Introduction to system Engineering

Final Project Report

FALCON HEAVY

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BACKGROUND

Humans have dreamed about space exploration since antiquity. But only in the 20th century rockets were developed that were powerful enough to overcome the force of gravity to reach orbital velocities that could open space to human exploration

SpaceX, also known as Space Exploration Technologies Corp, is a private American aerospace industry, founded by Elon Musk in 2002. The goal of the SpaceX is to reduce the space exploration costs and to colonize Mars. One of the problems in Space exploration is Economical Space Access. Today it costs about $10,000 USD to get a single pound of mass into low earth orbit. A significant part of a single space mission is related to the design and production of the launch system. According to NASA, nearly about 40% of the space mission's costs is related to ground and launch processing. Therefore, the total cost of the life cycle of a rocket or space shuttle must be lowered to enable frequent human and robotic operations in space. Thus Elon Musk came up with an idea of "Reusable Rockets". This idea of reusing the launch vehicle was his plans since from the beginning of SpaceX. In 2004, he started a new program "SpaceX Reusable Launch System Development Program". Some of the project objectives are returning the launch vehicle first stage and second stage to the launch site. These reusable launch systems are used for the first stages of the Falcon family rockets. In December 25, 2015, SpaceX successfully landed and returned the first stage and reused the first stage on March 2017.

On February 6, 2018, Falcon Heavy made history for the most powerful operational rocket successfully launched which uses partially reusable rockets and boosters. The scope of this study is to analysis the capabilities of Falcon Heavy and to compare it with the other existing

rockets and the need to improve them, as a result it will make the space travel simple, reliable, redundant and low cost.

CONCEPT DEVELOPMENT STAGE

NEED ANALYSIS

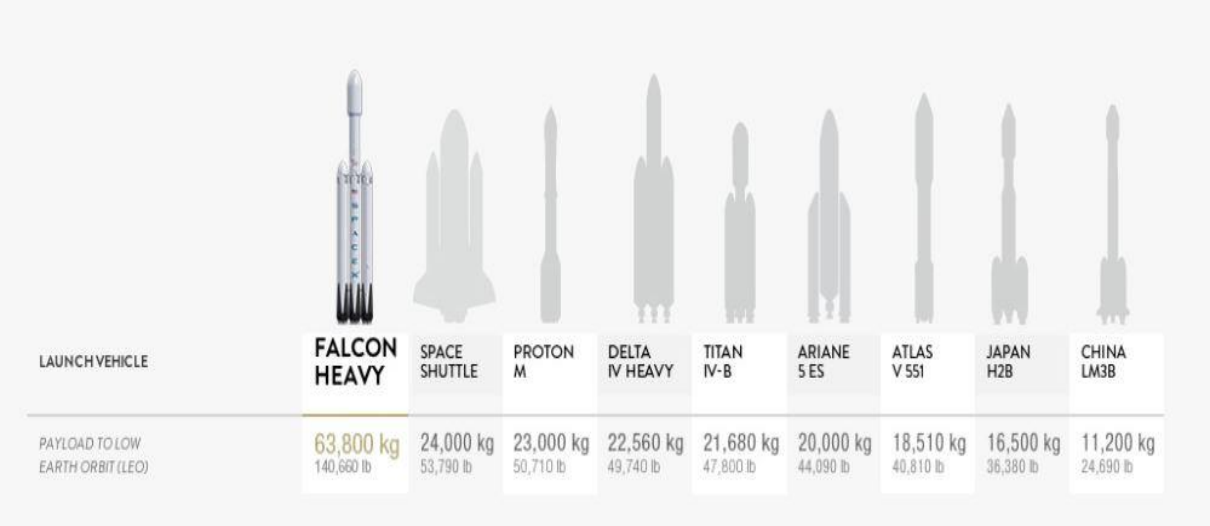
Operational Analysis:

As mentioned in the background, the need for most powerful and reusable rocket launch system is to reduce the space exploration costs and to improve the capacity of payload. The Falcon launch vehicle series have been designed to reduce the launch vehicle failures- separation events and engines. In December 2008, NASA made a contract with SpaceX to provide cargo resupply service to the International Space Station (ISS). It is believed that the cumulative total contract value will be up to $3.1 billion. Thus a superior launch vehicle is need to improve the reliability and performances.

