Space Launch Vehicle Technology*

Prof. Dr. Victor David Sánchez, Ph.D.
Brilliant Brains. Palo Alto, California

November, 2016

Abstract

Space Launch Vehicle (SLV) technology evolved dramatically during World War II mainly thank to the work by Wernher von Braun which led to the first space suborbital flight in history in 1944 using his legendary V-2 rocket launched from the German Army Research Center in Peenemünde and later to the development of the Saturn-V launch vehicle here in the U.S., which during the Apollo 11 spaceflight secured the human landing on the Moon in 1969 after being launched from launch pad 39A of NASA's Kennedy Space Center (KSC) in Florida. It is from this context that the former Soviet Union, now Russia, and the U.S.A. took both advantage from the experience of the original von Braun's team members who were relocated for that purpose to Russia and the U.S., and have dominated the advances of space technology development, in particular space launch vehicle technology whose primary purpose is to allow access to the space environment. In the meantime, the private industry and other countries have entered massively this race including Europe, Japan, and China among several others.

To provide from the start direct insight into where the status quo is, Figure 1 shows in (a) a expanded view of Block 1 of NASA's new Space Launch System (SLS), in (b) an aerial view of KSC in Florida and among others the location of the launch pad 39B (top center) reserved for the SLS, in (c) a closer view of launch pad 39B itself, and in (d) a comparison between the SLS initial lift capability (70 mT, left) with the 322-ft tall Block 1 and the SLS evolved lift capability (130 mT, right) with the 365-ft tall Block 2. The liftoff weight, cargo volume, and payload weight for Block 1 and 2 are: 5.75 and 6.5 Mlb, 9,00-22,000 ft^2 and 58,000 ft^2, 154,000 lb and 286,000 lb, respectively.

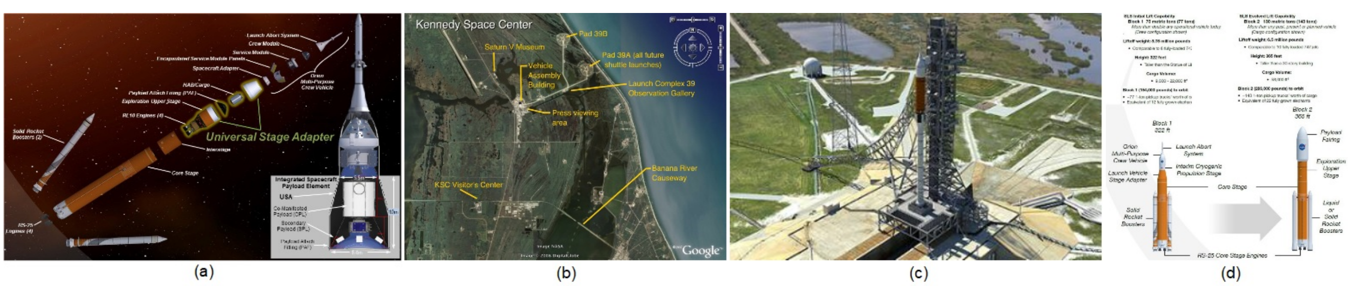


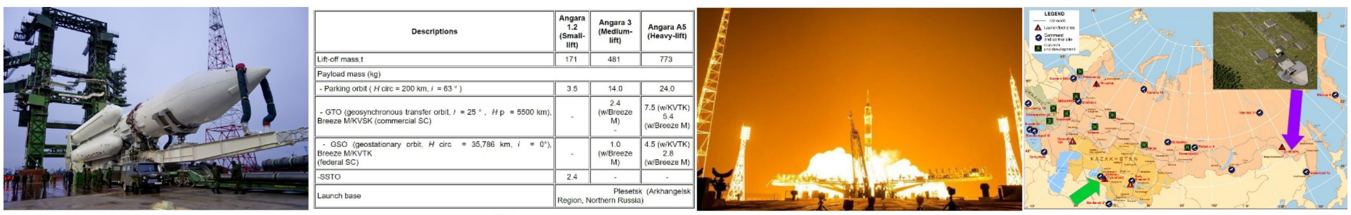
Figure 1: NASA's new SLS launch vehicle family [8] and launch pad 39B at KSC [7]

