SpaceX - Continuing to Drive Launch Costs Down and Launch Opportunities Up for the Small Sat Community

Lauren Dreyer, Brian Bjelde, Dustin Doud, Kimberly Lord
SpaceX
1 Rocket Road, Hawthorne; 310-363-6000
Lauren@spacex.com

ABSTRACT

SpaceX is revolutionizing access to space for the satellite community by providing highly reliable, low cost launch services. To this end, SpaceX has developed a family of orbital transportation solutions and aims to reduce the price of launch services by an order of magnitude. The small satellite community is critical to the future of our industry. SpaceX is committed to providing reliable, timely, and cost-effective launch services and will continue to innovate in this capacity. An overview of these efforts and how they will positively impact the small satellite community are discussed.

In 2010, SpaceX conducted two consecutive successful launches of its Falcon 9 launch vehicle and Dragon spacecraft, proving their capability and becoming the first commercial company to ever return a private spacecraft from orbit. Initial analysis shows Dragon will be reusable – an important factor in reducing long term costs of access to space. In addition to the near-perfect missions of this medium-class launcher and cargo transportation system, great strides were made for the small satellite community.

SPACEX OVERVIEW

SpaceX was founded in 2002 specifically to increase the reliability and decrease the cost of space transportation. Falcon 1, our pathfinder vehicle, provided light-lift capability. Falcon 9, the current workhorse of the SpaceX fleet of launch vehicles, provides medium-lift capability. Falcon Heavy, recently unveiled and set for delivery to Vandenberg Air Force Base at the end of 2012, is an intermediate- to heavy-lift launch vehicle. These launch vehicles can deliver spacecraft into a range of inclinations and altitudes, from low Earth orbit (LEO) to geosynchronous orbit (GEO) to planetary missions. The Dragon spacecraft further enhances our services by providing transportation to and from Earth for cargo, experiments, and eventually crew.

Falcon 9 is a two-stage vehicle powered by liquid oxygen (LOX) and rocket-grade kerosene (RP-1). The launch vehicle can carry up to 13,150 kg (29,000 lb) into LEO and up to 4,540 kg (10,000 lb) into geosynchronous transfer orbit (GTO). Falcon 9 has a 5.2-m (17 ft) diameter fairing and is the result of SpaceX's goal to produce an evolved expendable launch vehicle (EELV)-class system with significant improvements in reliability, cost and responsiveness over existing vehicles. Falcon 9 offers breakthrough reliability because the nine Merlin engines that power the first stage offer engine-out redundancy. In fact, Falcon 9 is the first American launch vehicle since the Saturn V to offer such redundancy and reliability. The vehicle is designed with the goal of carrying humans into space aboard the Dragon spacecraft. In 2010, the inaugural flight of Falcon 9 and the subsequent demonstration flight carried out as part of NASA's Commercial Orbital Transportation Services (COTS) program were both successful, with all mission objectives met.

Falcon Heavy, currently in development, will be capable of lifting over 53 metric tons (117,000 lb) to low Earth orbit, launching satellites and interplanetary spacecraft far beyond distances reachable by other launch vehicles operating today. The first stage is composed of three nine-engine cores, generating 1,700 metric tons (3.8 million lb) of thrust at liftoff. Propellant cross-feed from the side boosters to the center core leaves the center core with most of its propellant after the side boosters separate. Falcon Heavy performance thus compares with that of a three-stage launch vehicle, but is achieved with one less ignition in flight and increased reliability. Falcon Heavy will be delivered to the SpaceX launch complex at

Vandenberg Air Force Base in California at the end of 2012, with liftoff to follow soon after that.

The Dragon spacecraft was developed under the COTS program to fulfill the cargo resupply needs of the International Space Station (ISS) after the shuttle is retired. The free-flying spacecraft can transport pressurized and unpressurized cargo, and a modular rack system accommodates pressurized cargo of various standard sizes and forms. Dragon has all the subsystems and functions required for on-orbit operations and maneuvers, including avionics; guidance, navigation, and control; propulsion; power generation and distribution; thermal control; and environmental control inside the pressurized capsule. The spacecraft is fully recoverable and capable of returning cargo to Earth. All structures and mechanisms in Dragon are designed to support crew transportation, and Dragon may one day transport astronauts as well as cargo.