Functional Analysis:

A heavy-lift launch vehicles (HLV or HLLV) are orbital launch vehicles which can lift the payload to the low earth orbit. The Ariane 5, the Proton-M and the Delta IV heavy are the only operational heavy lift launch vehicles as of 2017. The Ariane 5 have the lifting capacity of 20,000 kg and it costs around $165-$220 million per launch. The Proton-M have the lifting capacity of 23,000 kg and it costs around $65 million per launch. The Delta-IV have the lifting capacity of 22,560 kg and it costs around $350 million. The total cost for the launch of Falcon Heavy is considered to be $90 million USD. In addition Space Shuttle is a partially reusable low earth orbital spacecraft with a lift capability of 24,000 kg and it cost around $450 million per launch. Thus current heavy launch vehicles are expensive and doesn't have the relaunchable features. Falcon Heavy have the capability of lifting 63,000 kg which is more than one third of the current availably vehicles and it costs only around $90 million and it have

the relaunchable capabilities which makes Falcon Heavy superior to the current launch vehicles.



LAUNCH VEHICLE	FALCON HEAVY	SPACE SHUTTLE	PROTON M	DELTA IV HEAVY	TITAN IV-B	ARIANE 5 ES	ATLAS V 551	JAPAN H2B	CHINA LM3B
PAYLOAD TO LOW EARTH ORBIT (LEO)	63,800 kg 140,660 lb	24,000 kg 53,790 lb	23,000 kg 50,710 lb	22,560 kg 49,740 lb	21,680 kg 47,800 lb	20,000 kg 44,090 lb	18,510 kg 40,810 lb	16,500 kg 36,380 lb	11,200 kg 24,690 lb

Feasibility Analysis:

Falcon Heavy is considered to have the two stage design for minimum number of separation events, Redundant stage and fairing separation systems, Dual redundant avionics system, Propulsion redundancy and simplicity, Robust structure with high margins, High strength to weight ratio and Limited number of independent subsystems such as high pressure kerosene tapped from turbo pump to drive trust vector control hydraulic system and Turbo pump exhaust gas is used for roll control

Needs Validation:

As per SpaceX the estimated cost of Falcon heavy is considered to be $90 million USD. By elimination of the traditional layers management internally and sub-contractors externally, it reduces the cost while streamlining decisions and delivery. It was based on by manufacturing vast majority of components in house, keep tighter quality control and ensuring a closed feedback loop between the engineering and manufacturing teams. The relaunchable feature also reduce the cost on future missions.

CONCEPT EXPLORATION AND DEFINITION

In 2001, Elon Musk came up with the idea of low cost launch vehicles and colonisation of mars. After learning the price of the launch vehicle after his trip to Russia, he decided to manufacture his own launch vehicle. Working with Mueller, they came up with two engines – Merlin and Kestrel. Merlin was designed to be engine for first stage in Falcon 1. Kestrel is the small engine to power up the upper to the space.

Falcon 1 is the world's first privately developed liquid fuel rocket. It was the smallest and have the partially reusable rocket. The first attempt of Falcon 1 was failed on 26 March, 2006, due to a fuel line rupture. The second flight was also a failure on 22 March 2007, due to spin stabilization problem. Even though the third Falcon 1 was designed with a new cooling system it failed. Only on the fourth attempt on 28th December Falcon 1 succeeded in reaching the orbit. It became the first commercial payload into the orbit on 13 July 2009, on its fifth launch. SpaceX cancelled further launch of Falcon 1 to focus on its future launch vehicles.

