TacSat-2: A Survival Story

A Success Story

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Agenda

• Program Overview and Objectives

• Making it to the Launch Pad

• Surviving the Birth

• On-Orbit
  • Objectives
  • Accomplishments
  • Lessons Learned

• Upcoming Activities
TacSat-2 Overview

- 13 Tactical and Non-Tactical Payloads
- Spacecraft Mass: 368 kg
- Spacecraft Power: ~500 Watts, dual junction cells
- Orbit: 415 km, 40º inclination
- Mission Life: 1 year funded goal

Mission Objectives
- Assess military utility of low-cost ISR satellites & ground stations
- Evaluate concepts for simplifying and expanding warfighter access to space assets
- Demonstrate concepts for faster acquisition, responsive launch & operations
- Accomplish 140 on-orbit requirements of many tactical and non-tactical payloads
Making it to the Launch Pad

TechSat-21 → Roadrunner → TacSat-2

• Lessons:
  • ↑ Payloads/Customers = ↑$ = ↑ Requirements (to use $) = ↑ Advocacy/Oversight
    • Do a cost-benefit analysis for each additional payload/partner
  • Orbit changes should occur during the design phase, but the correct orbit improves mission effectiveness.
  • It is unwise to tie your program to a LV in development.
Surviving the Birth

RR team figures out that the Air Force Space Control Network was using the wrong command configuration for communicating to the SC.

1st pass indicated spacecraft (SC) was tumbling at a high rate and the reaction wheels were fully saturated. Additionally the torque rods were at full control authority and the TERMA star tracker was giving bad attitude updates. Worse was the SC could not be commanded from the ground.

No telemetry for next 35 contacts after repeated commanding from ground stations

High powered Air Force Ground Assets confirm SC is tumbling about X axis and that panels are deployed

TLM indicates that the SC was power positive. The SC battery indicated approximately 29V on the bus in the orientation it was in.

A sign error found to exist in the momentum control system causing SC to tumble. SC commanded to go to semi manual ADCS mode

Onboard LN200 IMU used to measure body rates was thought to be outputting bad data

ISC Team dispatched to come to AFRL and help detumble the spacecraft using ISC gyros

Patches erased during planned reboot. SC reenters tumble because of failed contact planned to reinstall patches.

Patches reapplied and burned into EEPROM. SC now able to reach Sun Track automatically. ADCS code uses LN200 and Sun Sensors as primary attitude devices.
**TacSat-2 Puts ORS to the Test for Survival**

- Lessons:
  - A web-based ground system is a force multiplier during times of trouble.
  - Using RIMS, a very small Operations Team became a very large distributed group of experts.
  - Converting to more restrictive networks (e.g., SIPRNet) or a non-web system significantly reduces mission effectiveness.

- Complete a full End-to-End RF Communications and ADCS Test using the actual space and ground resources that will be used on-orbit.
Objectives, Accomplishments, and Lessons Learned
## On-Orbit Results Summary