DragonLab will offer fully commercial, free-flying missions independent of any ISS service missions for NASA. The spacecraft will be able to carry thousands of kilograms of payloads, experiments, instruments, and sensors into space and return them to Earth, commercializing access to microgravity. DragonLab offers the opportunity to get in-space results, acquire flight heritage and raise technology readiness levels much faster and likely at lower costs than typical ground-test approaches. Missions can last from 1 week to 2 years, depending on customer requirements. The first DragonLab mission is scheduled for launch in 2013, with at least one flight per year thereafter.

The SpaceX corporate structure is flat and our business processes are lean, a combination that yields expedited decision-making and delivery. Our products are designed to require fewer infrastructure facilities (production and launch) with low overhead for maintenance. Our vehicle design teams are co-located with Production and Quality Assurance staff to tighten the feedback loop for these critical disciplines; the result is highly producible, low-cost designs with quality embedded.

SpaceX has demonstrated core competency in rapid and efficient development, operating under unprecedented timeframes and setting the bar for low development costs. In sum, in 9 years SpaceX has:

- Developed, built, tested and successfully launched the Falcon 1 and Falcon 9 vehicles, with four continually upgraded versions of the Merlin engine and two versions of the second-stage Kestrel engine.
- Developed, built, tested, successfully launched and recovered the reusable Dragon spacecraft.
- Successfully developed manufacturing capabilities, testing facilities, and two launch pads.

FACILITIES, IN BRIEF

SpaceX headquarters in Hawthorne, CA, is currently a 700,000-sq-ft facility with modern office, manufacturing and production space. One of the largest manufacturing facilities in California, it accommodates multiple Falcon 9 manufacturing lines, nearly two dozen Merlin engine assembly stations, and Dragon capsule production areas. The latest technology for machining, quality control, welding, and composite production is used, and the site includes testing laboratories, thermal chambers, and a mission control center. Almost 1,100 employees work at the facility, conveniently located a few miles east of Los Angeles International Airport (LAX).

All structural and propulsion testing takes place at the SpaceX Rocket Development Facility in McGregor, TX. Since beginning operations in McGregor in 2003, SpaceX has invested $50 million in upgrading the existing infrastructure. The site has state-of-the-art remote and/or automatic controls and high-speed data acquisition systems, and more than 1,800 engine test have been conducted on the multiple test stands there. The facility is fully staffed with over 100 test and propulsion engineers, technicians and management personnel. The SpaceX facility, originally 300 acres, is now more than twice that size. The site was used by Beal Aerospace until 1998 and is now part of the McGregor Industrial Park, located just 2 hours from Austin and Dallas-Fort Worth.

SpaceX currently uses the launch site at Space Launch Complex 40 (SLC-40), former home of the Titan IV heavy lift rockets, on Cape Canaveral Air Force Station (CCAFS), Florida. This site will also accommodate Falcon 9 Heavy missions. We are also establishing a launch facility at Vandenberg Air Force Base (VAFB) in central California to meet customer needs for polar and sun-synchronous capability. We are working with the US Air Force to finalize the details of the Falcon launch site at Space Launch Complex 4 East (SLC-4E), an existing pad at Vandenberg.

FALCON 9 OVERVIEW & FLIGHT HERITAGE

Falcon 9 is a two-stage launch vehicle powered by liquid oxygen and rocket-grade kerosene (RP-1). Our design philosophy is rooted in architectural simplicity, and with Falcon 9 we adhered to the same principles as with its predecessor, Falcon 1, including an emphasis on minimizing or even eliminating failure modes. Further, our large structural design and flight control margins mean our launch vehicle boasts the kind of high launch availability that facilitates flexible manifests and launch schedules.

Figure 1: Falcon 9 Liftoffs on June 4, 2010

By using nine engines in the first stage, Falcon 9 offers propulsion redundancy—a reliability feature no other major launch system can claim. Falcon 9 has engine-out capability starting early in the first-stage burn. Late in the first-stage burn, Falcon 9 nominally shuts down two engines to limit acceleration. In fact, the Falcon 9 can successfully continue a mission even without two of its nine first-stage engines.

For added reliability, the second-stage engine has dual-redundant pyrophoric igniters with four injection ports. All engines are gimbaled for thrust vector control.

