Northrop Grumman Pegasus

Pegasus is an air-launched rocket developed by Orbital Sciences Corporation and now built and launched by Northrop Grumman. Capable of carrying small payloads of up to 443 kilograms (977 lb) into low Earth orbit, Pegasus first flew in 1990 and remains active as of 2019. The vehicle consists of three solid propellant stages and an optional monopropellant fourth stage. Pegasus is released from its carrier aircraft at approximately 40,000 ft (12,000 m), and its first stage has a wing and a tail to provide lift and attitude control while in the atmosphere. Notably, the first stage does not have a Thrust Vector Control (TVC) system.[1] Pegasus is the world's first privately developed space launch vehicle.[2]

Contents

Pegasus

Pegasus XL attached to mothership Stargazer

Function	Launch vehicle
Manufacturer	Northrop Grumman
Country of origin	United States
Cost per launch	US$40 million [1] (http://www.gao.gov/products/GAO-17-609)
	Size
Height	16.9 meters (55 ft) (Pegasus) 17.6 meters (58 ft) (Pegasus XL)
Diameter	1.27 meters (4.2 ft)
Mass	18,500 kilograms (40,800 lb) (Pegasus) 23,130 kilograms (50,990 lb) (Pegasus XL)
Stages	3
	Capacity
	Payload to LEO
Mass	443 kilograms (977 lb) (1.18 by 2.13 meters (3.9 ft × 7.0 ft))
	Associated rockets
Family	Air launch to orbit
Derivatives	Minotaur-C
	Launch history
Status	Active
Launch sites	Air launch to orbit
Total launches	44
Success(es)	39
Failure(s)	3
Partial failure(s)	2
First flight	5 April 1990 (Pegsat / NavySat)
Last flight	11 October 2019 (ICON)

History

Pegasus was designed by a team led by Antonio Elias.[3] The Pegasus's three Orion solid motors were developed by Hercules Aerospace (later Alliant Techsystems) specifically for the Pegasus launcher but using advanced carbon fiber, propellant formulation and case insulation technologies originally developed for the terminated USAF Small ICBM program. The wing and fins' structures were designed by Burt Rutan and his company, Scaled Composites, which manufactured them for Orbital.

- Mass: 18,500 kg (Pegasus), 23,130 kg (Pegasus XL)[1]:3
- Length: 16.9 m (Pegasus), 17.6 m (Pegasus XL)[1]:3
- Diameter: 1.27 m
- Wing span: 6.7 m
- Payload: 443 kg (1.18 m diameter, 2.13 m length)

Started in the spring of 1987,[4] the development project was funded by Orbital Sciences Corporation and Hercules Aerospace, and did not receive any government funding.[5] NASA did provide the use of the B-52 carrier aircraft on a cost-reimbursable basis during the development (captive carry tests) and the first few flights. Two Orbital internal projects, the Orbcomm communications constellation and the OrbView observation satellites, served as anchor customers to help justify the private funding. [6]

DARPA purchased the first flight and options for five more, but only exercised the first of the five options. The DARPA contract was subsequently transferred to the U.S. Air Force which exercised the remaining four options. In 1993 NASA issued a Request for Proposals for a Small Expendable Launch Vehicles Services (SELVS) requiring a performance slightly higher than the original Pegasus, resulting in Orbital and Hercules developing the XL version to satisfy the NASA SELVS requirement.

There were no Pegasus test launches prior to the first operational launch on April 5, 1990 with NASA test pilot and former astronaut Gordon Fullerton in command of the carrier aircraft. Initially, a NASA-owned B-52 Stratofortress NB-008 served as the carrier aircraft. By 1994, Orbital had transitioned to their "Stargazer" L-1011, a converted airliner which was formerly owned by Air Canada. The name "Stargazer" is an homage to the television series *Star Trek: The Next Generation*: the character Jean-Luc Picard was captain of a ship named *Stargazer* prior to the events of the series, and his first officer William Riker once served aboard a ship named *Pegasus*.[7]

During its 44-launch history, the Pegasus program had three mission failures (STEP-1, STEP-2 and HETI/SAC-B), and two partial failures, (USAF Microsat and STEP-2) followed by 30 consecutive successful flights for a total program success rate of 89%.[8] The first partial failure on July 17, 1991 caused the 7 USAF microsatellites to be delivered to a lower than planned orbit, significantly reducing the mission lifetime. The last mission failure on November 4, 1996 resulted in the loss of gamma-burst identifying satellite HETE (High Energy Transient Explorer) in 1996.[9]

