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Pegasus XL–HESSI: Last-Minute Decisions in Flight-Based Launch

Background

The *Pegasus XL* flight with the *High Energy Solar Spectroscopic Imager* (*HESSI*) spacecraft aboard was scheduled to launch on February 5, 2002. *HESSI* was the sixth mission in NASA's Small Explorers (SMEX) Program. It was designed to provide high-resolution imaging of solar flares, gigantic explosions on the Sun that can damage orbiting satellites and wreak havoc with radio communications and power grids on Earth. The *Pegasus* rocket was to be dropped from a Lockheed *L-1011* aircraft at approximately 39,000 feet over the Atlantic Ocean, and then ignited to carry the solar explorer on a 10-minute ride to nearly 400 miles above Earth.

Figure 1 - A Pegasus Being Loaded onto a NASA B-52. NASA

The SMEX program provides frequent flight opportunities for highly focused, relatively inexpensive space-science missions. SMEX spacecraft are 180-250 kilograms with an orbit-average power consumption of 50-200 watts. The first five SMEX missions, most of which were launched in *Pegasus* rockets, were:

- Solar Anomalous and Magnetospheric Particle Explorer *(SAMPEX)*

- Fast Auroral Snapshot *(FAST)*
- Submillimeter Wave Astronomy Satellite *(SWAS)*
- Transition Region and Coronal Explorer *(TRACE)*
- Wide-Field Infrared Explorer *(WIRE)*.

Flight-based launches are always dynamic and exciting—even hectic—events for launch teams. As NASA Launch Manager (NLM) Chuck Dovale put it, "That hour of captive carry definitely gets your heartbeat up. As soon as the flight takes off, it's a stress test. It's entirely different from a ground-based mission."

A Long Launch Tradition

The three-stage, solid-motor *Pegasus XL* rocket was built by Orbital Sciences Corporation and assembled at Vandenberg Air Force Base (VAFB) in California. The three Orion motors were developed specifically for the *Pegasus* launcher by Hercules Aerospace, now Alliant Techsystems. An award-winning team led by Dr. Antonio Elias developed the launcher with help from aerospace engineer and pilot Burt Rutan, the designer of the spaceplane *SpaceShipOne*, and Scale Composites.

The first successful *Pegasus* launch occurred on April 5, 1990. Initially, a NASA-owned *B-52 Stratofortress* served as the carrier aircraft. By 1994, Orbital had transitioned to its Lockheed *"Stargazer" L-1011*, a converted airliner. The *Pegasus XL* was introduced in 1994 with lengthened stages to provide an increased payload. At inception, the launch price was just over $6 million; in 2008, it would be approximately $30 million, including extra testing, design and analysis, and launch site support.

The *HESSI* mission was the 32nd flight of the *Pegasus* launch vehicle, the 21st of the *XL* configuration and, with the *L-1011* taking off from Cape Canaveral Air Force Station, the first managed by NASA from Kennedy Space Center. Table 1 contains the *Pegasus XL* specifications.

Mass: 18,500 kilograms (kg) (*Pegasus*); 23,130 (*XL*)
Length: 16.9 meters (m) (*Pegasus*); 17.6 m (*XL*)
Diameter: 1.27 m
Wing span: 6.7 m
Payload: 443 kg (1.18 m dia., 2.13 m length)

Table 1. *Pegasus XL* Specifications.

Figure 2 - Pegasus XL Rocket and Payload Slung under L-1011. NASA image

The Lockheed *L-1011* carries the *Pegasus* attached to its belly. It drops the rocket at 39,000 feet, where it free-falls for about five seconds before the first-stage motor ignites. The first stage burns for 74 seconds, while the guidance and control systems (wing and fin elevons/rudder) keep the attitude within specifications.

After the first stage of the rocket separates, the second stage ignites and burns for 71 seconds. The second and third stages have a thrust vector control system to maintain proper attitude along the flight path. A coasting period occurs after jettison of the fairing halves, followed by second-stage separation. The third stage then ignites for 68 seconds. Following completion of the third-stage burn, *Pegasus* was to carry *HESSI* to its orbit 373 miles above Earth. The entire flight duration to spacecraft separation would be 9 minutes and 42 seconds.

The point of air-launched vehicles, such as *Pegasus*, is simply cost reduction. No blast-proof pad, blockhouse, or associated equipment is needed. The airliner is designed for approximately Mach 0.8, about 3% of orbital velocity; 40,000 feet is only about 10% of the minimum altitude needed for a temporarily stable orbit, and 4% of a generally stable, low-Earth orbit.

Weather is the number-one cause of traditional launch delays. At 40,000 feet, however, the booster is in the stratosphere—above the troposphere and conventional weather. In addition, there is less of a problem with crosswinds in the stratosphere. So, while *Pegasus* launches are generally immune to weather delays once at altitude, there is still the issue of weather complications during takeoff, ascent, and during transit flight to the staging point.

NASA's Launch Services Program, based at Kennedy Space Center, provided mission acquisition, integration, and launch management for the expendable launch-vehicle fleet, including *Pegasus*. The NASA launch manager led the launch team. (See Exhibit 1 for *Pegasus XL's* flight path.)