The author has enjoyed working over decades providing breakthroughs in literally all segments of space technology and associated terrestrial infrastructures and applications, including having helped NASA in the development of the current SLS launch vehicle family at NASA MSFC [10]. In all his space programs, diverse launch vehicles have played a key role towards accomplishing mission objectives. His pioneering work extends to earth orbital and deep space spacecraft and missions around the Earth and to planets, moons, and asteroids as well as operational communications, navigation, and earth observation satellite systems. National laboratory centers in the U.S. and Europe he has worked at or with include the NASA Jet Propulsion Laboratory (JPL) in Pasadena, California, the NASA Marshall Space Flight Center (MSFC) in Huntsville, Alabama, ESA's European Space Research and Technology Centre (ESTEC) in Noordwijk, the Netherlands, and as civil servant of the German Federal Government for almost a decade at the German Aerospace Center DLR Institutes of Communications and

*This abstract has been granted permission for public release.

Navigation, and of Robotics and Mechatronics in Oberpfaffenhofen by Munich, Germany. Companies he has worked with include Lockheed Martin, Boeing, SpaceDev, SAIC, Airbus Defense & Space, and Astrium. For example, the author has worked with the Boeing group at NASA MSFC in the development of the newest NASA's SLS launch vehicle family.

Russia has also been renewing its SLV technology and infrastructure. For example, after the end of the Soviet Union in 1991, Russia has had to rent the Baikonur cosmodrome, the world's first and largest operational space launch facility, from Kazakhstan, for instance to launch Soyuz manned missions to the International Space Station (ISS). To become independent of the new situation, the Russian space agency Roskosmos decided to build a new strategic spaceport in its own Russian territory and chose a nuclear missile base near Svobodny in Siberia, about 3,400 miles east of Moscow, now called the Vostochny cosmodrome, which is located almost on the same latitude as Baikonur allowing launch vehicles to carry same sized payloads and having the Pacific Ocean to the east, very convenient for the typical rocket launches heading eastward to take advantage of getting a boost from the spin of the Earth that also rotates eastward, that is done from NASA KSC as well. Since the Russian next-generation high precision landing spacecraft is too heavy for a Soyuz, a new launch vehicle family, Angara, is being developed and a launch pad for it has been reserved in the Vostochny cosmodrome. Figure 2 shows in (a) an Angara V launch vehicle, the successful maiden launch from the Plesetsk cosmodrome took place in December 2014, in (b) the Angara launch vehicle family performance data, in (c) the launch of a Soyuz rocket from the Baikonur cosmodrome, and in (d) two of the main spaceports Russia uses for launches in its territory and adjacent including the Baikonur cosmodrome (green arrow) and the Vostochny cosmodrome (purple arrow).