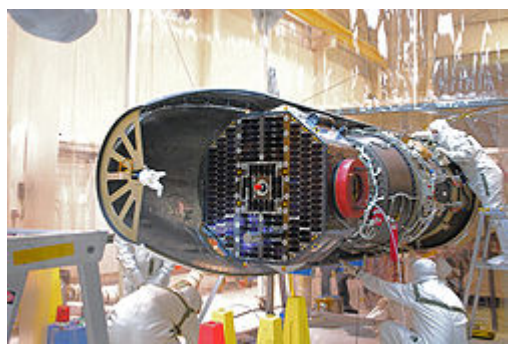
The Pegasus XL, introduced in 1994 has lengthened stages to increase payload performance. In the Pegasus XL, the first and second stages are lengthened into the Orion 50SXL and Orion 50XL, respectively. Higher stages are unchanged; flight operations are similar. The wing is strengthened slightly to handle the higher weight. The standard Pegasus has been discontinued; the Pegasus XL is still active as of 2019. Pegasus has flown 44 missions in both configurations, launching 91 satellites as of October 12, 2019.[10][11]

Preparations for launch of Pegasus XL carrying the NASA Interstellar Boundary Explorer (IBEX) spacecraft.

Dual payloads can be launched, with a canister that encloses the lower spacecraft and mounts the upper spacecraft. The upper spacecraft deploys, the canister opens, then the lower spacecraft separates from the third-stage adapter. Since the fairing is unchanged for cost and aerodynamic reasons, each of the two payloads must be relatively compact. Other multiple-satellite launches involve "self-stacking" configurations, such as the ORBCOMM spacecraft.

For their work in developing the rocket, the Pegasus team led by Antonio Elias was awarded the 1991 National Medal of Technology by U.S. President George H. W. Bush.

The initial launch price offered was US$6 million, without options or a HAPS (Hydrazine Auxiliary Propulsion System) maneuvering stage. With the enlargement to Pegasus XL and the associated improvements to the vehicle, baseline prices increased. In addition, customers usually purchase additional services, such as extra testing, design and analysis, and launch-site support.[12]



The Pegasus XL with fairing removed exposing payload bay and the IBEX satellite

As of 2015, the most recent Pegasus XL to be purchased—a planned June 2017 launch of NASA's Ionospheric Connection Explorer (ICON) mission—had a total cost of $56.3 million, which NASA notes includes "firm-fixed launch service costs, spacecraft processing, payload integration, tracking, data and telemetry and other launch support requirements."[12] A series of technical problems delayed this launch, which finally took place on 11 October 2019.

In July 2019, it was announced that Northrop had lost the launch contract of the IXPE satellite to SpaceX. IXPE had been planned to be launched by a Pegasus XL rocket, and had been designed so as to fit within the Pegasus XL rocket constraints. With the IXPE launch removed from the Pegasus XL rocket, there are currently (as of 12 October 2019, after the launch of ICON) no space launch missions announced for the Pegasus XL rocket. The future (under construction as of 2019) NASA Explorer program mission PUNCH was planned to be launched by Pegasus XL; but then NASA decided to merge the launches of PUNCH and another Explorer mission, TRACERS (also under construction as of 2019). These two space missions, consisting of 6 satellites in total, are to be launched by one rocket. It is expected that a larger launcher will be chosen for this dual mission launch. [13]

Northrop has 2 Pegasus XL's remaining in its inventory (as of 12 October 2019). It is looking for customers for those rockets. Northrop does not plan on retiring the Pegasus XL rocket as of October 2019.[14]

For many small satellites it is desirable to be the primary payload and be placed into the orbit desired, rather than be a secondary payload placed in a compromise orbit. For example, Pegasus launched from equatorial launch sites can put spacecraft in orbits avoiding the South Atlantic Anomaly (a high radiation region over the South Atlantic Ocean) which is desirable for many scientific spacecraft. For some payloads, this may justify the higher cost of Pegasus relative to satellites launched as secondary cargoes on larger launchers.