On 09 September, 2005, SpaceX announced the Falcon 9 rocket. It contains 9 Merlin engines in the first stage. The first version of Falcon 9 - Falcon 9 v1.0 was developed and launched in 2010. It successfully made 5 flights in 2010 - 2013. Then it was retired.

The second version Falcon 9 v1.1 was launched in September 2013. It is considered to have 60% heavier, longer fuel tanks and more thrust than the first version.

Falcon 9 v1.2 also known as Falcon 9 Full thrust was first launched in December 2015. It was launched 29 times, as of February 29 2018

Some of the concepts like Falcon 5 and Falcon 9 Air was cancelled to concentrate the resources on Falcon Heavy.

Falcon Heavy comes under heavy lift launch vehicle category. It is also known as FH. It has the ability to carry the payload over 63,000 kg. It is a variant of the Falcon 9 launch vehicle. The first stage of Falcon Heavy uses three nine engine cores, a reinforced engine core and two side boosters. All the three boosters can be recovered and reused. Falcon Heavy made it first launch on February 6 2018. It was the most powerful operations rocket ever launched.

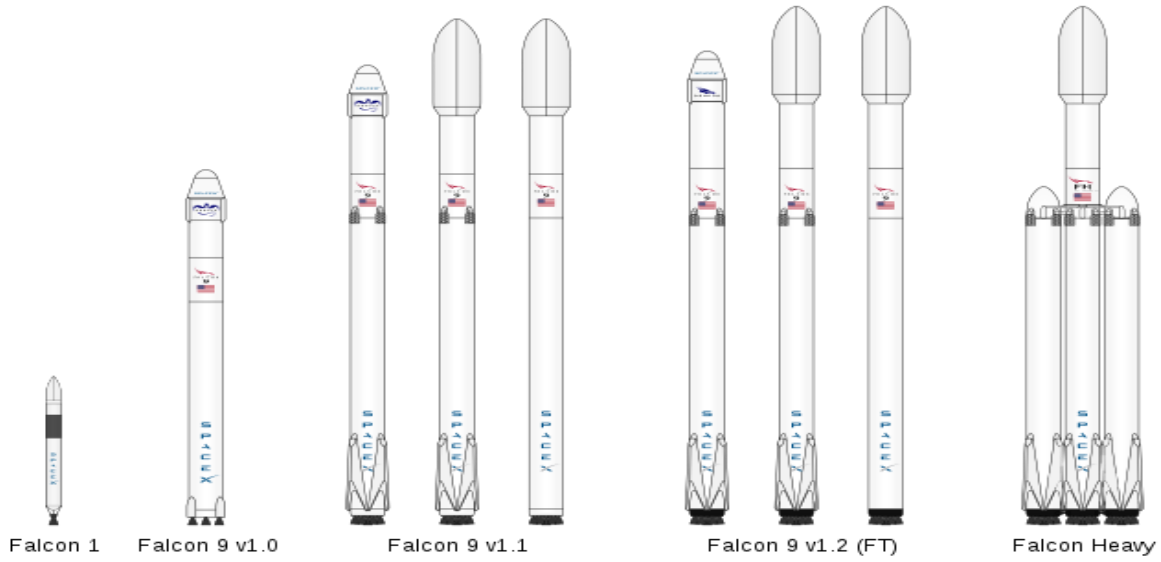


Fig: Variants of Falcon rocket

ENGINEERING DEVELOPMENT

ADVANCE DEVELOPMENT STAGE

The system design specifications and a validated system development model is obtained in advance development stage. Advance development stage is the practical implementation of the concept development stage. Majority of the uncertainties are resolved through analysis and development. Since Falcon Heavy come under heavy lift, the subsystems should perfectly designed to meet the necessary specifications. Some of the uncertainties in the Falcon heavy may include the weather conditions during launch, external turbulence, engine heat and singularities etc.

