21 July 1969

Massimo Guarnieri

I remember the day. In July 1969, I was not yet 14, and I was spending some vacation days in the country near Venice, Italy, at my uncle's home. Early in the morning on 21 July, he woke up my cousin and me to watch on TV the event that was going to be broadcast worldwide. Today, it may not be easy to grasp the hurdles that had been overcome before the feat we were going to witness could take place.

In the middle of the Cold War, the space race began on 4 October 1957, when the Soviet Union successfully put *Sputnik 1*, the first artificial satellite, into orbit around Earth, shocking the world and, particularly, the Americans, who felt that their U.S. technological supremacy was being menaced, and prestige and strategic issues were emerging [1]. The Soviets were building ever more powerful atomic bombs after their first test explosion in 1949, and the possession of ballistic missiles capable of taking satellites into orbit demonstrated that they also had the technology for launching intercontinental ballistic missiles carrying nuclear weapons. The American space program, which had been started by President Eisenhower in July 1955, was ramped up, but the first launch by the U.S. Navy, on 6 December 1957, ended with the explosion at liftoff of a Vanguard rocket carrying a TV3 satellite, after it had risen just 1.2 m.

At that time, German rocket engineer Wernher von Braun (1912–1977), the leading designer of the Nazi V2 flying bomb, and his German team were working for the U.S. Army on the ballistic missile Redstone as a carrier of nuclear weapons, and this had been successfully tested in 1955 [2]. By modifying a Redstone, von Braun and his team developed the Jupiter-C rocket for space missions, which could be launched by 1956. After the Vanguard TV3 failure, von Braun was authorized to launch his rocket, and on 31 January 1958, it put the *Explorer 1* satellite, built at the Jet Propulsion Laboratory of the California Institute of Technology, into orbit. This satellite was powered by mercury batteries, and its electronic circuits used 29 silicon and germanium transistors, chosen for their robustness, lightness, and low consumption: it was one of the very first scientific uses of transistors [3].

The instrumentation, designed by a group led by James Alfred Van Allen (1914–2006), performed the surveys that led to the discovery of the eponymous belts of subatomic particles trapped in the Earth's magnetic field. In March 1958, the U.S. Navy successfully launched the Vanguard 1: it was the fourth orbiting satellite and the first one powered by solar cells, developed at Bell Labs by a group led by Gerald Pearson (1905–1987) in 1954. Yet, on 17 August 1958, the U.S. Air Force's launch of the *Pioneer 0* probe, intended to orbit the moon, resulted in the explosion of the rocket 73 s after liftoff.

NASA was established in July 1958 by President Eisenhower to collect and organize national efforts in the space race. Nevertheless, the Soviets' supremacy persisted in the early years. *Sputnik 2* took into orbit the first living being, the dog Laika, in November 1957, and the space probe *Luna 1*, launched in January 1959, was the first artificial object that escaped Earth's gravitational attraction, transiting only 5,995 km off the lunar surface [4]. Soviet Yuri Gagarin (1934–1968), aboard the *Vostok 1* spacecraft, was the first man to orbit Earth, on 12 April 1961 [5]. Two years later, Valentina Tereškova (born 1937) was the first woman to go into orbit. On 18 March 1965, Alexey Leonov (born 1934) performed the first spacewalk, while orbiting in the *Vostok 2*. On 3 February 1966, the *Luna 9* probe made the first soft landing on the lunar surface.

The Soviet space program, however, paid a heavy price in failures and human lives as a result of several ground and in-flight accidents [6]. The nation that had chosen an economic and political system completely driven by central planning failed to join up its space programs, leaving them in the hands of a number of design bureaus, often working in fierce competition. Two major leaders of these groups, Sergei Korolev (1907–1966) and Valentin Glushko (1908–1989), were divided by a personal antagonism. Several failures, which eventually resulted in the Soviets losing their initial lead, were not disclosed. Overall, the entire program was handled with extreme secrecy: the names of the chief leaders, Korolev and his successor, Kerimov, were revealed only with the advent of Gorbachev's glasnost after 1986. Such confidentiality cost Korolev the Nobel Prize, which the Nobel Committee was determined to assign after Gagarin's flight, except that they did not know who should be named.

Early NASA steps were not so successful. The first launch, on 11 October 1958, carried the *Pioneer 1* probe, which, like *Pioneer 0*, was intended to reach the moon but instead covered only a ballistic path as high as 113.8 km. The first successful American probe was *Pioneer 5*, launched in 1960, after the Soviet *Luna 1*. In 1958, NASA also started Project Mercury, aimed at putting man into space in a single-man spacecraft and, in July 1960, the Marshall Space Flight Center was created, with von Braun as first director, with the objective of designing the Saturn rockets intended to launch the spacecrafts.