Making Movies of the Sun

While *Pegasus* was a tried-and-true vehicle, *HESSI* was brand-new. Conceived, developed, and built for Goddard Space Flight Center by the University of California-Berkeley, *HESSI's* sole instrument, the imaging spectrometer, was designed to deliver high-fidelity color movies of solar flares. The bursts, which pack as much energy as a billion megatons of TNT, are the biggest explosions in the solar system.

Figure 3 - Artist's Concept of HESSI Imaging Solar Flares. NASA image

Filming Solar Flares in Hi-Fi

The goal of the two- to three-year *HESSI* mission was to observe as many as a thousand solar flares, capturing X-rays and gamma rays emitted during the powerful explosions. The spectrometer was designed to allow scientists to construct flare images. They would build the images from the patterns of light and shadows produced by the high-energy radiation as it passes through the instrument's grids while the spacecraft rotates.

The preliminary design phase for *HESSI* commenced in October 1998. By early 2000, the 645-pound spacecraft and instrument were ready for launch simulation testing. The simulation test, however, would mark the beginning of more than a year and a half of delays before *Pegasus XL–HESSI* was ready to launch. (See Exhibit 2 for the project launch timeline.)

First, in October 2000, a NASA risk-review team ordered an inspection of *HESSI's* internal electronics boards, delaying the launch. The following month, *HESSI* was delayed further, by a redesign of the *Pegasus XL* by Orbital. This stemmed from the discovery of problems with the separation system between the first and second stages. The problem had been found in a post-launch inspection of the *Pegasus* vehicle that launched into orbit NASA's *HETE-2* satellite.

On June 2, 2001, *Pegasus* and *HESSI* were flown to Cape Canaveral. The same day, a *Pegasus* first stage with NASA's *X-43* hypersonic test craft mounted on it failed and crashed into the Pacific Ocean. The problem was with the rocket's first stage—essentially the same as the *Pegasus XL–HESSI* first stage. This grounded the *HESSI* mission and led to a full investigation. Later that summer, *Pegasus* was cleared when the failure was not attributed to the rocket motor.

The situation was exacerbated on December 13, 2001, when the *HESSI* launch was delayed again. The delay was due to an investigation into a failed military missile launch using an Orbital-built motor. (See launch timeline in Exhibit 2.)

Launch Day: Blue Skies

Finally, it is launch day, February 5, 2002. All the hurdles seem to have been cleared; conditions for launch look favorable. The entire stack—rocket and spacecraft—was mated to the *L-1011* at VAFB four days earlier and ferried to Cape Canaveral for final checkout and launch. Anticipation among the launch team is running high.

Target drop for the *HESSI* spacecraft is scheduled for 3:26 P.M. EST. The *L-1011* has a nominal flight-time to drop point of 58 minutes. Weather is not a factor today: Winds are light, and there are no thunderstorms in the drop box or along the flight path.

There is a two-hour launch window, which allows for a second attempt if the primary one has to be aborted. However, in the history of the *Pegasus* program second attempts have been precluded by launch-window restrictions and concerns about the effects of cold temperatures on *Pegasus* flight hardware. In addition, on prior flights that aborted, the failures were significant enough for the aircraft to return to base without making a second attempt.

Soon after becoming airborne, the *L-1011* experiences the first of several communications dropouts with the mission director's center, where the NASA launch manager (NLM) is located. Communications dropouts are not uncommon in the *Pegasus* program, especially when the aircraft is making the final turn toward the launch point. Before releasing *Pegasus*, the pilot must receive a positive confirmation from the launch conductor (LC), on the ground, and the LC must receive the go (or no-go) from the NLM. The LC is an employee of Orbital Sciences Corporation.

At L-30 minutes, the only technical issue being worked is a lower-than-expected fin actuator system (FAS) temperature. The temperature is trending toward the redline limit listed in the mission constraints document. The redline criterion is that the temperature must be greater than or equal to –25º C (Celsius) prior to drop. The temperature is reading –20º C and is trending downward at a rate of 1º C every 10 minutes.

The technical team is evaluating the flight and acceptance test program (ATP) data. The technical team notes that the FAS went through ATP successfully with a lower limit of –36º C. Because it takes the *L-1011* some 30 minutes to circle around after an abort call, the FAS temperature will clearly violate the launch criteria if the launch does not occur on the first attempt.

Lost Communication: Silence Nearing Final Countdown

As the captive carry, or period after takeoff, progresses to the L–12 point, communication with the aircraft becomes more difficult. The LC starts to experience sporadic communication with the launch panel operator (LPO) onboard the *L-1011*.

During the final portion of the *Pegasus* countdown, as the pilot reaches each waypoint (a point at which the pilot can either proceed or change course), the L clock in the MCD is compared to the L clock onboard the aircraft. Many times, the two clocks do not match exactly—this is normal.[1]

Weather is reported "green" (good to go) at L-9, and waypoint PIP (*Pegasus* initial point) is achieved. At L–8, the NLM gets a go from his team before giving a go to the LC. At L–6, the LC continues to have intermittent communication with the LPO, and has to repeat step callouts and then wait for confirmation. The LC loses communication with the LPO on the primary communications net, but is able to hear the LPO confirm "avionics to internal" on the backup channel. At L–5, the LC loses the backup channel with the LPO for approximately two minutes.