Launch profile

In a Pegasus launch, the carrier aircraft takes off from a runway with support and checkout facilities. Such locations have included Kennedy Space Center / Cape Canaveral Air Force Station, Florida; Vandenberg Air Force Base and Dryden Flight Research Center, California; Wallops Flight Facility, Virginia; Kwajalein Range in the Pacific Ocean, and the Canary Islands in the Atlantic. Orbital offers launches from Alcantara, Brazil, but no known customers have performed any.

Orbital's Lockheed L-1011 Stargazer launches Pegasus carrying the three Space Technology 5 satellites, 2006

Upon reaching a predetermined staging time, location, and velocity the aircraft releases the Pegasus. After five seconds of free-fall, the first stage ignites and the vehicle pitches up. The 45-degree delta wing (of carbon composite construction and double-wedge airfoil) aids pitch-up and provides some lift. The tail fins provide steering for first-stage flight, as the Orion 50S motor does not have a thrust-vectoring nozzle.

Approximately 1 minute and 17 seconds later, the Orion 50S motor burns out. The vehicle is at over 200,000 feet (61 km) in altitude and hypersonic speed. The first stage falls away, taking the wing and tail surfaces, and the second stage ignites. The Orion 50 burns for approximately 1 minute and 18 seconds. Attitude control is by thrust vectoring the Orion 50 motor around two axes, pitch and yaw; roll control is provided by nitrogen thrusters on the third stage.

Midway through second-stage flight, the launcher has reached a near-vacuum altitude. The fairing splits and falls away, uncovering the payload and third stage. Upon burnout of the second-stage motor, the stack coasts until reaching a suitable point in its trajectory, depending on mission. Then the Orion 50 is discarded, and the third stage's Orion 38 motor ignites. It too has a thrust-vectoring nozzle, assisted by the nitrogen thrusters for roll. After approximately 64 seconds, the third stage burns out.

A fourth stage is sometimes added for a higher altitude, finer altitude accuracy, or more complex maneuvers. The HAPS (Hydrazine Auxiliary Propulsion System) is powered by three restartable, monopropellant hydrazine thrusters. As with dual launches, the HAPS cuts into the fixed volume available for payload. In at least one instance, the spacecraft was built around the HAPS.

Guidance is via a 32-bit computer and an IMU. A GPS receiver gives additional information. Due to the air launch and wing lift, the first-stage flight algorithm is custom-designed. The second- and third-stage trajectories are ballistic, and their guidance is derived from a Space Shuttle algorithm.

Carrier aircraft

Pegasus engine fires following release from its host, a Boeing B-52 Stratofortress, 1991

The carrier aircraft (initially a NASA B-52, now an L-1011 owned by Orbital) serves as a booster to increase payloads at reduced cost. 40,000 feet (12,000 m) is only about 4% of a low earth orbital altitude, and the subsonic aircraft reaches only about 3% of orbital velocity, yet by delivering the launch vehicle to this speed and altitude, the reusable aircraft replaces a costly first-stage booster.

The single biggest cause of traditional launch delays is weather. Carriage to 40,000 feet takes the Pegasus above the troposphere, into the stratosphere. Conventional weather is limited to the troposphere, and crosswinds are much gentler at 40,000 feet. Thus the Pegasus is largely immune to weather-induced delays and their associated costs, once at altitude. (Bad weather is still a factor during takeoff, ascent, and the transit to the staging point).

Air launching reduces range costs. No blastproof pad, blockhouse, or associated equipment are needed. This permits takeoff from a wide variety of sites, generally limited by the support and preparation requirements of the payload. The travel range of the aircraft allows launches at the equator, which increases performance and is a requirement for some mission orbits. Launching over oceans also reduces insurance costs, which are often large for a vehicle filled with volatile fuel and oxidizer.

Launch at altitude allows a larger, more efficient, yet cheaper first-stage nozzle. Its expansion ratio can be designed for low ambient air pressures, without risking flow separation and flight instability during low-altitude flight. The extra diameter of the high-altitude nozzle would be difficult to gimbal. But with reduced crosswinds, the fins can provide sufficient first-stage steering. This allows a fixed nozzle, which saves cost and weight versus a hot joint.