Again, the beginnings were fraught with failures. On 21 November 1960, the *Mercury-Redstone 1* (unmanned and with one of von Braun's rockets) lifted off just a few centimeters: it was later referred to as the "four-inch flight." A few months later, on 5 May 1961, the Mercury-Redstone 3 Freedom 7 mission finally took Alan Shepard (1923–1998) into a 15-min suborbital flight. He was the first American astronaut, almost one month after Gagarin's flight. The first American to orbit Earth was John Glenn (1921–2016) on board *Mercury 6* on 6 February 1962.

The race to the moon was started by U.S. President John Fitzgerald Kennedy (1917–1963) in an address to Congress on 25 May 1961 in which he appealed to U.S. national pride: "No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish" [7]. In a speech at Rice University on 12 September 1962, Kennedy relaunched: "We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard; because that goal will serve to organize and measure the best of our energies and skills." Given the state of space exploration in 1961, the win could only come from a much more ambitious goal than orbiting Earth. Kennedy chose a goal where the United States and Soviet Union could start from a position of equality to maximize the chances of winning.

In September 1961, the NASA Manned Spacecraft Center was created in Houston on land donated by Rice University. This NASA Center would later include the Mission Control Center of the manned missions. The three-astronaut Apollo program, conceived during the Eisenhower administration, was upgraded to the moon target, and the two-astronaut Project Gemini was announced in January 1962 as an intermediate step to develop the technologies and techniques required for *Apollo* [8]. On 3 June 1965, Edward White (1930–1967) became the first American to perform a spacewalk, completed while orbiting in the *Gemini 4* spacecraft, almost three months after Leonov's analog. Then, in December 1965, *Gemini 6* and *Gemini 7* performed the first rendezvous, approaching as close as 30 cm and zeroing their relative speed. Four months later, *Gemini 8* performed the first docking rendezvous with an unmanned satellite. Nevertheless, the challenge took a heavy toll also on the American side. On 27 January 1967, a fire aboard the *Apollo 1* spacecraft during a ground test killed the three astronauts, including White.

From *Apollo 4* on, the spacecrafts were launched by the *Saturn V*, the gigantic rocket 110 m tall and with a 3,000-t mass built under the direction of von Braun. *Saturn V* was a three-stage vector. Those stages were equipped, respectively, with five F-1 engines fed with super-refined kerosene and liquid-oxygen, and each eventually capable of 715-t thrust; five J-2 hydrogen and oxygen engines, each with 105-t thrust; and a 105-t J-2 engine that could be restarted. The *Saturn V* could take a 140-t payload into low Earth orbit or launch a 41-t payload to the moon. It was, and remains, the tallest, heaviest, and most powerful (in terms of impulse) rocket taken into operation. Thirteen *Saturn Vs* were launched from Kennedy Space Center at Cape Canaveral, Florida, with no human or payload loss. The first four manned missions, *Apollo 7* to *Apollo 10*, were preparatory, for testing maneuvers in Earth and lunar orbit.

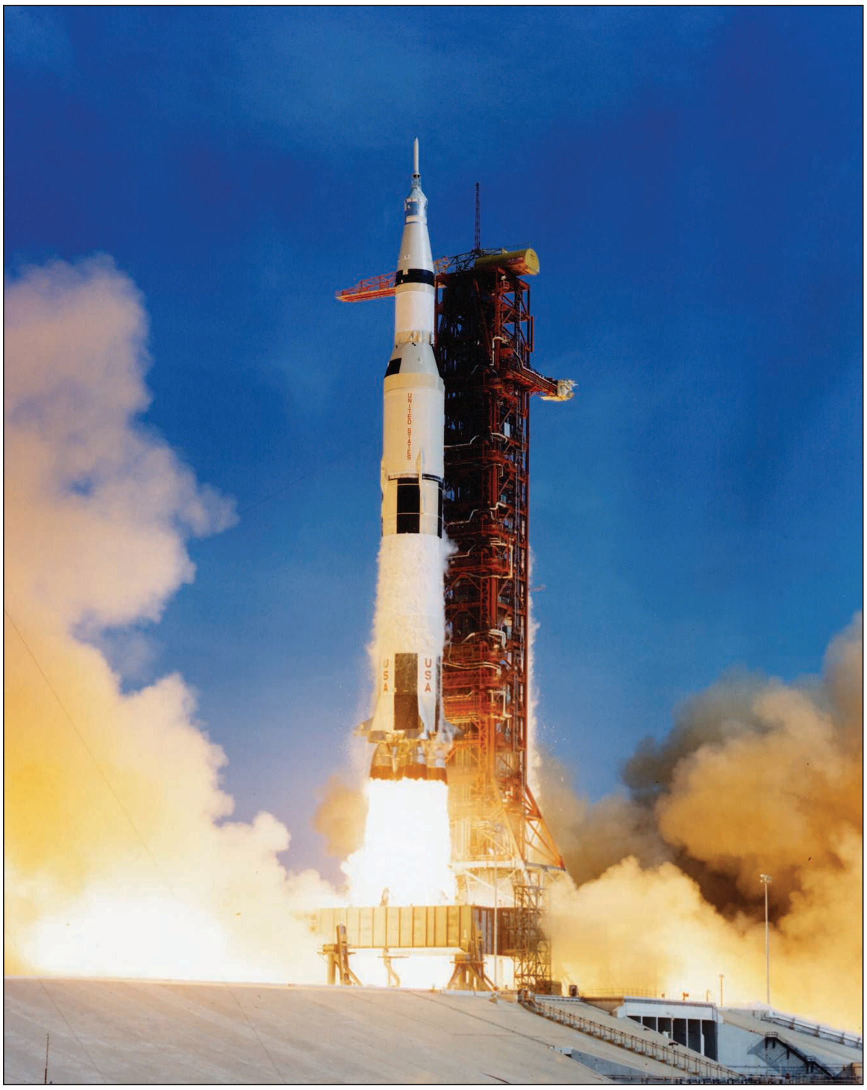
The *Apollo 11* mission began on 16 July 1969. About 1 million people were estimated to have attended the liftoff in the vicinity of Cape Canaveral, including many U.S. dignitaries, 60 ambassadors, and 3,500 media representatives (Figure 1). The launch was televised live in 33 countries. Four days later, while Michael Collins (born 1930) was orbiting around the moon in the command and service module (CSM) *Columbia* (Figure 2), the spider-like, light-structured lunar module (LM) *Eagle* landed gently on the lunar surface in the Sea of Tranquility.