<table>
<thead>
<tr>
<th>Payload/Experimental Subsystem</th>
<th>Advertised Capability</th>
<th>Demonstrated Capability</th>
<th>Remaining Plan</th>
<th>Sponsor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imager</td>
<td>Visible 3-color, 1m GSD imager</td>
<td>NIIRS 3-4</td>
<td>Improve image resolution Test 3-color capability</td>
<td>AFRL</td>
</tr>
<tr>
<td>Roadrunner Onboard Processing Experiment (ROPE)</td>
<td>Image processing and storage</td>
<td>Limited storage 14:1 compression</td>
<td>Other compression ratios Non-uniformity correction 3-color image storage</td>
<td>AFRL</td>
</tr>
<tr>
<td>Target Indicator Experiment (TIE)</td>
<td>Signal detection, identification, and geolocation</td>
<td>Signal detection and identification in limited range of frequencies</td>
<td>Geolocation</td>
<td>NRL</td>
</tr>
<tr>
<td>Common Data Link (CDL)</td>
<td>High-rate mobile uplink and downlink</td>
<td>Fully capable</td>
<td>Improve reliability</td>
<td>JASPO</td>
</tr>
<tr>
<td>Hall Effect Thruster (HET)</td>
<td>High efficiency electric thruster</td>
<td>Fully capable</td>
<td>Long duration burns</td>
<td>AFRL</td>
</tr>
<tr>
<td>Propulsion Instrument Electronics (PIE)</td>
<td>Analyze HET’s effect on local environment</td>
<td>Fully capable</td>
<td>Collect data</td>
<td>AFRL/JPL</td>
</tr>
<tr>
<td>Autonomous Tasking Experiment (ATE)</td>
<td>Autonomously schedule and execute image collects and ground contacts</td>
<td>Autonomous image collects, ground contacts, and scheduled script execution</td>
<td>Tactical Field Experiment Objective prioritization and replanning</td>
<td>AFRL/ICS</td>
</tr>
<tr>
<td>Orbit Control Kit (OCK)</td>
<td>Autonomous station keeping</td>
<td>Short-term autonomous station keeping</td>
<td>Long-duration station keeping Tracking avoidance</td>
<td>Space Battleship Microcosm</td>
</tr>
<tr>
<td>Low Power Transceiver (LPT)</td>
<td>Combination SGLS/TDRSS transceiver and GPS receiver</td>
<td>SGLS Tx/Rx TDRSS Tx Unreliable GPS</td>
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<td></td>
<td></td>
<td>Unreliable GPS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atmospheric Density Mass Spectrometer (ADMS)</td>
<td>Measure neutral and ionospheric composition and density</td>
<td>Correlated instrument data to older models</td>
<td>Collect data</td>
<td>AFRL</td>
</tr>
<tr>
<td>Inertial Stellar Compass (ISC)</td>
<td>Low power, 1/10&lt;sup&gt;th&lt;/sup&gt; accurate attitude determination - Blend gyro-based and camera-based sensing to maintain accurate attitude during dynamic operations</td>
<td>Accurately and reliably calculated a valid attitude solution during slews. Space validate the 1&lt;sup&gt;st&lt;/sup&gt; ever set of MEMS gyros to fly in space</td>
<td>Diagnostic data collects</td>
<td>Draper Lab</td>
</tr>
<tr>
<td>Integrated GPS Occultation Receiver (IGOR)</td>
<td>Collect occultation science data as well as provide precision orbit determination data to ADCS</td>
<td>Provided accurate position and velocity data to the ADCS with occasional extended outages</td>
<td>Collect data</td>
<td>AFRL/Broadreach</td>
</tr>
<tr>
<td>Experimental Solar Arrays</td>
<td>Thin-film photovoltaics</td>
<td>One wing is deployed, one partially deployed, and there is some power being generated from one side of the array</td>
<td>Determine why they are not providing power</td>
<td>AFRL/Microsatellite Systems</td>
</tr>
<tr>
<td>Miniature Vibration Isolation System (MVIS)</td>
<td>Damp vibration during imaging to improve resolution</td>
<td>Locked</td>
<td>Remove launch locks Use in passive mode Use in active mode</td>
<td>AFRL</td>
</tr>
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Tactical Sensors

- Objective = Collect tactically relevant imagery and SIGINT data from both uncooperative ground-based emitters and cooperative sea-based AIS transmitters.

- Result = Imager and TIE are consistently producing tactically relevant products in operational scenarios.

- Lessons:
  - Calibrating an imager is a complex process that requires an extended period.
  - Producing a high quality image within a day of launch was impossible for this mission.
  - There are a number of restrictions imposed by a number of organizations that affect the process of space imagery collection during checkout and operation. The Operations Team should familiarize themselves with this process well in advance of launch.
  - Different Users assign different usefulness scores to SIGINT data. The design team needs to familiarize themselves with their customer and their customer’s needs.
Tactical Commanding and Data Distribution

- Objective =
  - Tasking directly from theater
    - Web vs. in-theater resource
  - Data products directly to theater
    - Web vs. in-theater resource

- Results:
  - First ever remote CDL Command and downlink from space
  - First-ever telemetry access and direct commanding of military spacecraft via wireless web connection
  - Image collect and downlink thru low and high speed links
  - Reliable daily web-based tasking and data distribution

- Lessons:
  - The web is a more executable method of supplying theater tasking and data distribution capability than a direct up/downlink to theater.
  - CDL is an effective mechanism for uploading and downloading data at a high rate and the CDL link should be pursued for future ORS missions.
  - It is not straightforward to track a SV with a ground antenna built to track aircraft.
  - Sustainment of a MIST requires competent, dedicated personnel.
Hall Effect Thruster

- **Objective**: Demonstrate the first-ever short duration (< 5 sec) firings to validate the use of Hall Thrusters for small impulse bit applications, as well as very long duration firings (up to 30 minutes) sufficient to provide all the propulsion necessary to keep the TacSat-2 spacecraft on-orbit for more than three years.

