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The STP-2 Mission: Rideshare Lessons Learned from the Air Force's First Falcon Heavy Launch

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ABSTRACT

On 25 June 2019, the Department of Defense (DoD) Space Test Program (STP) launched the STP-2 mission from Kennedy Space Center's Launch Complex 39A on a SpaceX Falcon Heavy. This groundbreaking mission carried twenty-four space vehicles to three different orbits and achieved many firsts. As might be expected in such a complex rideshare mission, there were many lessons learned. This paper discusses some of those lessons learned, particularly related to managing and working with multiple organizations, performing interface control, sorting through policy and compliance, and conducting mission assurance, fit checks, and launch integration.

STP has a 50+ year history of providing access to space for research and development satellites, most of them small satellites. The STP-2 launch represents the latest in a long line of multi-manifest rideshare missions. Our hope is to enlighten similar mission teams attempting large rideshare efforts across the entire space system development and launch community.

MISSION DESCRIPTION

On June 25, 2019, a combined Department of Defense (DoD) Space Test Program (STP) and SpaceX team successfully launched the STP-2 mission from the historic Kennedy Space Center's Launch Complex 39A (LC-39A) in Florida. The STP-2 mission marked the third launch of SpaceX's newest and most powerful launch vehicle - the Falcon Heavy - and the first Falcon Heavy launch for DoD. It also demonstrated the first-ever re-use of launch vehicle first-stage boosters and was the first multi-payload, multi-orbit mission for the Falcon Heavy. The STP-2 mission had a complex integrated payload stack (IPS) of 24 space vehicles from 13 launch partner organizations separating in three different orbits.

Goals/Objectives

Since the STP-2 mission consisted of so many launch partners, there were many objectives at many different levels. The space vehicle providers, experiment payload providers, STP, the Air Force Space and Missile Systems Center (SMC), and SpaceX all had their own objectives. Combining all the participants into a mission where each had an opportunity to succeed was the role of the STP and SpaceX.

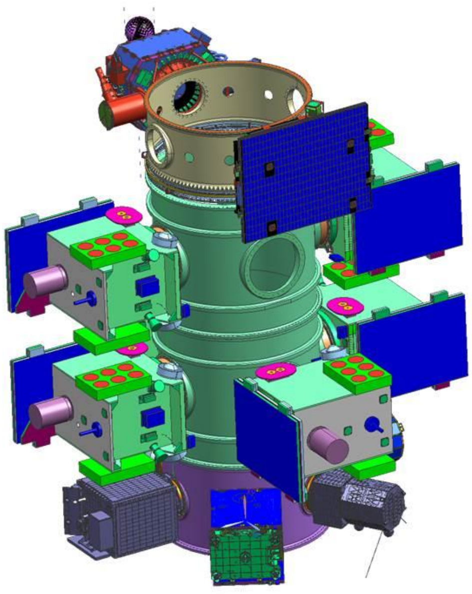
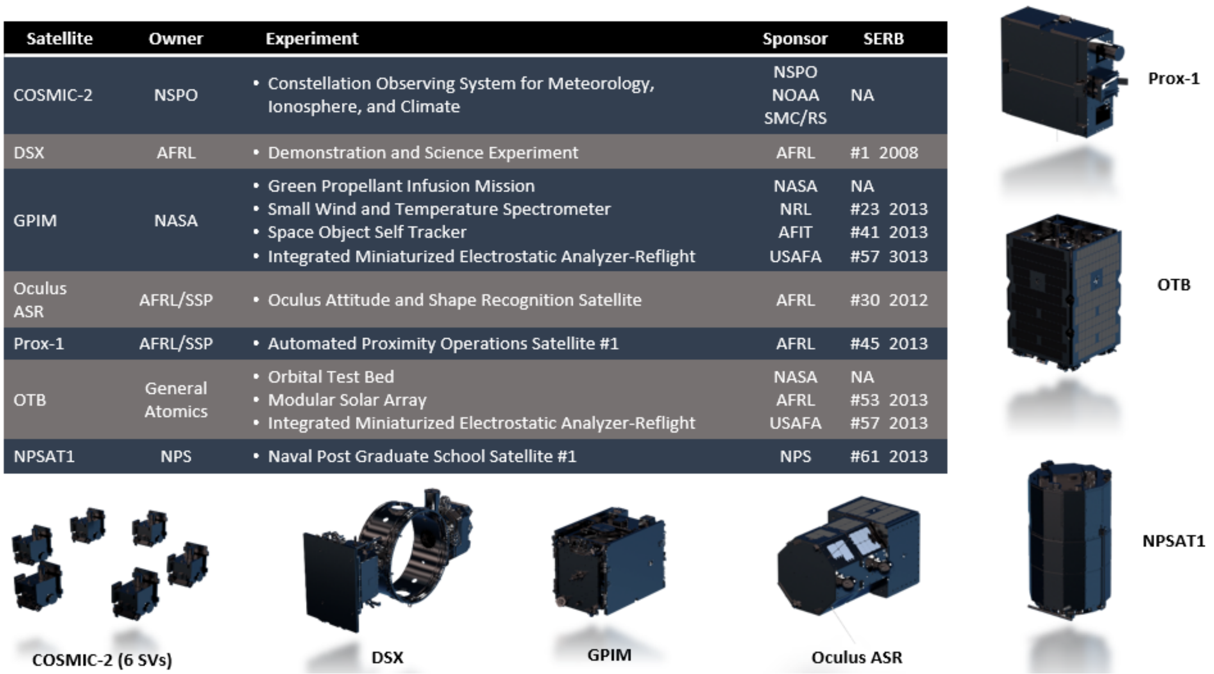


Photo courtesy of SpaceX

Figure 1: STP-2 Integrated Payload Stack

For SpaceX, demonstration of the Falcon Heavy capabilities was a primary purpose. National Security Space Launch New Entrant Certification, reusability of