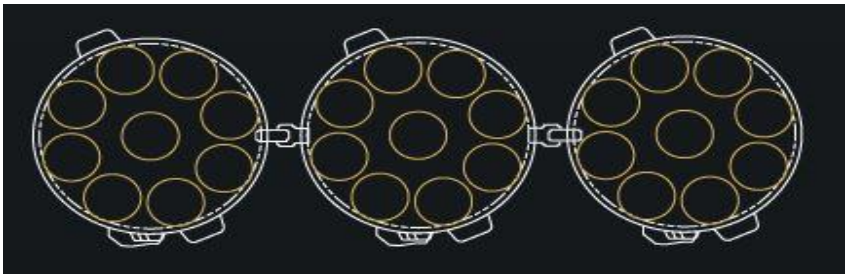
ENGINEERING DESIGN

Elon Musk initial plan is to buy the rockets from the other rocket manufactures. During the concept development stage he searched for many rocket models and after analysing he decide to manufacture rocket by himself. Thus with the help of engineers he developed Merlin engines. This was the first rocket engine which uses liquid oxygen. Several revisions of merlin engines are developed. They are merlin 1A, 1B, 1C, 1C vacuum and 1D. Thus these engines found its place in the future technologies because of its performance and its cost. The engineering design was based on the Falcon 9's fuselage and engines. In April 2011, after completely understanding the capabilities and performance of the Falcon 9, SpaceX came up with two missions, one was reignition of second-stage engine. Thus Falcon heavy is an upgrade of Falcon 9.

Some of the crucial subsystems in Falcon Heavy are Engines, First stage, Second stage, Boosters.

ENGINE:

Falcon Heavy consists of three cores. Each core consists of a cluster of nine Merlin engines. Falcon 9 also uses the same Merlin engines, thus it makes Falcon heavy cost effective. Merlin 1D engines are first developed by SpaceX in 2011. These engines used Rp-1 and Liquid Oxygen for proponent. The total of 27 merlin engines can produce a total thrust of 7.6 MN at sea level and 8.2 MN at vacuum. Even though during extreme conditions like shutdown of one or more engines, the other engines can sustain. Merlin engine arrangement is shown below.



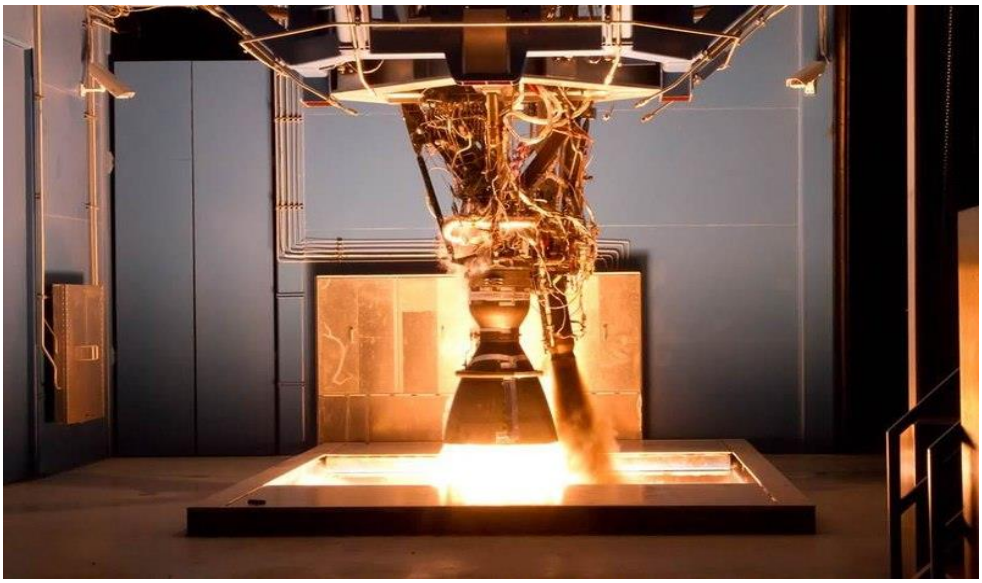


Fig: Testing of Merlin 1D engine

FIRST STAGE:

The first stage consists of three cores. These 3 cores with 27 merlin engine can generate 22,819 kilonewtons (5.13 million pounds) of thrust at lift off. The side cores or the boosters are connected to the base core at the base and top of the liquid oxygen tank. Tank walls and the domes are made of aluminium-lithium (because of its superior performance and high strength to weight ratio). The First stage is designed in such a way that after a lift off the core engine is throttled down and after the separation of the booster it throttles back up to full thrust.

