ABSTRACT

On 28 September 2008, Space Exploration Technologies (SpaceX) made history when its Falcon 1 became the first privately-developed, liquid-fueled rocket to achieve Earth orbit. This was the fourth flight of the Falcon 1 launch vehicle from the SpaceX launch site on Omelek Island at the U.S. Army Kwajalein Atoll (USAKA) in the central Pacific Ocean. It achieved an elliptical orbit of 621 x 643 km, 9.34 degrees inclination, with full intended performance. With this flight, SpaceX has successfully flight proven 100% of its subsystems including 1st stage ascent, stage separation, 2nd stage ignition, fairing separation, guidance and control accuracies, stage 2 engine shutdown and orbital insertion, payload separation signaling, and stage 2 engine restart capability. A review of the successes and achievements is presented.

The successful flight of SpaceX’s Falcon 1 is both historically noteworthy and represents a major opportunity for the satellite industry to finally have access to a low-cost demonstrated launch capability. Developed by SpaceX to provide reliable, low-cost access to space, the capabilities of the Falcon 1 launch vehicle provide unique opportunities for small satellite programs. Two Falcon 1 vehicles have included accommodations for the carriage of multiple secondary satellites in the mission design. A top-level overview of past multiple payload integration activities is discussed, along with the future plans for the Falcon 1 launch vehicle – which are focused on better servicing the needs of the small satellite community. An overview of these plans and how they will positively impact the small satellite community is discussed.

FALCON 1 LAUNCH VEHICLE

The Falcon 1 is designed to provide the world’s lowest cost access to orbit. The vehicle was designed above all for high reliability, followed by low cost and a benign payload flight environment.

Overview

The Falcon 1 is a two-stage, liquid oxygen (LOX) and rocket-grade kerosene (RP-1) powered launch vehicle which combines a turbopump-fed first stage powered by a SpaceX-developed Merlin engine with a pressure-fed second stage powered by a SpaceX-developed Kestrel engine.
The first stage of the Falcon 1 generates 78,400 lbf (349 kN) of sea-level thrust using a single Merlin engine. The Merlin rocket engine was designed and developed internally at SpaceX. Like the rest of the Falcon 1, the Merlin was designed for high reliability and low cost. This was achieved by keeping the design as simple as possible and drawing on a long heritage of space-proven engines. The Merlin engine has demonstrated large margins in heat flux, mixture ratio tolerance and turbo pump operating speed during ground testing, and has exceeded the performance goals set during the design phase.

The second stage of the Falcon 1 generates 7,000 lbf (31 kN) of vacuum thrust using a single Kestrel engine, which is capable of multiple on-orbit restarts. Propellant is pressure-fed to the engine via a heated helium blowdown system. Attitude control in pitch and yaw is accomplished via electro-mechanical thrust vector control (TVC) actuators; roll control and on-orbit attitude control are accomplished via cold gas helium thrusters. The second stage is constructed from a lighter aluminum alloy for mass savings. The propellant and oxidizer tanks are separated by a common dome (similar to the design of the first stage).

FLIGHT 4 MISSION OVERVIEW

Overview

On 28 September 2008, SpaceX launched the fourth flight of the Falcon 1 launch vehicle. This mission served as a return to flight of the Falcon 1 following an unsuccessful launch attempt of the Operationally Responsive Space (ORS) “Jumpstart” mission just one month earlier. Like all previous Falcon 1 flights, this mission was launched from the SpaceX facilities on Omelek Island, part of the Reagan Test Site (RTS) located at the Kwajalein Atoll in the Marshall Islands. All launch and control facilities, including the Mission Control Center, the launch pad and the vehicle and payload integration facilities were also developed entirely by SpaceX.

Flight 4 Mission Objectives

The mission objectives for Flight 4 centered on demonstrating the full spectrum of launch and payload deployment capabilities, including:

- Ground control & support systems, including highly autonomous control & operations software
- 1st stage performance and control from lift-off through Main Engine Cut-Off (MECO)
- Vehicle structural performance & margins through lift-off, transonic & max-Q
- Stage separation
- 2nd stage ignition
- Fairing separation
- 2nd stage slosh baffle performance
- 2nd stage engine performance in vacuum
- 2nd stage engine on-orbit restart
- Payload deployment signal transmission & receipt
- Guidance, navigation & control performance through transonic, orbit insertion, coast and restart
- Flight software through all flight domains
- Store and forward data links
- RF links though orbit insertion, recontact for apogee burn, and recontact for first pass
- Launch & flight environments: thermal, acoustic, shock & vibration
- Aero-thermal and base-heating results for both stages

The final orbit achieved had a perigee of 621.55 km, an apogee of 643.21 km, and an inclination of 9.34 degrees based on the averaged NORAD data. As this was a test flight, the 2nd stage carried a spacecraft mass simulator and went into a slightly eccentric parking orbit, with an orbit-raising second burn demonstration over Ascension Island. RF links were established with Roi-Namur (Kwajalein), a down-range vessel, and Ascension Island. The stage then made contact with Kwajalein again during the first orbital pass overhead.