Satellite	Owner	Experiment	Sponsor	SERB
COSMIC-2	NSPO	• Constellation Observing System for Meteorology, Ionosphere, and Climate	NSPO NOAA SMC/RS	NA
DSX	AFRL	• Demonstration and Science Experiment	AFRL	#1 2008
GPIM	NASA	• Green Propellant Infusion Mission • Small Wind and Temperature Spectrometer • Space Object Self Tracker • Integrated Miniaturized Electrostatic Analyzer-Reflight	NASA NRL AFIT USAFA	NA #23 2013 #41 2013 #57 3013
Oculus ASR	AFRL/SSP	• Oculus Attitude and Shape Recognition Satellite	AFRL	#30 2012
Prox-1	AFRL/SSP	• Automated Proximity Operations Satellite #1	AFRL	#45 2013
OTB	General Atomics	• Orbital Test Bed • Modular Solar Array • Integrated Miniaturized Electrostatic Analyzer-Reflight	NASA AFRL USAFA	NA #53 2013 #57 2013
NPSAT1	NPS	• Naval Post Graduate School Satellite #1	NPS	#61 2013

Figure 2: Co-prime and auxiliary payloads on STP-2

flight hardware, delivery of spacecraft to three different orbits, and additional flight data for future launches were all objectives. SMC had similar objectives to SpaceX. STP desired successful launch of the six COSMIC-2 spacecraft, the single DSX spacecraft, the five ESPA-class spacecraft, and 24U of CubeSats without spacecraft harming each other or the launch, so each spacecraft would have the opportunity to demonstrate technology, provide desired data, and advance relevant knowledge. In addition, fourteen of the experiments on board were selected through the DoD Space Experiments Review Board (SERB); access to space for SERB experiments is STP's primary mission. COSMIC-2 and DSX were designated the co-primes of the STP-2 mission by virtue of their driving orbit requirements, with secondary priority given to the ESPA-class spacecraft, and tertiary priority given to the CubeSats.

SMC and SpaceX also leveraged the STP-2 mission to gain insight into the SpaceX process for recovering and refurbishing first-stage boosters on the Falcon family of launch vehicles for DoD use. Such insight will lead the way for future technical and management teams to balance the risks and benefits of using previously flown rockets to meet warfighting requirements.

Spacecraft Descriptions and Organizations

The 24 spacecraft on the STP-2 mission consisted of the following satellites, which are also listed in Figures 2 and 3.

DSX (Demonstration and Science Experiments), from Air Force Research Laboratory, benefits future military and civil space assets by performing the basic research to understand space weather phenomena, improve the operation of space systems in the space weather environment, and experiment with advanced techniques that could alter these phenomena and reduce space weather degradation of critical space assets.

COSMIC-2 (Constellation Observing System for Meteorology, Ionosphere and Climate-2), from the Taiwanese National Space Organization (NSPO), National Oceanic and Atmospheric Administration (NOAA), and SMC is a six-satellite constellation providing next-generation global navigational satellite system radio occultation data. Radio occultation data is collected by measuring the changes in a radio signal as it is refracted in the atmosphere, allowing temperature and moisture to be determined. This data will lead to better weather forecasting and trending for climate change applications.

GPIM (Green Propellant Infusion Mission) is a NASA mission that develops a "green" alternative to

CubeSat/Owner	Units	Experiment	MOA/Sponsor	SERB
E-TBEx University of Michigan	Two 3U	• Enhanced Tandem Beacon Experiment	AFRL NASA	#24 2014
TEPCE Navy Research Lab	Two 1.5U connected by a tether	• Tethered Electrodynamic Propulsion CubeSat Experiment	NRL	#25 2016
ARMADILLO University of Texas	3U	• Atmospheric Related Measurements and Detection of Submillimeter Objects	AFRL NASA	#36 2014
DOTSI USAFA	3U	• Deployable Optical Telescope for SSA and ISR	USAFA DARPA	#49 2014
PSAT/BRICSat USNA	Two 1.5U	• Remote Data Transponder and Electric Propulsion Experiments	USNA	#55 2016
LEO/StangSat Cal Poly	One 2U, One 1U	• Launch Environments Observer and StangSat Experiments	NASA	NA
Prometheus USSOCOM	One 1.5 U One 1.5U Mass Sim	• USSOCOM Technology Demonstration	USSOCOM	NA
LightSail 2 Planetary Society	3U	• Solar Sail Propulsion Demonstration	Planetary Society	NA

Figure 3: CubeSats on STP-2

conventional spacecraft propulsion systems. With the green propellant, spacecraft fuel loading will be safer, faster and much less costly. The GPIM spacecraft also carries three other experiments from the SERB.

NPSat-1 (Naval Postgraduate School Satellite-1) hosts two experiments built by the Naval Research Laboratory (NRL) to investigate space weather and support space situational awareness, including the measurement of ionospheric electron density structures that cause radio scintillations.

Prox-1 (Proximity Ops-1) is a microsatellite developed by students at the Georgia Institute of Technology in Atlanta through the AFRL's University Nanosat Program. Its goal was to demonstrate satellite close proximity operations and rendezvous.

Oculus-ASR (Oculus-Attitude and Shape Recognition) was developed by students at the Michigan Technological University in Houghton, MI through the AFRL's University Nanosatellite Program. Its goal is to provide calibration opportunities for ground-based observers attempting to determine spacecraft attitude and configuration using unresolved optical imagery.

OTB (Orbital Test Bed) is a versatile, modular platform based on a flight-proven "hosting" model, built by General Atomics Electromagnetic Systems to test and qualify technologies. On STP-2, OTB hosts several payloads for technology demonstration, including a Deep Space Atomic Clock designed and built by NASA's Jet Propulsion Laboratory on behalf of the Space Technology Mission Directorate for deep space navigation and exploration, as well as two other experiments from the SERB.

E-TBEx (Extended Tandem Beacon Experiment) consists of two 3U CubeSats from University of Michigan and observes how radio signals are distorted by transit through the ionosphere using tones transmitted from eight separate orbital locations (two separate CubeSats and the six COSMIC-II satellites). Better understanding of this distortion can lead to improved communication techniques.