At L–4 minutes (when the *L-1011* navigation unit indicates there are four minutes to the launch point), both clocks are reset and the operation is synchronized from that point forward. No other adjustments to the clocks are made.

When the LPO calls the LC next, he reads out the clock time as L–2:40.

Crunch Time

The launch team is facing critical decisions, with little time to make them. The hour-long stress test during captive carry has reached decision time, with barely two minutes to launch. In addition, the recent problems with *Pegasus* are on the back of everyone's mind.

- *You are part of the technical team.* What is your next step? What is the rationale behind your decision?
- *You are part of the management team.* What is your next step? What is your rationale?

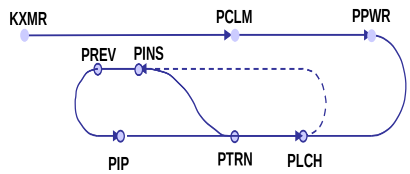
[1] Due in part to the dynamic environment of in-air launches, *Pegasus* is the only program in which clock-nonsynchronization occurs, as opposed to ground-based missions.

Flight Path

Fly Out
PCLM ("P-Climb") is the waypoint that defines the climb out segment

RECYCLE
If an Abort Has Been Declared, Another Launch May Be Attempted and the L-1011 will return to PINS

PPWR
The L-1011 begins a 180 degree turn, underflying the Drop Point



PLCH
LOCC clock is reset to L-25; report on turbulence, winds,and clouds

PTRN
Clock is approximately L-21

PREV
The L-1011 begins second 180 degree course reversal

PIP
The L-1011 rolls out on launch track; clock approximately L-9

Terminal Count
When the L-1011 INS indicates 4 minutes to PLCH ("P-Launch"), the pilot announces L-4 minutes, and the launch clock Is reset to L-4 minutes. All operations are referenced to the clock at that point

Pegasus / HESSI Flight Plan

Waypoint	Lat	Lon	Flight Level	Time (L-min)
KXMR	28°28'N	80°34'W	0	-58
PCLM	28°30'N	79°00'W	280	-43
PPWR	28°30'N	78°00'W	330	-36
PLCH	28°00'N	78°30'W	380	-26
PTRN	28°00'N	79°00'W	390	-22
PINS	28°20'N	79°42'W	390	-16
PREV	28°20'N	80°00'W	390	-14
PIP	28°00'N	79°50'W	390	-09
PLCH	28°00'N	78°30'W	390	-00

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Exhibit 1: *Pegasus XL* Flight Path

Source: NASA Kennedy Space Center Launch Director; Orbital Sciences Corporation

Date	Event
March 2000	*HESSI* badly damaged during vibration testing at Jet Propulsion Laboratory to simulate launch conditions. (Improper maintenance and oversight of the "shaker" mechanism faulted). *HESSI* rebuilt; launch reset for mid-November 2000.
Late spring 2000	*HESSI* spacecraft bolted to *Pegasus* at VAFB. *HESSI* and *Pegasus* mounted to *L-1011* carrier jet for flight to Cape Canaveral Air Force Station, Florida.
October/November 2000	Launch postponed when a NASA risk-review team orders inspection of *HESSI's* internal electronics boards. Launch reset for March 28, 2001. Post-launch analysis of a *Pegasus* rocket that carried NASA's *HETE-2* satellite into orbit reveals technical problem with separation system between first and second stages. Redesign of the system by Orbital Sciences Corp. and NASA slips *HESSI* launch date to June 7, 2001.
June 2, 2001	*Pegasus* and *HESSI* flown to Cape Canaveral. *Pegasus*/*X-43* mishap same day. Estimated delay for *HESSI* launch is brief, but with batteries on *Pegasus* nearing expiration, rocket and spacecraft are returned to VAFB for servicing.
Summer 2001	NASA inquiry of the *X-43* mishap continues through summer; *HESSI* hangared at VAFB.
December 20, 2001	*HESSI* is reattached to *Pegasus* in preparation for January 24, 2002 launch date.
December 2001/January 2002	Launch delayed for final time due to investigation of a December 13, 2001 failed military-missile launch, using a motor built by the same company that builds stages of *Pegasus*.
February 1, 2002	*Pegasus* and *HESSI* flown back to Cape Canaveral for February 5 launch attempt.
February 5, 2002	*Pegasus* and *HESSI* launched.

Exhibit 2: *Pegasus XL–HESSI* Launch Timeline: Setbacks and Schedule Slips

Sources: Justin Ray, "The Saga of HESSI," *Spaceflight Now*, February 3, 2002; Todd Halverson, "Pegasus Investigation Delays Solar Satellite Launch," space.com, June 8, 2001, http://www.space.com/businesstechnology/technology/x43a_pegasus_hessi_010608.html.