SECOND STAGE:

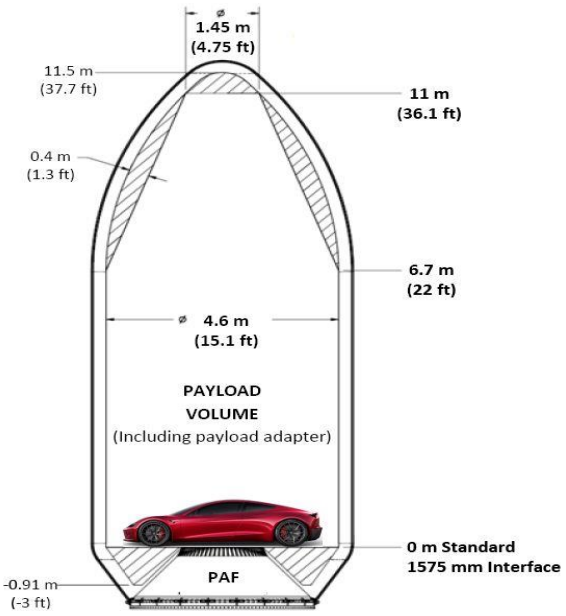
The second stage in Falcon Heavy is identical to Falcon 9. It delivers the payload to the desired path of the orbit after the main engine cut off and the first stage core separate. It is designed in such a way to minimize the stage separation so as to increase the reliability. It is a single Merlin engine with a larger vacuum nozzle for efficiency. The engine has a burn time of 397 sec and can produce a thrust of 934 KN in vacuum. The tank is the shorter version of the first stage tank which is also mostly made of aluminium-lithium materials. To increase the reliability the engine is added with dual redundant pyrophoric igniters and four injection ports to ensure the engine ignition.

BOOSTERS:

The two side cores or boosters consists of 9 Merlin engines each. These are equivalent to Falcon 9's first stage. These booster and first stage rockets are designed in such a way to return back to specific locations which makes them cost effective.

PAYLOAD:

Falcon Heavy can carry a payload of 63,800 kg into the space which make it the most powerful rocket. During the launch on Feb 6, 2018, It carried a Tesla Roadstar as a payload during its maiden launch. It is designed in such a way to reduce the turbulence. The payload have a 5.2 meter Fairing.