TEPCE (Tether Electrodynamic Propulsion CubeSat Experiment), which consists of two 1.5U CubeSats from NRL, demonstrates electrodynamic propulsion in the space environment by using a conductive tether strung between the two CubeSats to generate energy.

PSAT (Parkinson Satellite), a 1.5U CubeSat from the United States Naval Academy, supports global amateur radio data relay capabilities to assist students and researchers around the world.

BRICSat-2 (Ballistically Reinforced Communication Satellite-2), a 1.5U CubeSat from the United States Naval Academy, is designed to be small, affordable, and an ideal platform for testing new space technology such as a micro-cathode thruster system. Specifically, on the STP-2 mission, a small, low power electric propulsion system is being tested.

LEO (Launch Environment Observer) & StangSat, a 2U CubeSat from California Polytechnic State University and a 1U CubeSat from_Merritt Island High School, sponsored by NASA. Together these vehicles measure thermal and vibration environments during launch and transmit the information to the ground while demonstrating Wi-Fi data transmission between CubeSats during launch.

Prometheus is a constellation of United States Special Operations Command (USSOCOM) CubeSats developed by Los Alamos National Laboratory. The 1.5U CubeSat is part a technology development and demonstration effort to explore the viability of using a CubeSat constellation to meet existing Special Operation Forces mission requirements. Specifically, these CubeSats are demonstrating the capability to transfer audio, video, and data files from man-portable, low-profile, remotely located field units to deployable ground terminals using over the horizon satellite communications.

LightSail 2, a 3U CubeSat from the Planetary Society, demonstrates solar sailing as a method of propulsion for CubeSats.

FalconSat-7, also known as DOTSI (Deployable Optical Telescope for Space Situational Awareness and Intelligence, Surveillance and Reconnaissance) from the United States Air Force Academy (USAFA) and Defense Advanced Research Projects Agency is a mission to deploy a membrane photon sieve from a 3U CubeSat and image the Sun. This novel technique will allow for high-resolution space-based imagery from a small, low-cost telescope.

ARMADILLO (Atmosphere Related Measurements and Detection of Submillimeter Objects) is a 3U CubeSat to characterize the submillimeter dust particle environment in low-Earth orbit using a 10 cm Piezoelectric Dust Detector screen located on the bottom face of the spacecraft. This knowledge will help future satellite designers build better satellites.

Partnership Composition

As a multi-manifest mission with 13 partners launching 15 satellite programs consisting of 24 space vehicles separating in three different orbits, STP-2 was a complicated mission. The STP-2 payloads were assembled from a host of mission partners including the NOAA, NASA, DoD research laboratories (Air Force Research Laboratory, Naval Research Laboratory), universities and academia (Michigan Technological University, University of Texas at Austin, University of Michigan, Georgia Institute of Technology, USAFA, Naval Post Graduate School, and Merritt Island High School), operational DoD entities (USSOCOM), and commercial industry (Planetary Society). Strong working relationships were also developed with the international partners (National Space Organization of Taiwan and Surrey UK) for the COSMIC-2 spacecraft.

The assorted satellite manifest was managed by the DoD Space Test Program (2018 Air Force Program Office of the Year / Secretary Wilson Award winner), and the Falcon Heavy was procured by SMC's Launch Enterprise Directorate. SMC's Remote Sensing experts provided sensor technology for the NOAA-sponsored COSMIC-2 mission. Ten of the 24 satellites launched were from universities and one was from a high school, fostering education and community involvement. The DSX and GPIM satellites are operated out of the Research, Development, Test, and Evaluation Support Complex (RSC) in Albuquerque, New Mexico, run by SMC's Development Corps Innovation and Prototyping Directorate at Kirtland Air Force Base. The Innovation and Prototyping Directorate also led guest operations for almost 4,000 visitors and 400 dignitaries who came to view the launch.

RIDESHARE INTEGRATION

For a complex mission such as STP-2, effective rideshare management is of the utmost importance. For STP-2, rideshare integration was generally assigned to the launch vehicle contractor. However, the STP-2 Mission Manager was also involved in this process on a continuous basis. STP was also responsible, in coordination with SMC and SpaceX, for designing the mission manifest, and balancing the overarching mission objectives with the needs of the manifested space vehicles and payloads.

Selecting and Accommodating Missions

The candidate list for STP missions is generated primarily from the SERB list. The SERB looks at potential technologies and capabilities that need to be flown in space to enable future missions to employ these technologies. STP offered candidates from the SERB list the option to fly on the STP-2 mission, if their needs were met by the mission's characteristics, including altitude, inclination, and the capabilities of the launch vehicle. After the SERB payload list was accommodated, additional missions were offered a ride, where possible, to fill the stack and dispenser ports as much as possible.

Since COSMIC-2 and DSX were designated "co-prime" missions, they (and the SpaceX and SMC objectives related to launch certification) drove mission requirements. The remaining space vehicles needed to be accommodated within some existing phase of the launch, ascent, and deployment capabilities of the mission. Managing the satellite manifest, ensuring the suitability of the orbits, and ensuring that the launch vehicle could deliver all satellites to usable orbits was part of the rideshare integration task. Managing the rideshare integration also involved determining how individual space vehicles could be hosted without interfering with adjacent space vehicles on the stack during ascent, and how the 24 satellites could be processed at the launch site without interfering with each other.

To accommodate the many different missions on STP-2, STP-2's rideshare management team defined a basic set of "services" provided for each space vehicle, depending on whether they were co-primes, auxiliary payloads (APLs), or CubeSats. This basic set of services gave each space vehicle an idea of what services would be provided by default and helped each mission determine if additional services would be required. Most space vehicle missions were satisfied with the basic services. In some cases, the space vehicle mission provided additional hardware to adapt to the basic service supplied by the launch vehicle. In these cases, the launch vehicle manager and the individual space vehicle managers worked together to determine who should supply the additional hardware in a manner beneficial to both parties.