- **Results**: Thruster and sensor suite have worked reliably through very long and very short burns on a daily basis

- **Lesson**:
  - HET team investment is best example of resource devotion necessary to ensure mission success.
  - Low thrust propulsion is invasive (time and power) to tactical operations.
Autonomous Tasking Experiment

- Objective = Automate the tasking and data processing/distribution processes sufficiently that the Tactical Operator can use the system without understanding how to operate a spacecraft or process raw data into useful products.

- Results = ATE has been remarkably successful and currently executes all nominal activities (tactical, scientific, and health maintenance) for TacSat-2.
Imager Scheduling

Selected values must be highlighted to be used

Expiration Time  Aug 16 2004

Target Latitude  0° N 0° 0’

Target Longitude  0° E 0° 0’

Target Slant Angle  Minimum: 0° Maximum 30°

Priority  HIGH MEDIUM LOW

Image Size  6km x 6km

Add Activity  Cancel

Preview Target Location

Powered By Raster Roam (www.NGA.mil)
**Autonomous Tasking Experiment**

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- **Results** = ATE has been remarkably successful and currently executes all nominal activities (tactical, scientific, and health maintenance) for TacSat-2.

- **Lesson:**
  - It is possible to add sufficient onboard autonomy to a spacecraft to allow an untrained Tactical Operator to directly control a spacecraft analogously to the way they directly call for fire with Close Air Support aircraft.
Orbit Control Kit

- Objective = Autonomous station keeping.
Orbit Control Kit Live Test 2

S/C Position Vector Magnitude, Cumulative Time Late at Ascending Node, dV Requests, dV Executions

Cumulative Time Late [sec]

Orbits

Orbits
Orbit Control Kit

• Tactical Applications:
  • Ensure low-altitude spacecraft is where it should be when it is supposed to be there
  • Make the trajectory of a tactical spacecraft too unpredictable for an adversary to track

• Lessons:
  • GPS is essential.
  • Combination of TacSat-2 thruster, ADCS, and EPS make it difficult to demonstrate the true usefulness of OCK.
Low Power Transceiver

**Objectives:**
- Two-way SGLS communication
- Two-way TDRSS communication
- Dual-frequency GPS

**Results:**
- Both TDRSS and SGLS links have worked reliably.
  - 8-10 SGLS contacts/day
  - No TDRSS commanding
- GPS has been unable to sustain a solution for an extended period.
  - SC relies almost exclusively on the backup IGOR GPS for ephemeris data

**Lessons:**
- Complete a full End-to-End RF Communications Test using the actual space and ground resources that will be used on-orbit.
- Payload developers need to accompany a payload delivery.
Atmospheric Density Mass Spectrometer

• Objective = Provide unprecedented high-accuracy measurements of inputs critical for understanding the dynamic processes that affect the variability of the upper atmosphere.
  • Only instrument that provides both density and composition data simultaneously

• Results:
  • ADMS is performing perfectly.
  • Dataset is insufficient to adequately compare ADMS with present atmospheric models.

• Lessons:
  • Changing orbits to accommodate one mission objective adversely affects other payloads.
  • It is difficult to balance the requirements of tactical and scientific payloads.
**Inertial Stellar Compass**

- **Objectives:**
  - Demonstrate the ability to self-initialize on-orbit.
  - Demonstrate the ability to maintain accurate attitude during dynamic operations.
  - Demonstrate the ability to blend gyro-based and camera-based sensing with the required 1/10th of a degree accuracy.

- **Results:**
  - Self-initialized properly on 27 Dec 06
  - Collected data in background mode, correctly identified the slew maneuver, and most importantly, correctly identified its attitude during inertial hold to better than 1/10th of a degree
  - First successful use of MEMS (low power/mass) gyros in space

- **Lessons:**
  - With appropriate payloader involvement, late mission additions can be successful.
Experimental Solar Arrays

- Objectives:
  - Successfully deploy the FITS solar array in zero-G.
  - Generate power with Thin Film Photovoltaics (TFPV) in space.
  - Enhance Roadrunner mission with increased power.
  - Obtain full IV curves and characterize degradation of TFPV technologies.