A single-impulse launch results in an elliptical orbit, with a high apogee and low perigee. The use of three stages, plus the coast period between second- and third-stage firings, help to circularize the orbit, ensuring the perigee clears the Earth's atmosphere. If the Pegasus launch had begun at low altitude, the coast period or thrust profile of the stages would have to be modified to prevent skimming of the atmosphere after one pass.

For launches which do not originate from Vandenberg Air Force Base, the carrier aircraft is also used to ferry the assembled launch vehicle to the launch site. For such missions, the payload can either be installed at the base and ferried by the launch vehicle or be installed at the launch site.

In October 2016, Orbital ATK announced a partnership with Stratolaunch Systems to launch Pegasus-XL rockets from the giant Scaled Composites Stratolaunch, which could launch up to three Pegasus-XL rockets on a single flight.[15]

Related projects

Pegasus XL at the Steven F. Udvar-Hazy Center

Pegasus components have also been the basis of other Orbital Sciences Corporation launchers.[16] The ground-launched Taurus rocket places the Pegasus stages and a larger fairing atop a Castor 120 first stage, derived from the first stage of the MX *Peacekeeper* missile. Initial launches used refurbished MX first stages.

The Minotaur I, also ground-launched, is a combination of stages from Taurus launchers and Minuteman missiles, hence the name. The first two stages are from a Minuteman II; the upper stages are Orion 50XL and 38. Due to the use of surplus military rocket motors, it is only used for US Government and government-sponsored payloads.

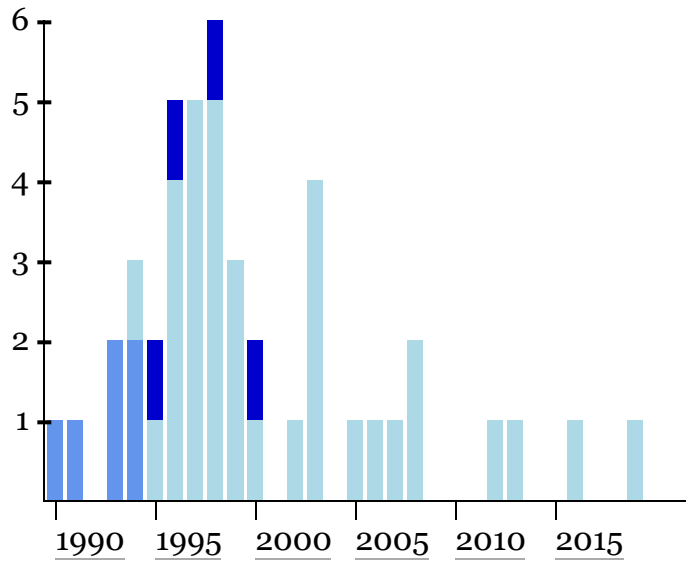
A third vehicle is dubbed Minotaur IV despite containing no Minuteman stages. It consists of a refurbished MX with an Orion 38 added as a fourth stage.

The NASA X-43A hypersonic test vehicles were boosted by Pegasus first stages. The upper stages were replaced by exposed models of a scramjet-powered vehicle. The Orion stages boosted the X-43 to its ignition speed and altitude, and were discarded. After firing the scramjet and gathering flight data, the test vehicles also fell into the Pacific.

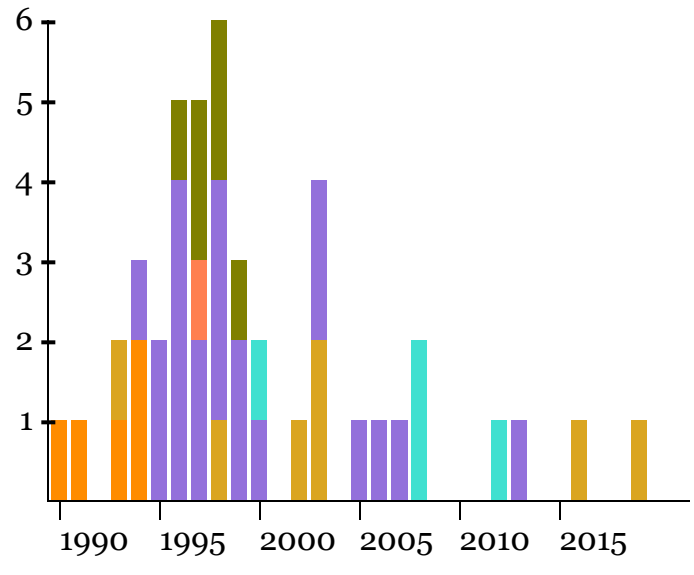
The most numerous derivative of Pegasus is the booster for the Ground-based Midcourse Defense (GBMD) interceptor, basically a vertical (silo) launched Pegasus minus wing and fins, and with the first stage modified by addition of a Thrust Vector Control (TVC) system.