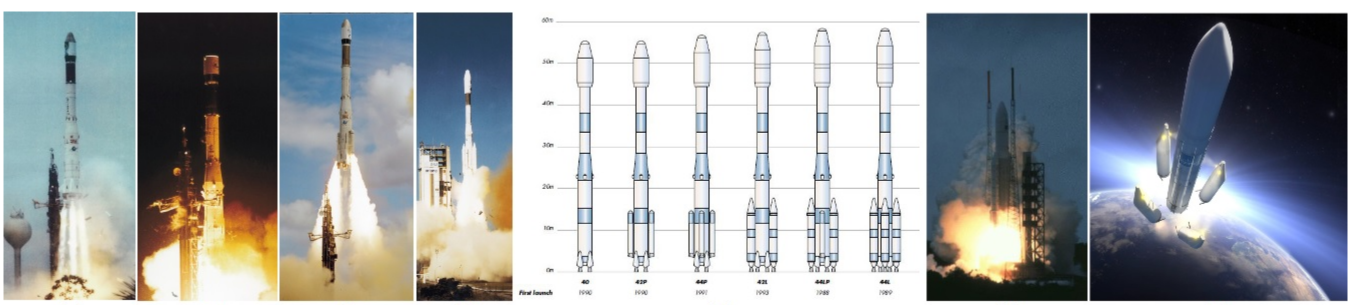


Descriptions	Angara 1.2 (Small-lift)	Angara 3 (Medium-lift)	Angara A5 (Heavy-lift)
Lift-off mass,t	171	481	773
Payload mass (kg)			
- Parking orbit (H circ = 200 km, i = 63 °)	3.5	14.0	24.0
- GTO (geosynchronous transfer orbit, i = 25 ° , H p = 5500 km), Breeze M/KVSK (commercial SC)	-	2.4 (w/Breeze M) -	7.5 (w/KVTK) 5.4 (w/Breeze M)
- GSO (geostationary orbit, H circ = 35,786 km, i = 0°), Breeze M/KVTK (federal SC)	-	1.0 (w/Breeze M)	4.5 (w/KVTK) 2.8 (w/Breeze M)
-SSTO	2.4	-	-
Launch base	Plesetsk (Arkhangelsk Region, Northern Russia)		

(a) (b) (c) (d)

Figure 2: Russia's new major Angara space launch vehicle and spaceport infrastructure [9]

The Angara space launch system is a family of launchers under development on the basis of the URM Common Core Booster (CCB) using LOX/kerosene engines. It includes small- to heavy-lift launchers featuring LEO payload capabilities of 3.5 mT to 37.5 mT. The CCB is comprised of an oxidizer tank and a fuel tank, interconnected via a spacer, and a propulsion bay. Each common core booster is equipped with one high-performance LOX/kerosene RD-191 liquid-propellant engine that uses an oxygen-rich staged combustion cycle. The engine design derives from the RD-170/171 engines, developed for the Energia multipurpose transportation system, and currently used in the Zenit launch vehicle. To significantly reduce the environmental impact, Angara launch vehicles do not use corrosive or toxic UDMH-based propellants.



(a) (b) (c) (d) (e) (f) (g)

Figure 3: Ariane launch vehicle family and Ariane-4 launch vehicle versions [2]

Next we outline two operational satellite systems launched to space for which the author was a main, originating contributor of the designs, the first one is a satellite communications system [11] and the second one is a satellite earth observation system [12]. The emphasis of the presentation here is on the launch vehicles used for making the respective space segments operational. They were launched to space with the Ariane-4 and the Vega launch vehicles in January 1997 and September 2016 respectively. The Ariane launch vehicle family recorded first flights for Ariane-1 in 1979, Ariane-2 in 1986, Ariane-3 in 1984, Ariane-4 in 1988, Ariane-5 in 1996, and for Ariane-6 it is planned for 2020. Ariane-4 was developed as a versatile launcher capable of being equipped with a wide variety of strap-on boosters by the French agency CNES and marketed by Arianespace after being approved as ESA program in 1982. From June 1988 to February 2003 it attained 113 of 116 successful launches.

Its successor, the human-rated, heavy-launch vehicle Ariane-5 attained so far 91 of 95 successful launches from 1996 to date. Figure 3 shows the first launch of Ariane-1, -2, -3, -4, and -5 in (a), (b), (c), (d) , and (f) respectively, in (g) the planned Ariane-6, and in (e) six versions of Ariane-4, one bare version (left most) and the others fitted with 2 or 4, solid or liquid strap-on boosters. The height, diameter, liftoff and maximum payload mass were up to 58.72 m, 3.8 m, 240-470 T, and 2-4.3 T respectively.

Ariane-4 was ideal to launch communications and earth observation satellites as well as scientific payloads. Two satellites could be launched at once using the dual-payload carrier structure SPELDA. For example, the Ariane-4 version called Ariane 44L, was the vehicle used to launch in January 1997 the Nahuelsat 1A communications satellite for Argentina [11], manufactured by the prime Dornier Satellite Systems and Aérospatiale providing the satellite bus Spacebus 2000NG. The launch mass, dry mass, and lifetime were 1,790 kg, 828 kg, and 12 yr respectively. It was successfully deployed to GTO in flight V93/465 with a companion satellite, the GE-2, a privately owned, American communications satellite, manufactured by Lockheed Martin with 2,648 kg, 1600 kg, and 15 yr as launch mass, dry mass, and lifetime respectively. The Ariane 44L version was equipped with 4 liquid strap-on boosters PAL (stage 0), each with a Viking 6 engine (752.003 kN thrust, fuel N_2O_4/UDMH) and could deliver up to 10,200 kg and 4,790 kg to LEO and GTO respectively. It was a 4-stage launcher, stages 1, 2, and 3 , called L220, L33, and H10, were powered by 4 Viking 5C, 1 Viking 4B, and 1 HM7-B engines with 3,034.1, 720.965, and 62.703 kN thrust respectively.