In addition to the co-prime missions and the APLs, the CubeSat payloads also required oversight. Like the APLs, each CubeSat deployment had to fit into some segment of the launch profile. This was accomplished by designing the mission to deploy the CubeSats at the initial parking orbit, at the lowest altitude. While CubeSat processing was somewhat simpler, since they were sent to the Payload Processing Facility (PPF) pre-packaged in their deployers, the process still required regular coordination and communication between the launch vehicle manager, the CubeSat integrator, and the responsible STP-2 payload manager.

Rideshare Program Office Composition

The STP-2 program office employed space vehicle mission managers who worked with each space vehicle contractor or supplier regularly. Some mission managers were responsible for multiple space vehicles, while a mission such as COSMIC-2, with multiple space vehicles on this launch, had a single program office mission manager. The program office space vehicle mission managers and their Aerospace engineering support were the STP-2 Mission Manager's eyes and ears for insight into all space vehicles and their integration with the launch vehicle. Issues or concerns could be elevated to the Mission Manager for adjudication when necessary. The program office also conducted internal meetings on a regular basis to enable communications up and down the management chain.

Responsiveness and Adaptability

The STP-2 team demonstrated adaptability and creativity when faced with re-work of the manifest within nine months of launch when one ESPA-class satellite was removed from the manifest (to launch on a different mission), and the eight CubeSat deployers were moved from the aft section of the second stage to two empty ESPA slots higher up on the stack (to mitigate excessive vibration and facilitate space vehicle / launch vehicle compatibility). Early on in the mission, the team also orchestrated a critical fit-check exercise that required building satellite models out of wood, cardboard, and 3D printed elements in some cases. This "fit check" is described in more detail in later sections.

The rideshare management team also developed and maintained the Interface Control Document (ICD) for the overall stack. The ICD functioned as an accommodation document, and a single place where rideshare management was accomplished for all space vehicles.

INTERFACE CONTROL DOCUMENTS

The Interface Control Document (ICD) was a cornerstone to the STP-2 mission, and a starting point for discussion of requirements on both the space vehicle and the launch vehicle side. The ICD for STP-2 contained all flight and ground requirements for the space vehicle missions riding on STP-2.

Composition

A generic ICD template was developed with placeholders for specific space vehicle data. Each space vehicle mission then populated their section of the template with appropriate data.

Some missions, such as the university satellites, easily fit into the generic ICD template, while others with more complexity added to the basic template. For example, space vehicles with propulsion and specific propulsion requirements added this information or modified the basic template. Furthermore, space vehicle organizations with more specific requirements, drawn from prior flights of their hardware, made further additions to the generic ICD template.

After the initial draft of the ICD, the Launch Vehicle Contractor, who also functioned as the Launch System Integrating Contractor, conducted regularly-occurring telecons with each space vehicle mission. These space vehicle-specific ICD telecons enabled discussion of interface requirements in detail as well as a better understanding of needs and capabilities on both the space vehicle and launch vehicle side. In addition, ICD discussions with the entire mission team were included in the agendas for face-to-face meetings, such as Ground Operations Working Groups (GOWGs). Using these forums, all team members shared issues, questions, and knowledge to reduce the risk of last-minute "gotchas" during space vehicle processing at the PPF.

The STP-2 program office was intimately involved in all ICD discussions, and facilitated resolution of issues and concerns from both space vehicle and launch vehicle organizations. This active engagement by the program office prevented issues from languishing and thereby kept the space vehicle/launch vehicle interfaces of STP-2 on track. Ad-hoc telecons or sessions at GOWGs were conducted whenever needed to quickly address concerns and drive towards resolutions, and an action item list / issues log was maintained by the team.

The frequency of individual space vehicle team ICD tag-ups with the launch vehicle contractor decreased, eventually, as the space vehicle/launch vehicle ICD became more defined. The ICD was revised often, with the final version of the ICD published within a month of launch.

Moving Forward with TBDs

In the early stages of STP-2—about mid-2013—the new Falcon Heavy launch vehicle was still in development. As such, detailed data on expected launch environment was not yet available. Coupled loads analysis still needed to be conducted, and each mission needed to know what vibration environments to use for design and test. Without specific vibration predictions for the Falcon Heavy, the STP-2 Mission Manager directed each mission to use the NASA Goddard Standard Document GSFC-STD-7000A, 4/22/2013 General Environmental Verification Standard (GEVS)[1] as an interim specification, until Falcon Heavy's predicted environment data was available, in the range of a year later. This enabled each mission to keep moving along in their development and test effort.

Another "TBD" involved the launch base interface for satellite fueling. While the ICD template contained the basic data on satellite fueling requirements at the PPF, it did not provide all the detailed interfaces and interactions required by the Cape Canaveral Air Force Station Range Safety team. However, early engagement with Range Safety in face-to-face meetings further defined ICD requirements and responsibilities, thus mitigating potential schedule risks. This enabled STP-2 to clear major hurdles early, although TBDs related to specifics of new Green Propellant ground support equipment (GSE) design, test, and operator experience continued to evolve until much later in the mission cycle.

Managing Technical Changes and New Information

The development and integration effort for STP-2 occurred over approximately six years, and as can be expected with such a complicated mission, technical changes occurred frequently. Relaying these changes to all stakeholders required good communications between SpaceX, the STP-2 Program Office, and the space vehicle missions. Again, regular telecons and face-to-face meetings were conducted to ensure that all team members were aware of technical changes as they occurred.

One example of technical change management was related to the use of GEVS, mentioned above. Specifying GEVS as a random vibration test standard allowed the space vehicle missions to maintain schedule and move forward with testing. However, the actual predicted environments for the new Falcon Heavy vehicle were different than those specified in GEVS. This led to follow-up technical evaluations by experts and consultants on the launch vehicle and space vehicle sides to assess impacts. In this case, multiple delays to STP-2 due to an unrelated Falcon-9 failure reduced the potential schedule pressure of space vehicle random vibration testing and allowed more detailed evaluation of the test envelopes for each space vehicle to satisfy launch vehicle constraints.

Other technical changes included PPF processing and integration locations, GSE arrival scheduling, hardware storage and removal from the PPF, and allocation of space and facility requirements within the PPF. Generally, these changes were managed through regular Payload IPT meetings, with ad-hoc breakout sessions to address impacts of changes to individual missions, where required.