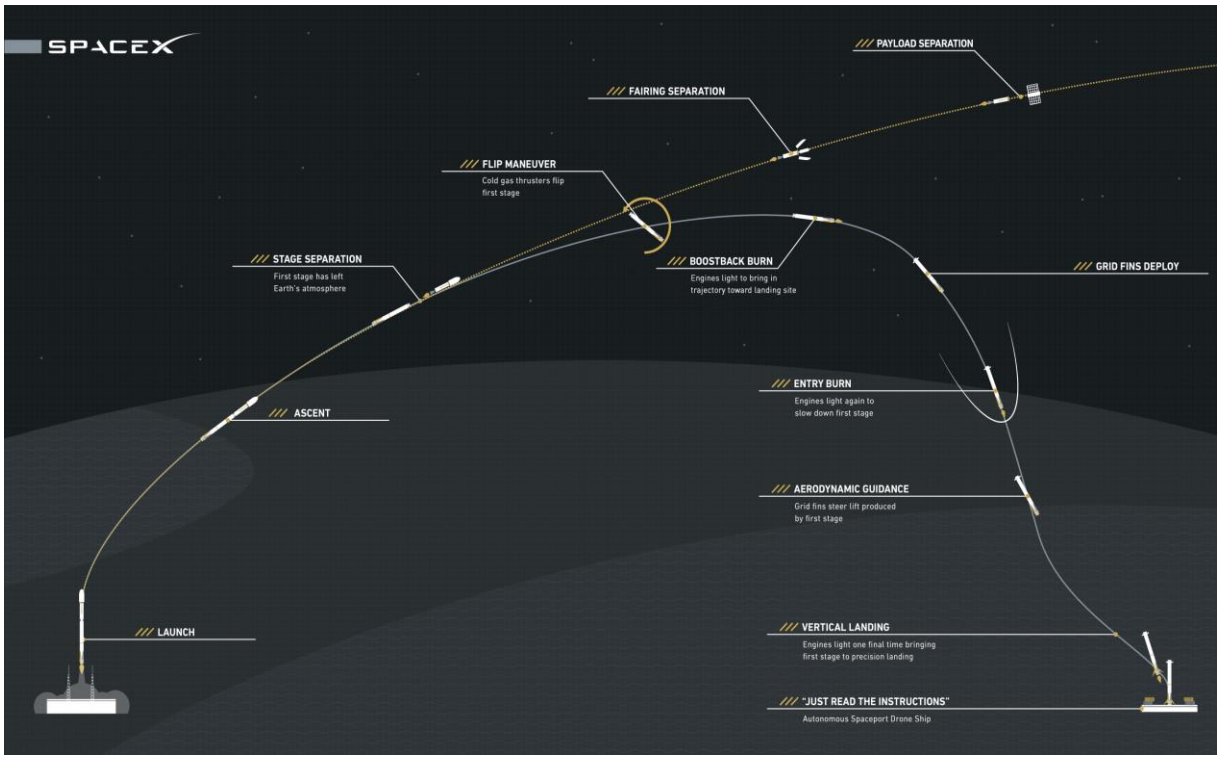


Fig: The trajectory of Falcon Heavy

INTEGRATION AND EVALUATION

Integration and evaluation phase are need to make sure the reliability of the engineering design. Before the maiden falcon heavy underwent a series of tests. Some of the important tests are hold down firing and static fire test. Both of them are successful. So they planned the launch on Feb6, 2018.

POST DEVELOPMENT STAGE

PRODUCTION

Falcon Heavy is considered to be the largest payload carrying vehicle. Thus it already plays a crucial role in the American space program. In December 2012, SpaceX and United States Department of Defense made a contract for the launch of Falcon Heavy. The United States Air Force Space and Missile Systems Center gave 2 Evolved Expendable Launch Vehicle to SpaceX. Most of the systems are manufactured with the headquarters of SpaceX, located at

Hawthrone, CA. Most of the testing of the rocket are undergone in SpaceX Rocket Development and Test Facility in McGregor, Texas. The facility validates every merlin engine with 16 specialized tests.

SpaceX plans to launch 2 Falcon Heavy missions in 2018. One of the launch is for Arabsat 6A communications satellite and the other launch will be for Space Test Program 2 into orbit for the U.S Air Force. They are deciding to sell each launch for 90 mil dollars compared to 62 million for the single core Falcon 9. Thus when considering overtime it will reduce the cost due to its reusable boosters.

SpaceX also planning to work on its cargo flights to International Space Station with its Dragon Spacecraft under NASA's Commercial Orbital Transportation Services (COTS) program. Dragon will be the first privately developed spacecraft to return from Earth orbit.

In future SpaceX also plans to develop the Big Falcon Rocket (BFR), which is considered to have twice of Falcon Heavy in terms of size and performance. It could also carry passengers to different destinations around the world and on to the mars. Elon Musk also stated that BFR could replace Falcon Heavy and Falcon 9. The concept of BFR is shown in the figure.