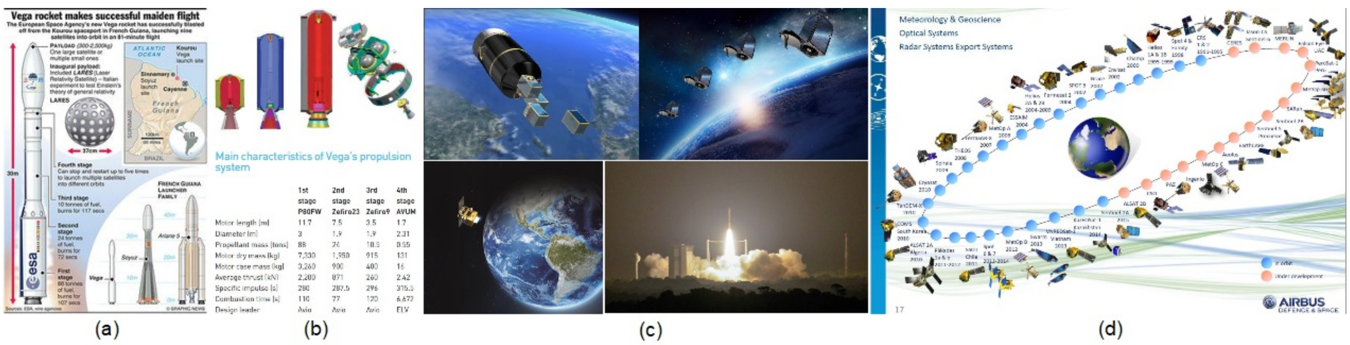


Figure 4: The Vega launch vehicle, multiple-payload (5 earth observation satellites) Vega mission [3]

On the other hand, our example earth observation satellite [12] was successfully launched using the Vega launch vehicle by Arianespace from the Guiana Space Centre (CSG) at Kourou in French Guiana. Figure 4 shows in (a) the Vega launch vehicle (LEO/SSO, 1500 kg payload mass, 700 km), now part of the launcher family launched from the CSG together with Soyuz (GTO, 3000 kg) and Ariane-5 (GTO, generic: 6600 kg, ECA: 10,000 kg), in (b) the main characteristics of the Vega's propulsion system, in (c) five earth observation satellites launched in one Arianespace Vega mission using the Vega secondary payload adaptor VESPA, flight VV07, four SkySat-4 to -7 (upper payload, 440 kg total liftoff mass) owned by Terra Bella, a Google company, their outlined deployment shown at the top left; that part of the space segment constellation shown at the top right; the 5th, PeruSat-1 earth observation satellite (lower payload, 430 kg liftoff mass) shown at the bottom left; and finally, the launch of Vega flight VV07 is shown at the bottom right, in (d) PeruSat-1 earth observation satellite system built by Airbus Defense & Space as a part of a large heritage of that type of satellite payloads, was launched to space with the Vega flight VV07 in September 2016. It is built on an AstroBus-S platform with a NAOMI optical instrument (high 0.7 m resolution) and was injected into SSO at an altitude of 675 km and to be operated at 695 km.