Launch statistics

Rocket configurations

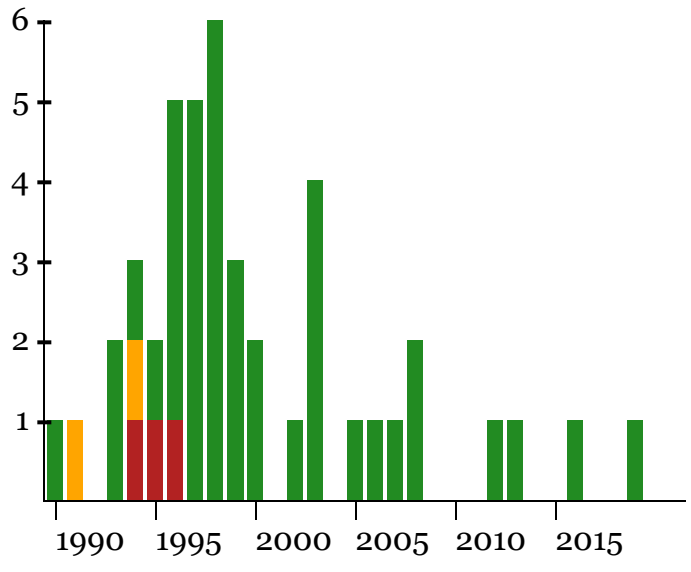


Launch sites

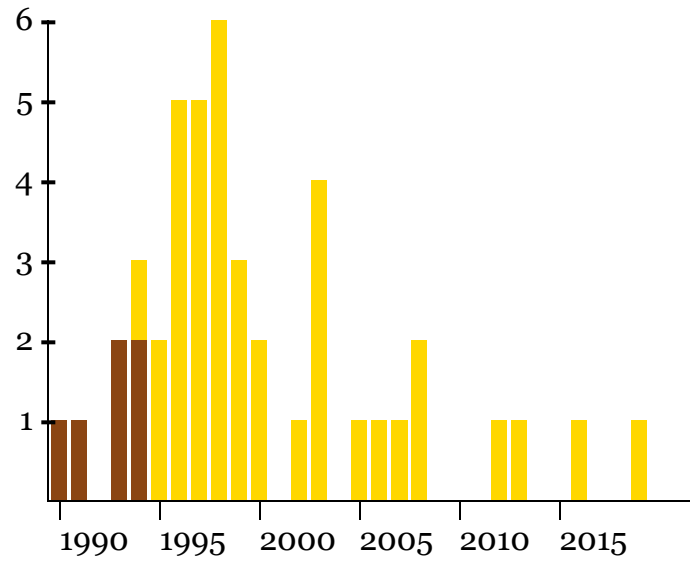


Standard
XL
Hybrid
Edwards AFB
Cape Canaveral
Vandenberg
Base Aerea de Gando
Wallops Flight Facility
Kwajalein Atoll

Launch outcomes



Carrier airplane



Failure
Partial failure
Success
Planned
B-52
L-1011

Launch history

Pegasus has flown 44 missions between 1990 and 2019.[10]