The second-stage tank of the Falcon 9 is simply a shorter version of the first-stage tank and uses most of the same tooling, material and manufacturing techniques. The result is increased production efficiencies and resulting schedule assurance.

The second-stage Merlin Vacuum engine can restart multiple times in orbit. Falcon 9 can place multiple payloads into different orbits, with the amount of orbit change between payloads driven by payload mass and orbit altitude.

The Falcon 9 propellant tank walls and domes are made from an aluminum-lithium alloy. SpaceX manufactures the tanks using friction stir welding, the strongest and most reliable welding technique available. The interstage, which connects the first and second stages and holds the mount for the stage separation system, is a composite structure with an aluminum honeycomb core and carbon fiber face sheets. The current design of the fairing is 5.2-m (17 ft) in diameter.

The Falcon 9 avionics have fault-tolerant architecture, and satellite customers benefit from the redundancies employed with the aim of meeting human-rating requirements and eventually transporting crew. Avionics include ruggedized flight computers, Global Positioning System (GPS) receivers, inertial measurement units, SpaceX-designed and manufactured controllers for vehicle control (propulsion, valve, pressurization, separation, and payload interfaces), and a C-band transponder for range safety tracking. Falcon 9 transmits telemetry from both the first and second stages, even after separation. S-band transmitters are used for both telemetry and video.

The guidance and navigation algorithms for Falcon 9 launch vehicles have been heavily influenced by the algorithms used on other launch vehicles, including SpaceX's own Falcon 1. If an engine is lost during first-stage burn, the guidance system takes into account the anomaly and adjusts the targeted trajectory. This mix of explicit and perturbation guidance schemes was selected to generate a smooth, computationally simple trajectory while maintaining orbital insertion accuracies.

On the inaugural Falcon 9 mission, for example, the targeted orbit was a 250-km circular orbit with a 34.5-deg inclination; the flight culminated with the second stage and Dragon spacecraft qualification unit inserted into a 249.2-km x 253.1-km at 34.49-deg inclination, well within 1-sigma accuracy estimates. During the second Falcon 9 mission (COTS Demo 1), the target was a 300-km circular orbit with a 34.5-deg inclination. The flight culminated with the Dragon spacecraft inserted into a 287.7-km x 300.8-km at 34.53-deg inclination orbit.

Falcon 9 has had two consecutive mission successes. The launch vehicle first reached Earth orbit in its inaugural flight on June 4, 2010, and confirmed its capabilities during its first demonstration flight for NASA under the COTS program on December 8, 2010. Key technical risks were mitigated by these flights, which included the successful demonstration of—

- Multi-engine ignition.
- Hold down and release of the launch vehicle, including umbilical release.
- Stage separation.
- Second-stage engine ignition.
- Nosecone separation.

- In-space operation of the second-stage Merlin Vacuum engine.
- Orbit target and insertion accuracy.
- Payload (Dragon) separation.
- Second-stage re-ignition and shutdown.
- Telemetry acquisition and dissemination.

All primary mission objectives were met, with nominal insertions of the second stage and Dragon spacecraft into the desired orbits. During the inaugural flight, the Dragon qualification unit was inserted into a 249.2 km x 253.1 km orbit at 34.49 deg inclination. The target was a 250-km circular orbit with 34.5-deg inclination. This targeted orbit was subsequently modified by a brief restart of the second-stage engine. In the second mission, the Dragon was inserted into a 287.7 km x 300.8 km orbit at 34.53-deg inclination. The target was a 300-km circular orbit with a 34.5-deg inclination. After Dragon separation, the second-stage Merlin Vacuum engine was restarted for 20 seconds, reaching a high-altitude apogee and demonstrating GTO mission readiness.

Further, SpaceX gathered important data on vehicle performance and environments during both flights. The data is being used in the final preparations for the next NASA COTS demonstration flight.

The first two Falcon 9s flew with the Dragon spacecraft, rather than a fairing. However, SpaceX experience designing, developing and qualifying fairings was established with four of four successful fairing separations on Falcon 1 flights and the nosecone deployment during the December 8, 2010, Falcon 9 flight.

DRAGON OVERVIEW & FLIGHT HERITAGE

Dragon is a fully autonomous spacecraft that contains all the structure and subsystems required for transporting pressurized and unpressurized cargo to and from the International Space Station (ISS) or other orbital platforms. Developed in support of NASA's Commercial Orbital Transportation Services (COTS) program, Dragon can deliver at least 2,550 kg (5,600 lb) of cargo to the ISS. The Dragon spacecraft made history on December 8, 2010, when it became the first private-sector spacecraft to enter the Earth's atmosphere and be successfully recovered (Figure 2).