Figure 5: Eurockot's Rockot launch vehicle, launch site, and some of the missions launched [6]

One of multiple overall criteria to take into account in the design of a launch vehicle is the flexibility of launches it will provide. We clarify this fact using an example of a private mission to an asteroid the author was involved with. While there is no space to go into so many relevant details, for example how to design the mission to fly over GTO or design the spacecraft or a spacecraft family that can fly to Mars, the Moon, asteroids [4, 5], the main point to draw attention to here is the fact that given mission objectives, i.e., specific requirements for a mission or a family of missions, there is more than one choice of launch vehicle that can fulfill those requirements and precisely those associated facts need to be considered when designing a (new) family of launch vehicles. In the specific case we outline here, the NEAP mission to an asteroid was initially designed by SpaceDev to use an Eurockot or an Ariane launch vehicle. Eurockot Launch Services GmbH is a joint venture of Astrium, now ArianeGroup (51%) and the Khrunichev Space Center (49%) headquartered in Bremen, Germany created in 1995, which performs launches of small satellites into LEO and SSO for institutional and commercial satellite operators with the Russian 3-staged Rockot launch vehicle, launch mass 107,000 kg, 29 m tall, main diameter of 2.5 m, payload fairing height of 6.7 m, from the Plesetsk cosmodrome located about 800 km northeast of Moscow, Russia at attractive prices. The Rockot launch vehicle itself has been launching payloads to space since 1990. The newly produced upper stage by Khrunichev is used in the Rockot/Breeze-KM launch vehicle. The first two stages are based on SS-19 Inter Continental Ballistic Missiles (ICBMs). Payloads launched to LEO and SSO can weigh up to 1950 kg and 1200 kg respectively.

Figure 5 shows in (a) a Rockot launch vehicle at the launch pad LC 133 of the Plesetsk Cosmodrome, in (b) the 3 stages of the Rockot launch vehicle, in (c) the Rockot launch vehicle configuration including among others the 1st stage main engine (3x RD-0233, 1xRD-0234, liquid rocket engines burning N_2O_4 and UDMH), the 2nd stage main engine (RD-0235 main engine, RD-0236 vernier engine for thrust vectoring), the Breeze-KM upper stage, and a payload inside the fairing, in (d) the location of the Plesetsk cosmodrome in Russia, in (e) the launch of a Rockot launch vehicle, in (f) the display of live telemetry in the remote Mission Control Center (MCC) some 30 km away from the launch pad, in (g) flight sequences of a typical SSO mission, and in (h) some past, present and future missions launched with the Rockot/Breeze-KM launch vehicle including the NASA-DLR twin research satellites Gravity Recovery and Climate Experiment GRACE-1 and -2 in 2002, the South Korean multipurpose reconnaissance satellite KOMPSAT-2 in 2006, ESA's earth observation satellites Gravity Field and Steady-State Ocean Circulation Explorer GOCE in 2009 and Copernicus Sentinel-3A dedicated to oceanography in 2016, among several others. Multiple successful launches are not shown, for example, the Russian first 3 LEO military communications satellites of the so called Strela constellation, Kosmos 2451/2/3 in 2009 or 3 second-generation communications satellites Gonets-M-11/12/13 in 2015.

When improved to MicroNEAP, the design of the asteroid mission and spacecraft was improved following a design that I with my consortium and Spacedev delivered to NASA JPL, the launch was designed as a secondary payload aboard an Ariane-5 launch vehicle using the structure for auxiliary payload ASAP. Figure 6 shows in (a) the different components of an Ariane-5 launch vehicle from the solid boosters and the main cryogenic stage at the bottom to the fairing at the top, in (b) the performance figures of Ariane-5 to different transfer orbits including GTO, SSO, LEO, Elliptical L2 Lagrange, and Moon transfer, feasible due to the designed flexibility of its upper configuration, from the smallest (1000^- kg) to the largest (20,000 kg) spacecraft can be handled, in either a dedicated or shared launch, in (c) the standard Ariane-5 mission profile for geostationary transfer orbit, from the initial liftoff and ascent phase to the final satellite orbit position in a geostationary orbit, the typical duration of the GTO mission is between 25 to 35 min, and in (d) the launch pad for Ariane-5 at the Guiana Space Center (CSG), which provides two Ariane-5 launch tables, i.e., dual launch vehicles can be prepared in parallel.

An in-depth review of SLV technology is provided covering main features of the most relevant space launch vehicles existent, their associated ground infrastructure, a diversity of launch payload capability, and some guidelines for future development of advanced space launch vehicles capable of launching from nano-satellites to spacecraft for human colonization of other celestial bodies beyond Earth.