OPERATION

In February 6, 2018, SpaceX successfully launched the maiden flight of Falcon Heavy from the Kennedy Space Center Launch Complex 39A after delaying for more than 3 months dude to NASA shutdown. The launch was delayed for two hours due to strong winds and it was launched at 3.45 pm EST with its side boosters landing successfully at the landing zone 1 and 2.

SYSTEM ENGINEERING CHALLENGES

During earlier days, Elon Musk was criticized and not many investors believed in him about his new concept of space exploration. He was able to connect with the right people to proceed further. Finding the better environment both on management and engineering side was a big challenge. Some of the vital challenges faced by the SpaceX are to maintain the structural integrity of the central core, Safe landing of all the stages and Cross feeding of fuel between the stages.

The structure integrity of the central core should be considered since Falcon Heavy is a Falcon 9 with 2 side boosters. The two cores should be tightly attached so that it should fly in one piece. The side boosters puts a lot of pressure to the central core, hence necessary fortifications and the external forces should be nullified to make the rocket more stable. All the 27 merlin engines should be in equal throttle.

Cross feeding of fuel is the major challenge. In order to save fuel the remaining booster fuel should be pumped in the core to maximize the efficiency. It is more complicated and might results in technical failures. Elon Musk announced that the first few versions of Falcon Heavy will not have the cross feeding.

Landing of the 3 rockets was the major challenge. Out of 16 continuous tedious landing attempt 5 of them resulted in failure. Landing of these rockets are important for reusability of the launch vehicle. After the launch of Falcon Heavy the Centre Core booster was expected to land on the drone ship of SpaceX. But it crashed into the ocean by missing the ship by 328 feet and crashed at 300 mph. The reason for the crash is said to be the shortage of the fuel. The side booster landed perfectly.

The payload Roadster was designed to set its path in Mars orbit, but it also missed its path. The reason was found to be using excessive ignition during the third burn. It is still unclear what

will happen to the Roadster, however it was headed towards the asteroid belt of Mars. The below figure shows the path of the Roadster.