Flight №	Date / time (UTC)	Rocket, Configuration	Launch site	Payload	Payload mass	Orbit	Customer	Launch outcome
1	April 5, 1990 19:10:17	Standard (B-52)	Edwards AFB	Pegsat, NavySat				Success
2	July 17, 1991 17:33:53	Standard w/ HAPS (B-52)	Edwards AFB	Microsats (7 satellites)				Partial failure
	Orbit too low, spacecraft reentered after 6 months instead of planned 3-years lifetime							
3	February 9, 1993 14:30:00	Standard (B-52)	Kennedy Space Center	SCD-1				Success
4	April 25, 1993 13:56:00	Standard (B-52)	Edwards AFB	ALEXIS – Array of Low Energy X-ray Imaging Sensors				Success
5	May 19, 1994 17:03:00	Standard w/ HAPS (B-52)	Edwards AFB	STEP-2 (Space Test Experiments Platform/Mission 2/SIDEX)				Partial failure
	Orbit slightly low							
6	June 27, 1994 21:15:00	XL (L-1011)	Vandenberg AFB	STEP-1 (Space Test Experiments Platform/Mission 1)				Failure
	Loss of vehicle control 35s into flight, flight terminated							
7	August 3, 1994 14:38:00	Standard (B-52)	Edwards AFB	APEX				Success
8	April 3, 1995 13:48:00	Hybrid (L-1011)	Vandenberg AFB	Orbcomm (2 satellites), OrbView-1				Success
9	June 22, 1995 19:58:00	XL (L-1011)	Vandenberg AFB	STEP-3 (Space Test Experiments Platform/Mission 3)				Failure
	Destroyed during second-stage flight							
10	March 9, 1996 01:53:00	XL (L-1011)	Vandenberg AFB	REX II				Success
11	May 17, 1996 02:44:00	Hybrid (L-1011)	Vandenberg AFB	MSTI-3				Success
12	July 2, 1996 07:48:00	XL (L-1011)	Vandenberg AFB	TOMS-EP				Success
13	August 21, 1996 09:47:00	XL (L-1011)	Vandenberg AFB	FAST (Fast Auroral Snapshot Explorer)				Success
14	November 4, 1996 17:08:00	XL (L-1011)	Wallops Flight Facility	HETE, SAC-B				Failure
	Satellites not ejected from third stage							
15	April 21, 1997 11:59:00	XL (L-1011)	Base Aerea de Gando, Gran Canaria, Spain	MiniSat, Celestis space burial				Success
16	August 1, 1997 20:20:00	XL (L-1011)	Vandenberg AFB	OrbView-2				Success
	On the line with partial success							
17	August 29, 1997 15:02:00	XL (L-1011)	Vandenberg AFB	FORTE				Success
18	October 22, 1997 13:13:00	XL (L-1011)	Wallops Flight Facility	STEP-4 (Space Test Experiments Platform/Mission 4)				Success
19	December 23, 1997 19:11:00	XL w/ HAPS (L-1011)	Wallops Flight Facility	Orbcomm (8 satellites)				Success

20	February 26, 1998 07:07:00	XL (L-1011)	Vandenberg AFB	SNOE, BATSAT				Success
21	April 2, 1998 02:42:00	XL (L-1011)	Vandenberg AFB	TRACE				Success
22	August 2, 1998 16:24:00	XL w/ HAPS (L-1011)	Wallops Flight Facility	Orbcomm (8 satellites)				Success
23	September 23, 1998 05:06:00	XL w/ HAPS (L-1011)	Wallops Flight Facility	Orbcomm (8 satellites)				Success
24	October 22, 1998 00:02:00	Hybrid (L-1011)	Cape Canaveral	SCD-2				Success
25	December 6, 1998 00:57:00	XL (L-1011)	Vandenberg AFB	SWAS				Success
26	March 5, 1999 02:56:00	XL (L-1011)	Vandenberg AFB	WIRE – Wide Field Infrared Explorer				Success
27	May 18, 1999 05:09:00	XL w/ HAPS (L-1011)	Vandenberg AFB	Terriers, MUBLCOM				Success
28	December 4, 1999 18:53:00	XL w/ HAPS (L-1011)	Wallops Flight Facility	Orbcomm (7 satellites)				Success
29	June 7, 2000 13:19:00	XL (L-1011)	Vandenberg AFB	TSX-5 (Tri-Services Experiments Platform/Mission 5)				Success
30	October 9, 2000 05:38:00	Hybrid (L-1011)	Kwajalein Atoll	HETE 2				Success
31	February 5, 2002 20:58:00	XL (L-1011)	Cape Canaveral	RHESSI				Success
32	January 25, 2003 20:13:00	XL (L-1011)	Cape Canaveral	SORCE				Success
33	April 28, 2003 12:00:00	XL (L-1011)	Cape Canaveral	GALEX – Galaxy Evolution Explorer				Success
34	June 26, 2003 18:55:00	XL (L-1011)	Vandenberg AFB	OrbView-3				Success
35	August 13, 2003 02:09:00	XL (L-1011)	Vandenberg AFB	SCISAT-1				Success
36	April 15, 2005 17:27:00	XL w/ HAPS (L-1011)	Vandenberg AFB	DART				Success
37	March 22, 2006 14:03:00	XL (L-1011)	Vandenberg AFB	ST-5 – Space Technology 5 (3 satellites)				Success
38	April 25, 2007 20:26:00	XL (L-1011)	Vandenberg AFB	AIM – Aeronomy of Ice in the Mesosphere	197 kg (434 lb)[17]	LEO[17]	NASA[17]	Success
39	April 15, 2008 17:01:00	XL (L-1011)	Kwajalein Atoll	C/NOFS	384 kg (847 lb)[18]	LEO[18]	STP / AFRL / DMSG[18]	Success
40	October 19, 2008 17:47:23	XL (L-1011)	Kwajalein Atoll	IBEX – Interstellar Boundary Explorer	107 kg (236 lb)[19]		NASA	Success
41	June 13,	XL (L-1011)	Kwajalein Atoll	NuSTAR – Nuclear	350 kg	LEO[20]	NASA / JPL	Success