References

[1] Arianespace. Ariane 5 – The Heavy Launcher. `http://www.arianespace.com/vehicle/ariane-5/`.

[2] ESA. BR-150 – European launchers for the world, 1999.

[3] ESA. BR-257 – The European Small Launcher Vega, 2007.

[4] V.D. Sánchez et al. Mars MicroSpacecraft Bus Feasibility and Concept Design Study, Final Report, vol. I – Technical, March 1999. ACIS, JPL PO-No. 1202365, ISS No. 99-037-0.

[5] V.D. Sánchez et al. Mars MicroSpacecraft Bus Feasibility and Concept Design Study, Final Report, vol. II – Programmatic Assessment, March 1999. ACIS, JPL PO-No. 1202365, ISS No. 99-037-0.

[6] Eurockot. Rockot User's Guide, 2011.

[7] NASA KSC. Launch Pad 39B – NASA facts, 2012.

[8] NASA MSFC. Space Launch System – NASA facts, 2015.

[9] Khrunichev State Research and Production Space Center. Angara Launch Vehicles Family. `http://www.khrunichev.ru/main.php?lang=en/`.

[10] V.D. Sánchez. Human Space Flight – From Its Beginnings to the State of the Art. `http://profdrvdsaphd.lima-city.de/documents/HumanSpaceFlight.pdf`.

[11] V.D. Sánchez. Definition and Specification of a Domestic Satellite Communication System (in German), Final Report, DLR Institute of Communications and Navigation, 1985.

[12] V.D. Sánchez. A Multifunctional Earth Observation Satellite System, Final Congressional Report, Confidential, 2004.

Performance	GTO	SSO	LEO	Elliptical L2 Lagrange	Moon Transfer
Payloads, kg (including adapters)	>10,000	>10,000	20,000	6,600	7,000
Inclination (i), deg	6	0	51.6	14	12
Altitude of perigee (Zp), km	250	800	260	320	300
Altitude of apogee (Za), km	35,943		260	1 300,000	385,600
Argument of perigee (Wp), deg	178			208	

(b)

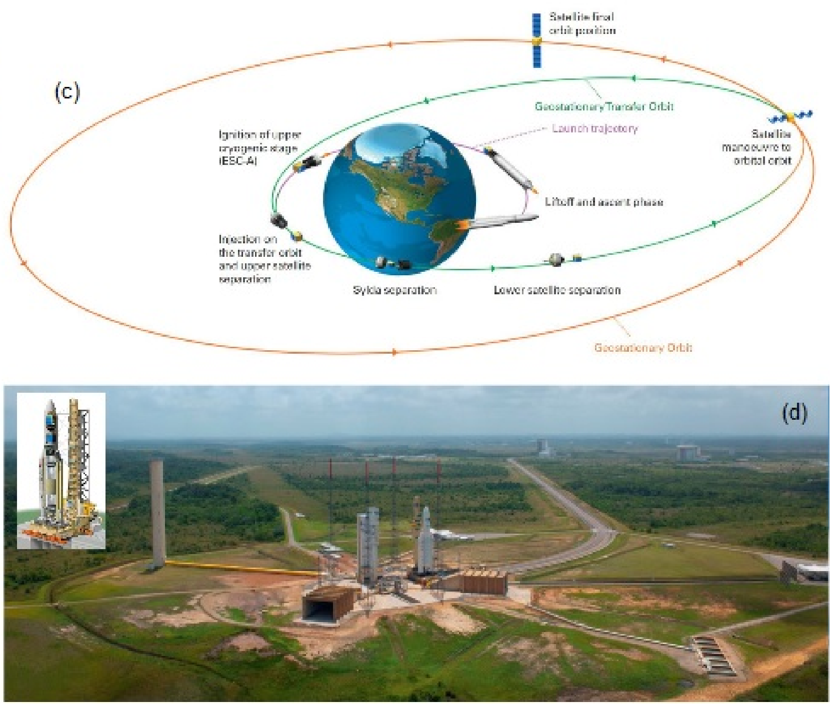


Figure 6: Ariane-5 launch vehicle and the launch infrastructure at the Guiana Space Center (CSG) [1]