An important part of managing technical changes was the use of a single mission manger on the launch vehicle side, with dedicated backup personnel. On the space vehicle contractor side, each mission provided an integration manager as a single point of contact for channeling questions and issues to and from the space vehicle team. The same rationale applied to the STP-2 program office team, with mission-dedicated Air Force and Aerospace personnel for each mission. Not only did this ensure continuity during the six-year duration of the mission, it also enabled quick responses to technical changes as they arose.

GOVERNMENT / COMMERCIAL WORKING RELATIONSHIPS AND PRACTICES

Cooperation

Accomplishing STP-2 required 15 separate program offices and all their individual mission partners and contractors to coalesce into one engineering team to create an integrated payload stack where each of the rideshare partners had to be accountable and responsible for the success of the others as well as the overall mission. Given the nature of the partnership, and the fact that few team members were bound to each other by contractual agreements, collaboration and voluntary support across the team were an essential requirement for success.

This common understanding set the stage for what a Forbes article labelled a "mighty good test of governmental cooperation."[2] Not only was the mission a good test of cooperation between the DoD, NOAA and NASA, but it was also a good test at the commercial and university levels, as well. Forging and managing this cooperation provided a lot of the lessons learned for STP-2, and the recommendations discussed next.

Agreements, Understanding, and Flexibility

In the absence of formal contracts between the participants, roles and responsibilities for the team members were established by agreements documented in numerous memoranda of understanding. The STP-2 team found it important to start the document off with what the agreement would accomplish, and why the agreement was mutually beneficial to each party. If those two facts remained constant over the course of executing the mission, the remaining statements in the memorandum could be modified and adjusted as needed.

The need for patience and flexibility cannot be overstated. Many R&D satellite developers have small teams, small businesses providing support, and little ability to acquire the specialized engineering services that large developers use. Many of the missions on STP-2 involved university teams that employed undergraduate-level labor, with graduate students acting as design and engineering leads, and a single professor providing management and continuity. Not all STP-2 team members had access to the same analysis, modeling, or testing tools, which made establishing standards across the teams a challenge. All this required flexibility and support from the integrator and the rideshare management team. In large, multi-agency rideshare missions, teams should ideally find a way to simplify and focus the required data information exchange to eliminate non-essential information and reduce the need for overly complex models. This is especially important in the effort required to complete analysis of the integrated payload stack.

To ensure space vehicle testing was adequate without placing unnecessary risk on the payloads, a significant amount of highly technical structural engineering and testing expertise was required. Few small satellite teams have this level of expertise, so the STP-2 program office augmented several of the teams with consultants and provided modelling and testing support as required.

Schedule Slips

STP-2 encountered several schedule slips as the Falcon Heavy development schedule unfolded and SpaceX dealt with two Falcon-9 issues. Most of the spacecraft teams found the additional schedule margin useful either in navigating technical challenges or resolving newly discovered performance issues from similar components on orbit. But the launch slips caused challenges, too. Missions had to track and monitor limited shelf-life items, as well as coordinate the right time to install flight batteries, tension any release mechanisms, and start operational readiness preparation. It's best to realize up front that a new launch vehicle's schedule, while helpful in organizing the sequence of work, isn't always a good indication of the duration of that work, since the work has never been done before.

A launch slip also affects cost and occasionally personnel depending on the duration and/or timing of the slip. The government, commercial and university teams STP-2 handled cost and personnel impacts differently. Universities are essentially graduating the workforce, so any slip is likely to a have an impact on personnel. Continuity within the university staff, coupled with a thorough handover to new staff and close supervision of new students touching flight hardware is key for success on any university program. Cost is typically only an issue if components require replacement; however, university programs are usually willing to accept a significant level of risk if the funding isn't available.

Government team members can typically absorb a launch slip with some re-planning or realigning of personnel to other projects. Personnel cost is less of an issue for government employees, but government contracts with mission assurance providers, consultants and other support contractors can get costly, require modification, and in some cases even undergo re-competition if the slip exceeds or occurs near the end of a period of performance. Once the program is on track it can be easier to bring government teams back on the project. Fiscal year budgets adjustments also create opportunities to absorb the cost growth.

Commercial businesses focus mostly on cost reduction and are motivated to minimize non-productive effort. Small businesses often don't have the ability to float employees across multiple programs like government and large businesses do. A finite cash flow makes it imperative to minimize labor costs and non-essential business expenses. A lengthy launch delay for a small commercial satellite provider may result in an untenable situation - an inability to generate revenue or recruit additional investors which could lead to bankruptcy or a sell-off of the company's assets.

Practice Differences

Other practice differences reflect the nature of the organizations involved. Government teams prefer methodical, detailed, specification-compliant processes defined by contractual requirements with the expectation that all engineering effort is subjected to a review by a large committee of peers. Engineering changes are expected to undergo thorough review, potentially even at the system level, to ensure second and third order effects are considered across the system. Configuration changes are closely managed and overseen by government and mission assurance engineers.

In contrast, commercial and educational mission managers tend to allow engineering teams to manage their efforts internally. The engineering teams have the authority and oversight of change requests and the customer typically has one or two engineers embedded in the team who are empowered to review and accept the design and any changes. Design reviews are often less formal events, and more focused engineering analysis reviews are by a smaller group of internal peers.

The payload teams on STP-2 managed events differently depending on whether they were a government-contracted spacecraft, a commercial spacecraft or a university spacecraft. What was most important at the integrated payload stack level was communication across the teams between the right engineering disciplines. Multi-manifest missions require well-understood interfaces and data is difficult to understand without open channels of discussion between responsible engineers on both sides of the interface. Documentation alone should not be expected to fully communicate the subtle complexities that need to be understood.

Knowledge Transfer

With limited documentation particularly early in the mission, some verbal agreements and information exchanged during early working group and technical interchange meetings were lost when individuals moved on. The team then had to put items that were previously closed back on the table for technical discussion and resolution with the new crew. On the lean, quick missions performed by STP, where meetings between engineers can take the place of more formal documentation, it is important to keep rigorous meeting minutes reviewed by the team and to get the few formal documents (such as the ICD) started as soon as possible. A byproduct of not having recorded meeting minutes were the issues that lingered without resolution week after week. Some integration issues were discussed for a year or more without resolution or assignment as action items to a lead point of contact.