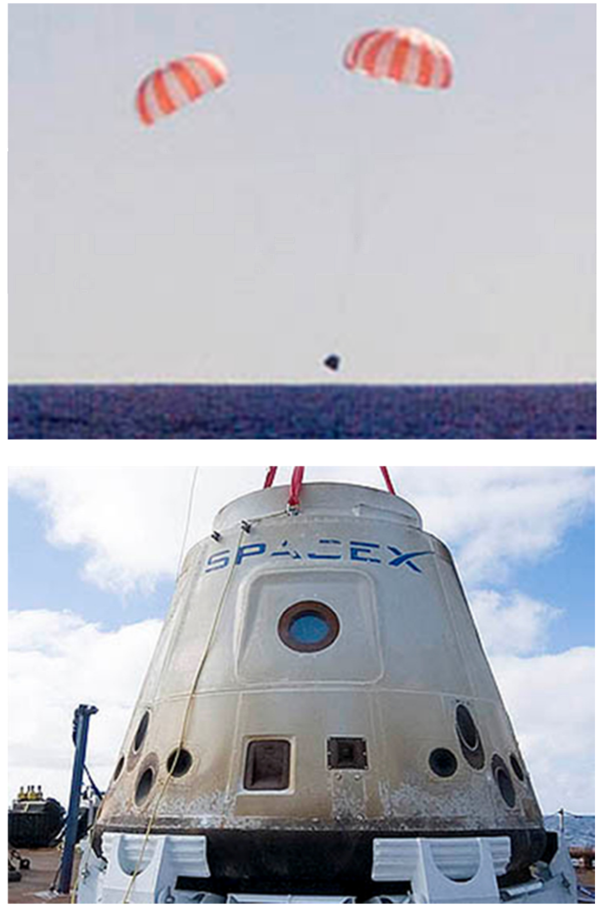

Figure 2: After a Successful Splashdown (top), Dragon Was Recovered After Its Inaugural Orbit (bottom) in December 2010

Dragon is shaped like a traditional reentry capsule, with a nosecone that is jettisoned like a payload fairing during the climb to orbit. It includes a pressurized section, a service section, and a trunk.

The maximum usable pressurized cargo volume is 10 m^3, and a modular cargo rack system accommodates pressurized cargo of various standard sizes and shapes.

The service section forms an unpressurized torus around the base of the pressurized section and includes the main heat shield, tanks for propellant and pressurized gas, thrusters, parachutes, additional avionics, and the trunk attachment. The capsule portion of Dragon, consisting of the pressurized section and the toroidal service section, is fully recoverable.

The trunk supports the capsule during ascent and remains attached to Dragon until shortly before reentry. The trunk contains a cargo carrier designed to support unpressurized cargo and flight releasable attach mechanisms (FRAMs). The trunk section can also be used to carry and deploy small spacecraft. SpaceX is evaluating the feasibility of integrating an evolved expendable launch vehicle (EELV) secondary payload adapter (ESPA) ring into this area.

Dragon is equipped with a heat shield and other recovery systems for a controlled atmospheric reentry. In preparation for reentry, Dragon performs a de-orbit burn then jettisons the unpressurized trunk along with any unpressurized cargo. In the December 2010 flight, Dragon executed a splashdown in the ocean under parachutes, and SpaceX led an ocean recovery.

The company plans to examine the feasibility of reusing the Dragon spacecraft.

The Dragon spacecraft made history on December 8, 2010, when it became the first private-sector spacecraft to enter the Earth's atmosphere and be successfully recovered by a commercial entity. Dragon twice circled the Earth during its first mission for NASA under the Commercial Orbital Transportation Services (COTS) program. Dragon orbited the Earth at speeds in excess of 7,600 m/s (17,000 mph) and landed within 1 mile of the center of the targeted landing zone in the Pacific Ocean. The landing took place within 1 minute of the predicted time.