	2012 16:00:00			Spectroscopic Telescope Array	(770 lb)[20]			[21]
42	June 28, 2013 02:27:46 [22]	XL (L-1011)	Vandenberg AFB	IRIS – Interface Region Imaging Spectrograph SMEX	183 kg (403 lb)[23]		NASA	Success [23]
43	December 15, 2016 13:37:00	XL (L-1011)	Cape Canaveral	Cyclone Global Navigation Satellite System (CYGNSS)[24]	345.6 kg (762 lb)[25]	LEO[26]	NASA	Success[27]
44	October 11, 2019 01:59:05	XL (L-1011)	Cape Canaveral	Ionospheric Connection Explorer (ICON)	281 kg (619 lb)[28][29]	LEO, 590 x 607 km[29]	UC Berkeley SSL / NASA	Success[30]

Planned launches

As of 12 October 2019 (after the launch of ICON) there are no space launch missions declared for the Pegasus XL rocket.

Launch failures

- Flight F-6, June 27, 1994: The vehicle lost control 35 seconds into flight, telemetry downlink lost 38 seconds into flight, range safety commanded flight termination 39 seconds into flight. The likely reason for loss of control was improper aerodynamic modelling of the longer (XL) version of which this was the first flight. The Pegasus carried the DoD Space Test Program's satellite - Space Test Experiments Platform, Mission 1 (STEP-1).
- Flight F-9, June 22, 1995: The interstage ring between the 1st and 2nd stages did not separate, constraining movement of the 2nd-stage nozzle. As a result, the rocket deviated from its intended trajectory and was ultimately destroyed by range safety. The Pegasus carried the DoD Space Test Program's satellite - Space Test Experiments Platform, Mission 3 (STEP-3).
- Flight F-14, November 4, 1996: Failed to separate payloads because of a discharged battery intended to start separation pyros. Battery damage during launch was the likely reason.

Partial successes

- Flight F-2, July 17, 1991: A faulty pyrotechnic system caused the rocket to veer off course during 1st-stage separation, resulting erratic maneuvers that prevented the rocket reaching the correct orbit, and the mission life, planned for 3 years, was reduced to 6 months[31]
- Flight F-5, May 19, 1994: A software navigation error caused the HAPS upper stage to shut down early, resulting in a lower than planned orbit. The Pegasus carried the DoD Space Test Program's satellite - Space Test Experiments Platform, Mission 2 (STEP-2).

See also

- Air launch to orbit
- Comparison of orbital launchers families
- Comparison of orbital launch systems
- Pegasus II (rocket)

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External links

- Pegasus/ICON website at Northrop Grumman (http://www.northropgrumman.com/Capabilities/Pegasus/Pages/Pegasus-Missions.aspx)
- Pegasus (https://web.archive.org/web/20080905015100/http://astronautix.com/lvs/pegasus.htm) at Encyclopedia Astronautica
- The Pegasus XL Rocket (http://www.nasa.gov/mission_pages/launch/L-1011-pegasus.html)