The loss of legacy knowledge was most keenly felt at the range for launch integration. Several of the people performing the integration work did not have the full-mission familiarity with the stack or even their own mission segment. It is most striking to compare the attendance list at the STP-2 fit check with the participants at the launch integration. The overwhelming majority of the original crew had left the program by launch. Documentation of the fit check was further limited by the fact that SpaceX uses electronic procedures that are difficult to print out and annotate. The as-run record remained electronic and in SpaceX's possession, not distributed to the team.

One of the best methods to ensure continuity despite personnel change was the shared document site that held the critical documents for the team. This website, maintained by STP and accessible to all, was a safe repository of the latest mission data. The other best method of maintaining team integrity and transferring information was the effort made by each transitioning person to individually turn over their position, data, and knowledge. The fact that many of these professionals took that effort seriously, and of course that everyone didn't transition at the same time, kept some of the legacy knowledge alive.

Maintaining Communication Across the Disciplines

Teams need to have the ability to contact and discuss the interface details between the responsible engineers during the design process. The names and contact information of responsible engineers need to be shared across each of the interfaces so when questions are thought of they can be asked by the right person and answered by the right person - ideally before the answer

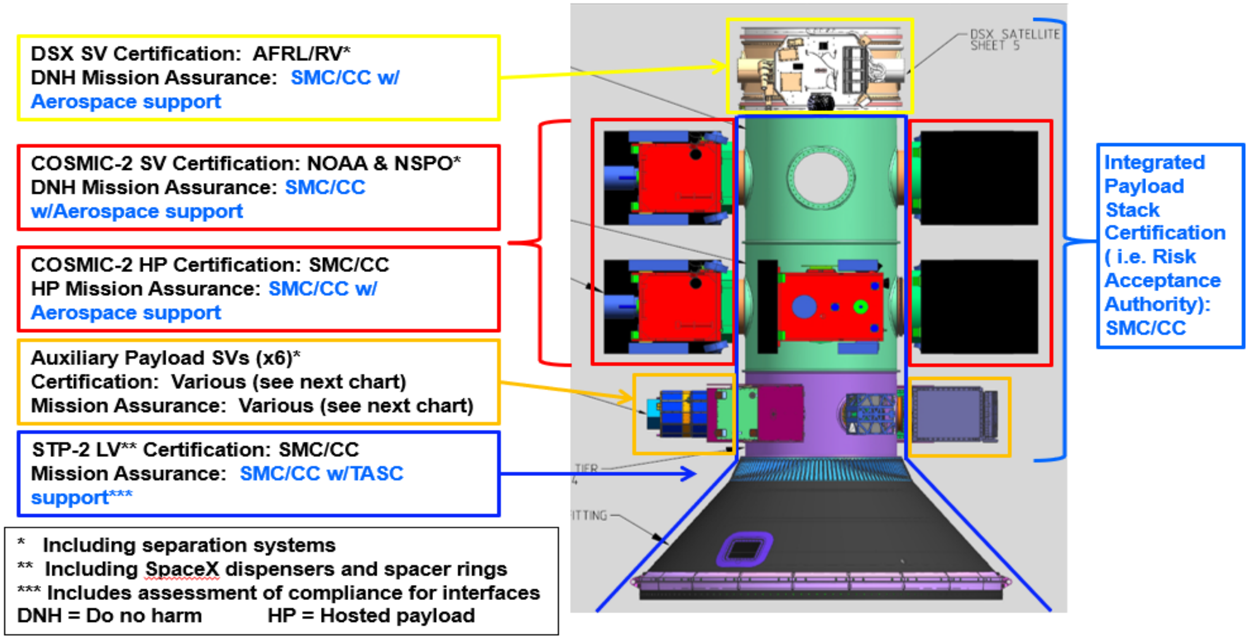


Figure 4: Certification responsibilities for the STP-2 Integrated Payload Stack

is needed, and not once the interface has been fully designed and adjustments are difficult.

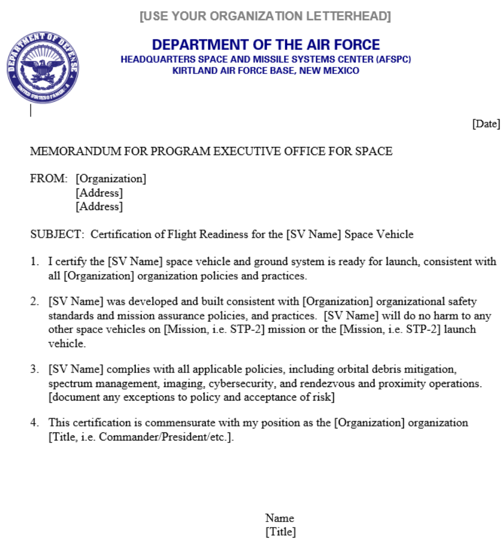
Hierarchies within teams tend to squelch such direct communication for several reasons that are valid concerns but can be handled appropriately once understood and brought to light. Sending questions up the chain and then down the chain and answers back in the same way often leads to confusion and extraneous discussion involving tangential issues. Managers or system engineers with good intentions can sometimes insert their answer and not allow the question to get to the right person.

Often management's biggest valid concern is that a lower level engineer will agree to an interface requirement that results in a design change causing cost growth or other system-level impacts outside the scope of that engineer. The solution in this case is to make it known that any discussion that results in cost growth or system level impacts are only approved at the management/system level. Another valid concern is that these discussions between the responsible engineers could distract them from the priorities set by management. The schedule can help resolve these concerns provided it's shared across the team and understood that if some activities are behind or in critical periods, the answer may not necessarily be available, or appropriate to ask at the time. Keep team members aware of the full schedule and status to help them understand when the best opportunity might be to communicate.