- Results:
  - +Y wing is deployed
  - Some power generation
  - -Y wing is mostly, but not fully, deployed for unknown reasons
  - Cannot verify that the Exp SA power is contributing to the satellite power bus
Continuing Challenges and Way Ahead
Challenges and Way Ahead

- Complete imager calibration
  1. Pointing: Hit target every time
  2. Find best focus
  3. Evaluate three-color images
- Complete cross-platform TIE-aircraft geolocation
- Achieve CDL-MIST contact reliability of >90%
- Excel during Valiant Shield (6-13 Aug)
- Transition a stable, effective, and suitable system to STRAT and Space Command on 1 Oct 07
Conclusion
Backups
**TacSat-2 ACTD Systems View**

**Assessment Focus Areas**

- Signal of Interest
- Image Target

**VMOC – Virtual Mission Operations Center**
**MIST – Modular Interoperable Surface Terminal**
**TES-LITE – Tactical Exploitation System**
**RTT – Remote Tasking Terminal**
**VAST – Vehicle Analysis and Simulation Tool**
**RIMS – Remote Intelligent Monitoring System**

**Users:**
- Ground Warfighter (In-Theater)
- Other Users with Theater Emphasis
- Other AORs

**JTF Collection Manager and Space Support Team**
(Mission Planning, Tasking, Exploitation, Dissemination)*
TacSat-2 Accomplishments and Lessons

**Rapid Development**

**Lessons:**
- The keys to rapid development are:
  1. Only use experimental systems when necessary.
  2. Use the most experienced team of developers, integrators, testers, and operators affordable.
  3. Accompany each delivered component with a system expert to actively participate in the integration and test of that component.
- It is possible to successfully execute a mission built with numerous experimental payloads and subsystems on a single-string design with a moderately experienced and an undermanned team.

**Rapid Deployment**

**Lessons:**
- Wallops Island is a good ORS launch facility.
- Minotaur I is a good ORS launch vehicle, but OSC’s strong desire to reduce mission risk prohibits accelerated launch schedule demonstrations.
- It is unwise to tie your program to a LV in development.
TacSat-2 Accomplishments and Lessons

• Web-based command and data distribution
  • The SV has reliably and exclusively been operated via the web, both Internet and SIPRNet.
  • Lessons:
    • A web-based ground system is a force multiplier during times of trouble.
    • The lowest classification web currently acceptable for ORS purposes is the SIPRNet.
    • The SIPRNet restricts SV access to both tactical personnel and spacecraft operators.
    • Automated scans adversely affect SV operation via the web.

• Time critical space vehicle tasking and retrieval
  • In an unprecedented demonstration, untrained tactical end user personnel have tasked the SV via satellite web connection within 52 minutes of being presented with requirement.
  • Lessons:
    • A continuous command and return link would go a long way to shortening the tasking and data retrieval timeline. This should be a primary objective of future ORS missions.
    • National Exercises are overly rigid and do little to test the abilities of TacSat-2 to respond to truly time critical taskings.
TacSat-2 Accomplishments and Lessons

• Autonomous Operation
  • Automated scheduling of orbit maintenance and tactical operations has been reliable and used consistently since the first days of the mission.
  • Lesson: Onboard Autonomy can make a spacecraft suitable for direct operation by a Tactical Warfighter.

• First ever all US-built Hall Effect Thruster flown in space
  • Lessons:
    • HET team investment is best example of resource devotion necessary to ensure mission success.
    • Low thrust propulsion is invasive (time and power) to tactical operations.
TacSat-2 Accomplishments and Lessons

• Other Lessons:

• Get to know your customer and build a SV and CONOPS that satisfies that customer’s need.

• Do not rely on National Exercises to assess an ORS SV and CONOPS. They are too rigid and don’t provide opportunities to demonstrate a new capability.

• Preserve an independent Assessment Team. Developers should not assess their own equipment and CONOPS.

• Complete a full End-to-End RF Communications Test using the actual space and ground resources that will be used on-orbit.

• If GPS is your sole source of ephemeris data, have dual GPS and verify sufficient antenna coverage.

• Optimizing an orbit for a single-ball TacSat greatly increases mission effectiveness (i.e., the number of times per day the target area is in view.)

• The Government Information Assurance process is severely flawed. Until it is fixed, an asymmetric amount of resources and time will be spent on responding to poorly defined and overly restrictive requirements.
ACTD Goals and Metrics

1. Rapid development
2. Rapid deployment
3. Collect tactically relevant image data*
4. Process and store image data on-orbit*
5. Theater tasking and data distribution Web-based command and data distribution
6. Time critical space vehicle tasking and retrieval*
7. Collect tactically relevant SIGINT data*
8. Cross platform emitter geolocation*
9. Autonomy

* = Ongoing Assessment
**TacSat-2’s Perception of the Operational Deficiency and Need**

**TacSat-2’s Perception of the Operational Deficiency and Need**

Tactical Warfighter has an immediate (i.e., within one day) need for current (i.e., less than one day old) sensor (imagery or ELINT) data in a secondary threat area. Tactical Warfighter can not retrieve that data within acceptable time (i.e., one day).

