparatus designed to actively damp spacecraft jitter and thereby improve the quality of imaging. Roadrunner does not have a problem with jitter affecting the image quality, however, the MVIS system would allow for significant improvements for spacecraft that may have larger jitter sources such as solar array gimbals or large reaction wheels. MVIS consists of a series of actuators placed at the imager telescope assembly

center of gravity. One of three MVIS actuators is shown in the figure below.

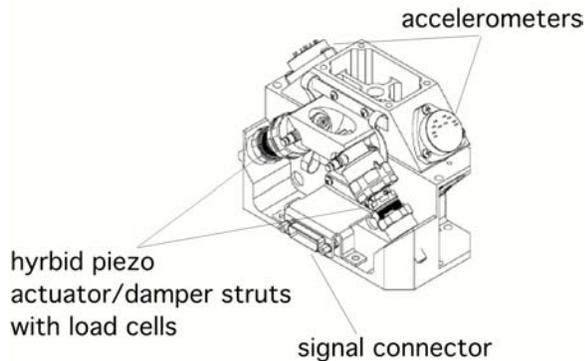


Figure 6 – MVIS Bipod layout

The Experimental Solar Array is a flexible thin film photovoltaic array designed to demonstrate two different cell technologies and two different deployment mechanisms. They are located at the tips of the main arrays and face the same direction. The experimental array is supported on MSI's patented Fold Integrated Thin film Stiffeners (FITS) which keep the arrays deployed with enough stiffness to avoid influencing the spacecraft ADCS. These arrays offer the potential to drastically reduce the storage volume needed for high power microsattellites and also reduce the mass and cost of the arrays. This payload is being developed by MSI under contract from AFRL.

The final payload is a suite of Autonomy Software that has two major components: the On-Orbit Checkout Experiment (OOCE) and the Autonomous Tasking Experiment (ATE). These experiments are being developed by Interface & Control Systems (ICS). The OOCE is the enabling technology for autonomously commissioning the spacecraft during its first 24 hours of life on orbit. This experiment is based very closely on software scripts developed during spacecraft I&T. The ATE experiment allows non-expert users in the tactical battlefield to send data requests to

the spacecraft (such as image a particular latitude and longitude) and receive the response back directly, sometimes in the same pass. ATE also serves as a long and short term experiment scheduler for all the payloads.

Integration & Test Phase

Starting July 30, the spacecraft bus components will begin test and integration at the AFRL's AEF under the direction of MSI and Jackson & Tull, which operates the AEF for AFRL. In the initial phase of I&T, MSI will focus on integrating the ADCS components to the C&DH and EPS system and verifying that the full suite of bus hardware and software meet the mission requirements. This work is conducted in the "flatsat" configuration with all components laid out flat on a workbench.

In the next phase, MSI will conduct initial system tests to ensure that the fault protection system is operating as planned and that simulated missions can be run in as realistic a manner as possible. To accomplish this testing, the team relies heavily on a built-in software simulation capability provided by ASI called ODySSy, which stands for On-board Dynamic Space Simulator. This software models the flight dynamics and replaces the actual sensor telemetry with calculated values to produce the illusion of orbital motion, position, orientation and vehicle dynamics.

While MSI is performing these tests, Jackson & Tull will be integrating payload engineering models (EM's) to the spacecraft to verify interface design and reduce risk for the following phases. Simultaneously, MSI's structures team will be performing proto-flight qualification testing on the bus structure using mass simulators for the bus

components and payloads. All of this testing will be conducted at the AEF on a vibration table and will include sine sweeps to verify structural frequency calculations, sine vibration, and finally sine burst.

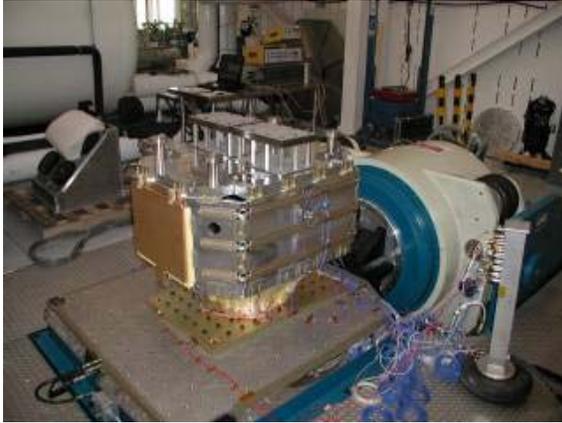


Figure 7 – The TechSat-21 bus undergoes qualification testing

After these tests are complete the flight bus components will be transferred to the flight structure and undergo a final set of systems tests prior to MSI turning the hardware over to Jackson & Tull for flight payload integration followed by environmental tests (thermal vacuum, thermal balance, and flight acceptance vibration) and final systems testing including a full week of simulated flight operation. Upon completion of these tests, the spacecraft will be crated and prepared for storage and shipment to the launch site.