Dragon's first-ever on-orbit performance was 100% successful in meeting test objectives, and the following capabilities were demonstrated:

- Separation from the Falcon 9 second stage.
- Precise firing in orbit of Dragon's 18 Draco engines.
- Orbital maneuvering as well as guidance, navigation and control.
- Ability of heatshield to withstand heat of entry, when temperatures reached more than 3,000 °F.
- Draco engine guidance during entry.
- Deployment of drogue and main parachutes at 10,000 ft to slow the spacecraft's descent to approximately 16 to 18 fps.

SpaceX gathered important data on Dragon's performance and environments. The data are being used to prepare for the second NASA demonstration flight, which involves berthing with the International Space Station as part of the COTS program. Furthermore, Initial analysis shows Dragon will be reusable – an important factor in reducing long term costs of access to space.

SECONDARY CAPABILITIES

With Falcon 9 and Dragon now flight proven, SpaceX is in a position to offer more reliable, affordable and regular flights for the small satellite community. Secondary launch capability is made possible by established interfaces and clear expectations:

- Known interfaces allow for regular incorporation and accommodation of secondary payloads;
- Proliferation of accepted and established standards stimulates development for those interfaces, and accommodation becomes standardized; and,
- Clear expectations of secondary mission management helps maintain low launch prices.

SpaceX has experience in safe, reliable and rapid integration of P-POD class systems. In December 2010 after separation of the Dragon spacecraft from the launch vehicle, six 3U P-PODs containing eight small satellites were deployed from the trunk of Falcon 9 Flight 2, including the US Army's first satellite in 50 years! In this single launch, SpaceX became the world's top provider of CubeSat flights. Furthermore, demonstrating a commitment to responsiveness, SpaceX integrated all six P-PODs, representing five different customers, within a 24 hour period at the SpaceX launch complex at Cape Canaveral Air Force Station, including one P-POD that was contracted only six months prior to launch.

Designed as a reusable upper stage, the Dragon spacecraft will be capable of delivering seven crew or over 2.5 metric tonnes of cargo to Low Earth Orbit (LEO) when launched on board the Falcon 9. Though its design initially addresses cargo and crew, its unique architecture can serve as a host for technology demonstrations and scientific instruments. The spacecraft can effectively serve as a recoverable and reusable host spacecraft bus with its own propulsion, avionics, attitude determination & control, communications, thermal control and power subsystems.

Dragon offers both pressurized and unpressurized payload accommodations, with the former being fully recoverable. Committed to small satellite community and having a backlog of at least 12 Falcon 9/Dragon missions under firm contract, SpaceX expects to have a ready source of reusable Dragon spacecraft, providing functions provided by both an upper stage as well as a spacecraft bus to customers in the future. This continues to decrease the cost to space.

SpaceX currently has the capability to offer launch services to secondary payloads ranging in size from 8kg to 180kg on an ad-hoc basis through various mounting mechanisms including 1U, 3U, 6U, and even ESPA rings. SpaceX is currently developing a firm-fixed price contracting method for launch of secondary payloads that both maximizes launch opportunities for the community and keeps costs low. Final decisions on the preferred business model/relationships are pending as of submission of this paper, and the latest status will be presented at the conference. Feedback is welcomed.

Flight opportunities on future NASA Cargo Resupply Services missions will exist for up to 4 P-PODs per launch. (For these specific flight opportunities, please contact NASA's Launch Services Program office.)

Additionally, SpaceX has studied methods for carrying P-PODs on every Falcon 9 that is produced. Final results of this study are not available as of submission of this paper, and the latest status will be presented at the conference. For more information, contact sales@spacex.com or the author.

Specific to P-PODs, the standard P-POD mission profile deploys P-PODs into the same orbit as the primary payload, after the primary payload has separated. Deployment options for either direct injection or multi-burn trajectories, with no reorientation necessary for P-POD deployment are considered standard. The timing of deployment will depend on the mission; for direct inject missions, the P-PODs will deploy at approximately T+15 minutes with approximately 30 seconds between each P-POD; for two-burn missions, the P-PODs will deploy at approximately T+60 minutes with the same interval between each P-POD deployment. Alternative mission profiles could also be made available as a nonstandard service. These alternatives could include delayed P-POD deployment for ground station coverage, deployment prior to the primary payload, or deployment into multiple orbits.

CONCLUSION

The small satellite community is critical to the future of our industry. SpaceX is committed to providing reliable, timely, and cost-effective launch services and will continue to innovate in this capacity.