NAVIGATING POLICY / SAFETY COMPLIANCE

Another challenge for STP-2 was policy compliance. With 24 satellites from 13 organizations flying on a rocket procured by the Air Force, it took a lot of effort to determine the compliance authorities and approvals required to launch. Many of the ridesharing partners were also universities new to launch, who required guidance through the process.

First, the STP-2 IPS team needed to determine the roles and responsibilities of all the mission players. As the launching agency, would the Air Force be required to obtain all licenses and perform all compliance certifications of the missions on STP-2? It seemed clear that this was not a tenable option. The mission included satellites from agencies as diverse as the Air Force, NASA, commercial entities, and the government of Taiwan. Not all Air Force policies were applicable to all payloads riding on STP-2, and it was inappropriate for the Air Force to request frequency licenses for commercial or private missions. Yet, the STP-2 Air Force team wanted to be certain that it was not launching satellites that would violate national or international guidelines on spectrum usage, debris, imaging, and so forth.



[USE YOUR ORGANIZATION LETTERHEAD]

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SPACE AND MISSILE SYSTEMS CENTER (AFSPC)
KIRTLAND AIR FORCE BASE, NEW MEXICO

[Date]

MEMORANDUM FOR PROGRAM EXECUTIVE OFFICE FOR SPACE

FROM: [Organization]
[Address]
[Address]

SUBJECT: Certification of Flight Readiness for the [SV Name] Space Vehicle

1. I certify the [SV Name] space vehicle and ground system is ready for launch, consistent with all [Organization] organization policies and practices.

2. [SV Name] was developed and built consistent with [Organization] organizational safety standards and mission assurance policies, and practices. [SV Name] will do no harm to any other space vehicles on [Mission, i.e. STP-2] mission or the [Mission, i.e. STP-2] launch vehicle.

3. [SV Name] complies with all applicable policies, including orbital debris mitigation, spectrum management, imaging, cybersecurity, and rendezvous and proximity operations. [document any exceptions to policy and acceptance of risk]

4. This certification is commensurate with my position as the [Organization] organization [Title, i.e. Commander/President/etc.].

Name
[Title]

Figure 5: Sample certification letter for STP-2 payloads

What emerged from these early discussions was a process by which the Air Force team divided the mission into areas of responsibility, as shown in Figure 4 for some of the satellites. Each satellite on the mission was responsible for its own licensing and certification process, to include its own mission assurance. So, the NASA satellites on the mission went through NASA channels for debris compliance, frequency allocation, and other certifications as needed; similarly, the Air Force satellites went through Air Force channels, and the private / commercial satellites went through commercial licensing processes. The foreign satellites followed law and policy applicable to their satellites. Each mission, however, was required to provide a certification letter (like the one shown in Figure 5) to the Air Force and the STP-2 IPS mission manager, signed by a representative of their organization, to certify that all applicable policies were followed, all necessary licenses were obtained, and that the satellite was ready for launch and would "do no harm" to the rest of the mission or the launch vehicle. For sponsored satellites (such as the university satellites overseen by AFRL as part of the University Nanosatellite Program), the sponsoring agency co-signed the certification letter; for the international partners on the mission (specifically the Taiwanese Space Agency for the COSMIC-2 satellites), the US partner on the mission (the National Oceanic and Atmospheric Administration) co-signed the letter.

The STP-2 team then performed a "do no harm" risk assessment as described later in this paper, not only on aspects related to launch failure such as structural soundness and testing, but also on policy compliance and "do no harm" to the space environment. The results of this assessment, along with the certification letters for each organization were presented to the Air Force launch approval authority for his consideration and final launch approval. This "trust but verify" approach was sufficient to satisfy US Air Force requirements for launch and space safety.

While the final responsibility for licensing and policy compliance rested with the individual satellite organizations, the STP-2 team provided guidance and advice to many of the organizations involved. To be effective in this task, the team spent many hours researching policy not only for the Air Force satellites on the mission, but also for the university and NASA satellites. In several cases, the team requested clarification of unclear or undetermined policy points from the policy owners. The team ultimately wrote a "roadmap" for policy compliance, which is now available online for use by the wider community.[3,4]

DO NO HARM AND FIT CHECKS

STP-2 is the first large-scale application of Do No Harm / Rideshare Mission Assurance, which The Aerospace Corporation at STP pioneered and is refining.[5,6] Each space vehicle mission was responsible for their own mission assurance. STP-2 merely provided the ride to orbit. However, the STP-2 program office took on the responsibility to assess do-no-harm risks for the entire stack of space vehicle payloads. This allowed the mission to proceed and succeed despite different risk tolerances among the 24 satellites (from the large ESPA-based DSX spacecraft to the university and high school CubeSats) and at the pace of commercial speed.

Aerospace conducted detailed and thorough analysis of more than 800 do-no-harm items. A set of heritage do-no-harm requirements was developed from prior STP missions. This list was reviewed and updated regularly by the STP-2 program office, and verification artifacts or data were requested from each space vehicle mission to ensure that do-no-harm requirements were met by all space vehicles. Examples of do-no-harm criteria include space vehicle compliance with: launch environment (random vibration, acoustics, shock, static loads, penalty testing), contamination, electromagnetic interference, pressure vessel requirements, electrical inhibits, deployment, and end of life safing. A do-no-harm matrix/checklist captured all space vehicle mission partners' compliance with the do-no-harm requirements. The do-no-harm document was used as an artifact of compliance for STP-2 readiness reviews.

A particularly critical risk-reduction activity related to the do-no-harm process was the space vehicle stack-level fit check. The fit check was performed in the actual PPF bay used for space vehicle/launch vehicle processing at Cape Canaveral Air Force Station. Each space vehicle team was required to participate with space vehicle models that were volume and mass representatives of the actual flight vehicles. In the case of COSMIC-2, with six space vehicles on the flight, only two were mass- and volumetrically-accurate models, while the other four were volumetrically-accurate models constructed from lightweight materials. A requirement of the "mass models" (the title mostly used for the fit check articles) was for accurate portrayal of appendages from each model, including antennas or sensors that protruded from the space vehicle bus. This accurate portrayal for the space vehicles, especially on the APL ring, was invaluable for practicing processing, lift, and installation on the dispenser ring, and exercising access constraints for adjacent space vehicles.