Flight 4 Mission Summary

All of the Flight 4 mission technical objectives were met by this return to flight. The complete success of this mission and the large amount of flight data obtained have greatly reduced the risks for all future Falcon 1 missions.
MULTIPLE PAYLOAD INTEGRATION

Highly reliable, low cost launch services offer considerable opportunities for small satellite programs. Two Falcon 1 mission designs have included accommodations for the carriage of multiple secondary satellites, as described below:

**Flight 3**

Falcon 1 Flight 3 included a Secondary Payload Adapter and Separation System (SPASS) developed and manufactured by Space Access Technologies (SAT) on behalf of ATSB of Malaysia. As shown in Figures 3 and 4, the SPASS allows for a single NanoSat class satellite and multiple PicoSat class satellites to be integrated along with a primary satellite which resides atop the RSA structure. On Flight 3, in addition to the primary ORS Trailblazer satellite, two Poly Picosat Orbital Deployers (P-PODs) were flown; containing the NASA PRESat and NanoSail-D CubeSats.
Flight 5

The mission design for Falcon 1 Flight 5 called for the incorporation of two secondary CubeSats in addition to the primary RazakSAT satellite provided by ATSB of Malaysia. Due to payload mass constraints, it was not possible to include a structure such as the SPASS flown on Flight 3. However, a method of integrating two P-PODs on the underside of the launch vehicle payload adapter was devised, as shown in Figures 5 and 6.

Figure 5: Flight 5 payload configuration

Future Falcon 1 RideShare Opportunities

For small satellites which would otherwise fly as secondary payloads, the Falcon 1 provides the opportunity to fly as a primary for less money than it might cost to fly as a secondary on someone else’s mission. This in turn results in a decreased risk of primary-related delays, due to fewer technical integration considerations and the elimination of the possibility for requirements conflicts.

A unique opportunity provided by the low cost of the Falcon 1 is that of “dedicated secondary missions”, where multiple small satellites which would otherwise compete for secondary slots on a space-available basis are flown together as the primary mission. Such missions could involve payloads from either a single customer which procures the entire launch, or multiple providers. Figures 7 through 9 provide an overview of some existing and contemplated secondary payload adapters which could be used to significantly increase launch opportunities for small and/or secondary satellites.

In addition to the concepts shown, SpaceX is also actively working to develop a commercial offering to specifically address the market for such “dedicated secondary missions”.

Figure 4: Trailblazer satellite atop the SPASS

Figure 5: Flight 5 payload configuration

Figure 6: P-POD mounting beneath the LV payload adapter
Consistent with SpaceX’s corporate philosophy of rapid and continuous improvement, Falcon 1 has a planned upgrade path based upon experience from the demonstration missions. These vehicle enhancements are being implemented as block upgrades and will increase the payload capability beyond that of the original Falcon 1 configuration.

**First Stage Upgrades**

The Merlin engine employed for the first two demonstration flights of the Falcon 1 utilized an ablatively cooled thrust chamber and nozzle. To increase reliability, performance and allow for potential reuse, the chamber and nozzle have been upgraded to regeneratively cooled designs. Because it is able to operate at higher temperatures and pressures, the regeneratively cooled (Merlin 1C) design provides a greater level of thrust, upwards of 125,000 lbf of sea-level thrust.

The full thrust of the Merlin 1C engine will exceed the structural margins of the existing Falcon 1 first stage tank design, which was originally qualified based on the lower thrust of the ablatively cooled engine. In addition, when operating at full thrust, the Merlin 1C
requires an increased propellant flow rate. Therefore, the first stage tank structure will be redesigned and qualified to meet the increased load requirements and propellant needs of the Merlin 1C engine. This full block upgrade, called the Falcon 1e (for enhanced) will be available beginning in the second quarter of 2010. However, as an interim upgrade, the Merlin 1C engine will be flown at a reduced thrust level for operational launches in 2008, 2009, and early 2010.

Second Stage Upgrades
As a weight savings measure, the stage 2 tank material has been changed from aluminum 2219 to a 2014 aluminum alloy. In addition, slosh baffles have been added to both the Fuel and LOX tanks to prevent further occurrences of the stage 2 loss of control anomaly experienced during the Demo 2 mission.

Reliability improvements have been made to the Kestrel engine, which also allowed for some mass reductions. For the Falcon 1e, additional mass savings will be achieved by changing the second stage tank material to a 2195 aluminum lithium alloy.

Payload Fairing Upgrades
The Falcon 1 employs a bi-conic aluminum payload fairing with a maximum inner diameter of 54 in (1.4 m) and an internal height of 110 in (2.8 m). Minimal changes were made to the fairing assembly in preparation for the operational launches following the Demo 2 mission. For mass savings and to provide increased payload volume, the payload fairing for the Falcon 1e will be a composite ogive with a maximum inner diameter of 61 in (1.55 m) and an internal height of 150 in (3.8 m). A dimensional comparison of the Falcon 1 and Falcon 1e payload fairings is provided in Figure 10.

Increased Payload Capability
The Falcon 1 is capable of delivering a 925 lb (420 kg) satellite into a circular reference orbit of 185 km inclined at 9.1 degrees, as shown in Figure 11. The Falcon 1e will provide an increased payload capability; with the ability to deliver a 2,225 lb (1,010 kg) satellite into a reference orbit of 185 km inclined at 9.1 degrees.

CONCLUSION
Falcon 1 Flight 4 represented a tremendous achievement for SpaceX and represents a major opportunity for the satellite industry to finally have access to a low-cost demonstrated launch capability. The Falcon 1 vehicle upgrade path will ensure that launch manifest commitments are met while continuing to improve on the baseline design, keep cost low, and reliability high. Additionally, the significantly lower cost of the Falcon 1 and Falcon 1e launch vehicles provides the possibility for missions dedicated to addressing the needs of the small satellite community – by allowing for “dedicated secondary missions”.

REFERENCES