Launch & Operations

Upon call-up, or when the launch vehicle is ready, the spacecraft will be removed from storage at the launch site and run through a quick series of automated tests lasting approximately 24 hours. The spacecraft will then be integrated to the launch vehicle, encapsulated, and placed in launch position while the launch vehicle undergoes with its normal processing. During the wait for launch, spacecraft operators will continue to

run tests of the system and monitor spacecraft health via the spacecraft umbilical. On the day of launch the final expected separation ephemeris will be loaded into software and the spacecraft timers and counters will be reset. In the final minutes before launch the spacecraft performs an autonomous self-check and reports status to ground controllers as “go” or “no-go”.

During launch the vehicle is passive. Upon detection of separation via voting of three separation switch indicators, the spacecraft will initiate entry into safe mode. This includes autonomously damping tip-off rates, deploying the main arrays, and reorienting the spacecraft toward the sun. Once this safe state is achieved, the fault protection system activates the command bridge for the autonomous software experiment, which had been in a quiescent, observation-only state.

Upon activation of the command bridge the autonomy software commences to perform a full suite of health checks on all bus systems and payload systems, deploys the remaining experiment components and begins coarse calibration and alignment efforts. Upon completion of this sequence, the autonomy software reports the status of its findings and relays to the ground its readiness for mission operations. The autonomous software is designed to achieve mission operations readiness within 24 hours of launch. The entire process from call-up to on-orbit mission readiness takes just one week.

Lessons Learned So Far

Roadrunner was constrained to operate with a large number of organizations actively involved. This was a consequence of the mission being only minimally funded to begin with, which required the management

to build a coalition of payloads to get access to the necessary resources to carry out the mission. As it now stands, there are 10 payload organizations and 7 major bus organizations. Each group has 5-20 members actively working which means coordinating hundreds of people plus their subcontractors. This has definitely slowed the pace of progress due to the amount of time necessary just to coordinate among the different organizations. This has had the consequence of making it harder for the systems team to focus efforts on working technical issues when they are distracted coordinating information transfers between organizations. The lesson is to conduct as much of your operations as possible under the umbrella of a single organization.

Simplifying requirements and documentation to the bare minimum essentials has allowed the design process to proceed at a much faster rate than would otherwise be possible. Due to the short development schedule we have found that the less formal documents such as e-mail, action item or issues lists, and informal tech memos have served quite well and allowed us to stay focused on just the critical elements while not getting bogged down in the minutia.

As a byproduct of the organizational complexity and the system complexity, it has taken nine months to get almost all of the major contractors and subcontractors under contract. As this paper goes to print there are still a few contracts left to sign with vendors and a potential payload addition and possibly a payload deletion if full funds don't materialize. This has greatly hampered the ability of the design team to formulate a comprehensive solution and move forward with a complete system design.

Consequently, assumptions had to be made and specifications finalized in the absence of full technical knowledge, which may lead to unwonted difficulty during integration. It has also caused the design team to repeat design and analysis efforts multiple times to handle late data. For an experimental spacecraft such as Roadrunner, it is much more cost efficient to get all the major contracts signed first, then the ICD's, and then unleash the full team to tackle design, fabrication, etc.

It seems a truism that as the program organizational complexity grows, the number of meetings grows and the amount of time spent preparing for them grows even faster. While Roadrunner has tried to resist this trend, we have not been entirely successful at devising a means to avoid formal reviews and standing meetings altogether. What we have found however, is that frequent, informal, relatively small, meetings with a tight technical focus are a great means to communicate with team members and synthesize global solutions to problems. These working technical meetings have been instrumental in allowing the design team to finalize various issues and move on to the next challenge.

The last key lesson we wish to impart is that the experiment in a "capabilities-driven" design approach has successfully eliminated the vast majority of design iterations that would have otherwise been required. Given the number of changes that have been accommodated as data from the various organizations became available, we were able to avoid many redesign efforts by simply making minor adjustments in the way we planned to operate the mission while still attaining the primary objectives. The lesson is to keep the implementation details flexible in your requirements and

focus on end goals, which are more qualitative than quantitative.

Conclusions

Roadrunner's combination of high-performance, low-cost, and rapid delivery is a significant advance of the state of the art for small satellites. If Roadrunner sets the standard for the follow-on TacSat missions we can expect to see a trend of higher power availability, higher payload mass fractions, very short development times, very high speed communications, flexible propulsion capabilities, powerful on-board data processing, and highly automated operations that begin and end in the tactical battlefield. These trends will greatly enhance the utility of smallsats for future military and civilian missions while minimizing cost and delivery times.