- Traditional Solution = Many people, “systems”, and processes between the person with the need and the device used to fulfill the need
  - Advantages
    - Optimizes use of on-orbit resources to fulfill majority of needs
  - Weaknesses
    - Expensive
    - “Passing a message around a circle” was hard in the 3rd Grade
    - Limited Access in the Underserved Tactical Theater
    - Tactical environment is dynamic

Very difficult to implement within the capabilities of the Tactical Operator in a timeline that meets the needs of their rapidly changing environment.
TacSat-2 Solution

- Create an asset that produces useful data.
- Give the true Tactical End User direct control of that asset.
- Make the asset simple enough that the Tactical End User can produce his desired effect.
Collect “tactically relevant” data

Tactically relevant imagery =
- NIIRS 4
- Panchromatic + 3 wavebands (colors) chosen for their distinct tactical relevance
- Onboard storage for multiple images
- Onboard processing
  - Non-uniformity correction
  - Compression

Tactically relevant ELINT =
- Ability to detect RF emissions in a specific frequency range
- Ability to identify the transmitter type, as well as its mode of operation
- Ability to geolocate the emitter
- Ability to collect the Automatic Identification System (AIS) signals, which are now required on large ships for port safety and homeland defense
Suitable for the Tactical Operator

- Problem = Tactical Operator is geographically separated from the equipment that communicates with a spacecraft

- Solution = Use the existing web infrastructure to connect the source of the requirement (i.e., the soldier) to the tool that will fulfill the requirement (i.e., the spacecraft)

- Solution = Make the spacecraft that can communicate with an antenna that is already used in the theater with the Tactical Operator (e.g. MIST)

- Problem = Tactical Operators don’t know how to operate spacecraft and Spacecraft Operators don’t fully understand tactical needs

- Solution = Build a spacecraft with sufficient autonomy to convert high-level tactical inputs (e.g., target coordinates) into the detailed series of commands that execute an activity (e.g., take a picture)
Suitable for the Tactical Operator

TacSat-2
Air Force Research Lab

Imager Scheduling

Selected values must be highlighted to be used

Expiration Time: Aug 16 2004

Target Latitude: 0° N 0° E 0° W

Target Longitude: 0° N 0° E 0° W

Target Slant Angle: Minimum 0° Maximum 90°

Priority: HIGH MEDIUM LOW

Image Size: 6km x 6km

https://tacsat2.afrl.kirtland.af.mil/RIMS
Payload Descriptions

- CDL - Tactical communications system
- Imager - Optical camera
- ROPE – Image processor
- TIE - Scans the earth to detect/identify/geolocate ground-based RF-emitters
- Autonomy
  - OOCE - Autonomous on-orbit checkout and scheduling of 1st Image collect
  - ATE - Maintains/executes schedule of activities populated from the ground
  - OCK - Uses GPS data to determine when SV should fire HET to maintain current orbit altitude and shape
- MPI – Microsatellite Propulsion Integration experiment
  - HET - Hall-Effect Thruster
  - PIE - Measures the electromagnetic environment around HET
- ExpSA - Experimental Solar Arrays
- MVIS - Actively dampens vibration to make image resolution better
- ADMS - Determines the mass density of the “space” around it
- IGOR - Determines atmospheric scintillation from GPS satellite signal
- ISC – JPL Experimental Star Camera with orbit propagator
- LPT – NASA-developed software programmable radio w/SGLS, TDRSS, GPS
Acronyms

ADMS (atmospheric density mass spectrometer)
ATE (autonomous tasking experiment)
CDL (common data link)
ESA (electronically steerable antenna)
ESI (earth surface imager)
IGOR (integrated GPS oscillation receiver)
IMU (Inertial Measurement Unit)
ISC (inertial stellar compass)
MEMS (Micro-ElectroMechanical Systems)
MIST (Modular Interoperable Surface Terminal)
MVIS (miniaturized vibration isolation experiment)
OOCE (on-orbit checkout experiment)
OCK (orbit control kit)
PIE (propulsion instrument electronics)
ROPE (roadrunner onboard processing experiment)
TIE (target indicator experiment, RF payload)