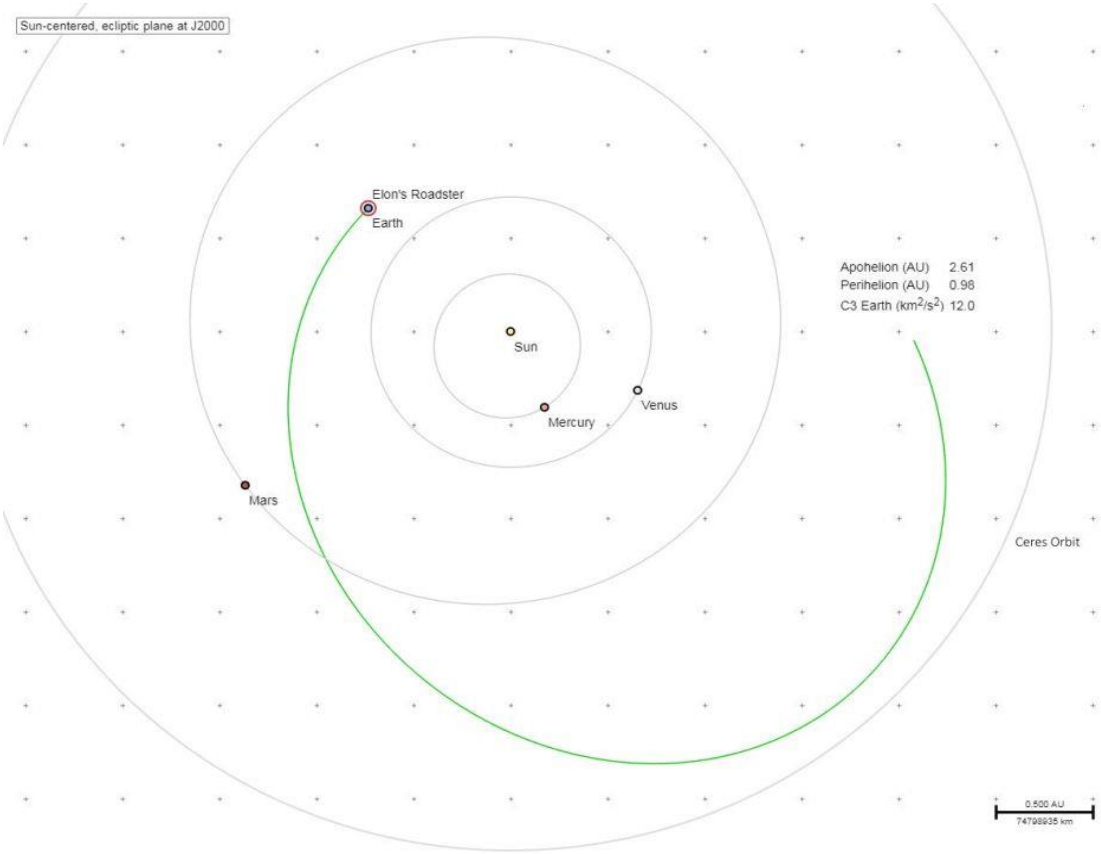


Fig: Path of the Roadster in the space

SUMMARY AND LESSON LEARNT

SpaceX's Falcon Heavy was the first ever heavy lift orbital vehicle which carry twice the weight of any other rocket in operation successfully launched. This is a historic moment for the space history. Since it also have the capabilities of reusing the booster and the centre core it reduce the costs drastically for the future flights. Even though there is failure in returning the center core and missing the path to be followed by the payload, the team in the SpaceX believes that these can be rectified and trying to improve the testing and evaluation of system engineering methods.

It is believed that the Elon Musk's dream to make the space exploration more accessible to the common people is coming true. The table shows the comparison of Falcon Heavy with the other operations rockets launched in 2017-2018.

Vehicle	Operator	Year of First Launch	Active Launch Sites	Mass to LEO kg (lb)	Mass to SSO kg (lb)	Mass to GTO kg (lb)	Estimated Price per Launch
Alpha	Firefly	TBD	TBD	400 (882)	200 (441)	N/A	$8M
Orbital Launch Vehicle	Blue Origin	2020	CCAFS	Undisclosed	Undisclosed	Undisclosed	Undisclosed
Cab-3A	CubeCab	2017	TBD	5 (11)	Undisclosed	N/A	$250K
Electron	Rocket Lab	2017	PSCA Mahia, NZ	Undisclosed	150 (331)	N/A	$4.9M
Falcon Heavy	SpaceX	2017	KSC VAFB	53,000 (116,845)	Undisclosed	21,200 (46,738)	$270M
LauncherOne	Virgin Galactic	2017	Spaceport America	400 (882)	225 (496)	N/A	$10M
Stratolaunch	Stratolaunch Systems	2018	Mojave KSC	3,000 (6,614)	1,400 (3,086)	N/A	Undisclosed
Vector R/H	Vector Space Systems	2017	CCAFS PSCA	60-110 (132-243)	40-75 (88-165)	N/A	$3M
Vulcan	ULA	2019	CCAFS VAFB	9,370-18,510 (20,657-40,510)	7,724-15,179 (17,029-33,464)	4,750-8,900 (10,472-19,621)	$85M-$260M

Some of the important facts to be noted from SpaceX Falcon Heavy are

- Falcon Heavy proves that the cost of the space exploration can be reduced drastically. SpaceX priced 90 million USD per launch of Falcon Heavy.
- It can carry 63,800 kg to LEO, 26,700 kg to GTO, 16,800 kg to Mars which is more than twice than any other operations rockets
- Reusable boosters and centre core plays sets paths for future rockets
- The fuel economy is impressive
- It is the foundation of the future BFR project

Thus from the system engineering study we can conclude that SpaceX's Falcon Heavy is far superior to any other operational rockets in terms of performance, efficiency and costs and future researches are going on to improve the space exploration.

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