The STP-2 program facilitated development of mass models, especially for university satellites, where a non-flight model did not exist, or would have been difficult to develop under the university or lab resource constraints. For the APL ring, a series of representative mass models were developed that could simulate multiple space vehicles through addition of small balance weights, and appropriate simulated appendages. In addition, these mass models could be flown on the launch vehicle if a space vehicle were de-manifested late in the mission cycle, to avoid new launch vehicle loads and control analyses. In other cases, space vehicle contractors also possessed non-flight space vehicles that were used for the fit check, and could be flown as mass models, if the need arose.

The fit check proved to be a success, resulting in a number of lessons learned, and the ability to mitigate problems or issues that might have become technical or schedule risks to the mission during actual space vehicle/launch vehicle processing. Over one hundred lessons learned were consolidated from individual space vehicle missions, the launch vehicle contractor, and the STP-2 program office. These lessons learned were reviewed by the entire team, and follow-up actions delegated for their implementation.

One example of the value of the fit check is the discovery of access problems for installation of omnidirectional antennas in a space vehicle area near the dispenser's mounting flange. The space vehicle contractor subsequently added an additional spacer ring to increase clearance for installing the antennas, and for installing and torqueing bolts for the space vehicle to dispenser flange mounting.

The fit check also enabled the actual team members from both the space vehicle and launch vehicle side to experience working together in a representative workspace, thus facilitating the surfacing of questions and issues through use of real hardware. It also required development of a processing schedule by the launch vehicle contractor, with estimates of the duration of each step in space vehicle processing. This took significant planning, as it included managing the date-staggered delivery of each space vehicle and its GSE, the space vehicle movement into the PPF highbay, the highbay work area setup for each space vehicle mission, the scheduling of the overhead crane, and the storage of GSE and related hardware before and after its use for processing. This led to discoveries such a need for additional pallet jacks, the need for more storage space for space vehicle hardware, and a revision in the space vehicle mounting sequence for the COSMIC-2 upper dispenser rings.

Initially, space vehicle processing was planned for the West Bay of the SpaceX PPF. However, in the timeframe of the Fit Check, the West Bay was processing flight hardware for an ISS resupply mission. Therefore, the Fit Check occurred in the PPF East Bay, which is not identical in layout to the planned processing area. Ultimately, the actual space vehicle/launch vehicle processing occurred in the same bay (East Bay) as the fit check. This was fortuitous, since the space vehicle teams were familiar with this workspace.

In summary, the importance of the fit check cannot be overstated, especially for rideshare missions. In the case of STP-2, the actual space vehicle/launch vehicle processing at the PPF would likely have incurred numerous technical issues, and the launch schedule could have been impacted had a Fit Check been omitted.

LAUNCH

SpaceX performed the IPS integration in the LC-39A Hangar, mounting six COSMIC-2 spacecraft, five ESPA-class auxiliary payloads, and eight Poly Picosat Orbital Deployers (i.e., 24U of CubeSats) on three SpaceX dispenser rings. The DSX spacecraft topped the stack creating an IPS totaling approximately 6000 kg.

After launch and second engine cutoff, the Oculus spacecraft and CubeSats were separated at approximately 28.5° inclination in a 300 x 860 km orbit. Then, after another second stage burn, the remaining four auxiliary spacecraft and the six COSMIC-2 spacecraft were separated at approximately 24° inclination in a 720 x 720 km orbit. After the third and fourth second engine burns, the DSX spacecraft was separated at approximately 42° inclination in a 6,000 x 12,000 km orbit. Finally, SpaceX performed a fifth second stage burn with the Falcon Heavy. The STP-2 mission flawlessly executed a six-hour deployment sequence, successfully placing 24 satellites in three unique orbits. All satellites were ultimately contacted by their respective agencies for mission operations.

CONCLUSION

STP-2 achieved many firsts: in addition to being the first DoD and Air Force use of the Falcon Heavy launch vehicle, it represented the first DoD reuse of Falcon boosters. It was also the first wide-scale application of STP "do no harm" processes, the first DoD test case for rideshare certification policy, and – with 13 organizations from military, civil, university, commercial, and foreign organizations involved – the most complex launch mission ever attempted by the Air Force.

STP-2 was a multi-nation, multi-agency, multi-organization rideshare effort that served as a pathfinder for how government, industry, academia, and international partners can work together on multi-manifest missions. It is the team's hope that by applying some of the lessons learned reflected in this document – by establishing good communications and mutual understanding up front, by implementing strong rideshare management techniques and interface control, by understanding policy compliance and do-no-harm considerations, and by facilitating knowledge transfer within and among payload teams – other missions can achieve the success STP experienced on its first Falcon Heavy mission.

Figure 6: STP-2 launch (photo courtesy of NASA)

REFERENCES

1. NASA Goddard Standard Document GSFC-STD-7000A, General Environmental Verification Standard, 2013.
2. Autry, G., "Falcon Heavy STP-2: One Mighty Good Test of Governmental Cooperation," Forbes.com, July 2019, Available: www.forbes.com
3. Braun, B., Sims, S., Reese, K., Butzin, D., Voss, D., "Navigating the Policy Compliance Roadmap for Small Satellites," AIAA / USU Conference on Small Satellites, Logan, UT, 2016.
4. Braun, B., Sims, S., "The Policy Compliance Roadmap for Small Satellites," The Aerospace Corporation, 2017. Available: https://aerospace.org/paper/policy-compliance-roadmap-small-satellites
5. Read, A., Chang, P., Braun, B., and Voelkel, D., TOR-2016-02946: *Rideshare Mission Assurance and the Do No Harm Process*. El Segundo, CA: The Aerospace Corporation, 2016.
6. Read, A., Chang, P., Braun, B., "Rideshare Mission Assurance on Multi-Payload Missions," AIAA/ USU Conference on Small Satellites, Logan, UT, 2015