Six hours later, Neil Armstrong (1930–2012) climbed down the LM ladder and, moving with circumspection, set his foot on the surface of the moon at 2:56 UTC (4:56 a.m. Central European Time). He was followed by Buzz Aldrin (born 1930) a few minutes later (Figure 3). While watching this, even as an Italian teenager, I could share the enthusiasm with my relatives, understanding the eagerness in the national TV studio in Rome, Italy, and perceiving the excitement at Mission Control Center in Houston, Texas. One sixth of humanity, about 600 million, shared that experience on live TV. It was an event of unprecedented technological and cultural importance, completed when Neil Armstrong, Michael Collins, and Buzz Aldrin safely splashed back down in the North Pacific Ocean on 24 July. The race to space, the great competition, was over.

The event iconography includes the beautiful still pictures taken with special Hasselblad cameras, some of which accompany this article, and the low-quality video derived from the lost slow-scan TV transmission. It includes Armstrong's memorable comment when first stepping on the moon: "That's one small step for [a] man, one giant leap for mankind." Although it had been started as a U.S. feat, at the moment of seizing the epoch-making goal, the conquest of the moon was presented in a different and wider perspective and was actually perceived worldwide as an achievement of mankind, as Armstrong had commented. This sentiment was expressed in the motto on the plaque left on the LM descent stage: "Here men from the planet Earth first set foot upon the moon, July 1969 A.D. We came in peace for all mankind" (Figure 4).

In his phone call to the astronauts soon after they landed on the moon, President Nixon stated, "For every American, this has to be the proudest day of our lives. And for people all over the world, I am sure they too join with Americans in recognizing what an immense feat this is. …. For one priceless moment in the whole history of man, all the people on this Earth are truly one." And Armstrong's answer to Nixon was "It's a great honor and privilege for us to be here, representing not only the United States, but men of peace of all nations."

Years later, on the occasion of the 40th anniversary in 2009, British scientists commented, "The Apollo program is arguably the greatest technical achievement of mankind to date … nothing since Apollo has come close [to] the excitement that was generated by those astronauts." On that 40th anniversary, Armstrong, Aldrin, and Collins celebrated with President Obama on 20 July 2009 and received the Congressional Gold Medal a few days later. We all wish Aldrin and Collins the best for the 50-year celebrations this year, but Armstrong, the first man on the moon, will not be present, having passed away in 2012.



NASA

FIGURE 1 – The *Apollo 11 Saturn V* space vehicle lifting off from Kennedy Space Center on 16 July 1969.

Six more Apollo missions, from 12 to 17, returned to the moon, and 10 more men walked on its surface, including Sheppard. Five moonwalkers are still alive, out of the twelve who stepped on the surface. A second serious accident, the explosion of an oxygen tank with potentially fatal outcomes, hit *Apollo 13* while it was heading for the moon, but the expertise of the astronauts and assistance from Mission Control Center allowed their safe return to Earth. The rendezvous of *Apollo 18* with the Soviet spacecraft *Soyuz 19* in July 1975 marked the end of the Apollo program and the start of a period of cooperation. Other planned missions were canceled: once a moon landing had been achieved, it was hard to justify continuing such expensive missions, and Apollo remains the only manned spacecraft program to fly beyond low Earth orbit.

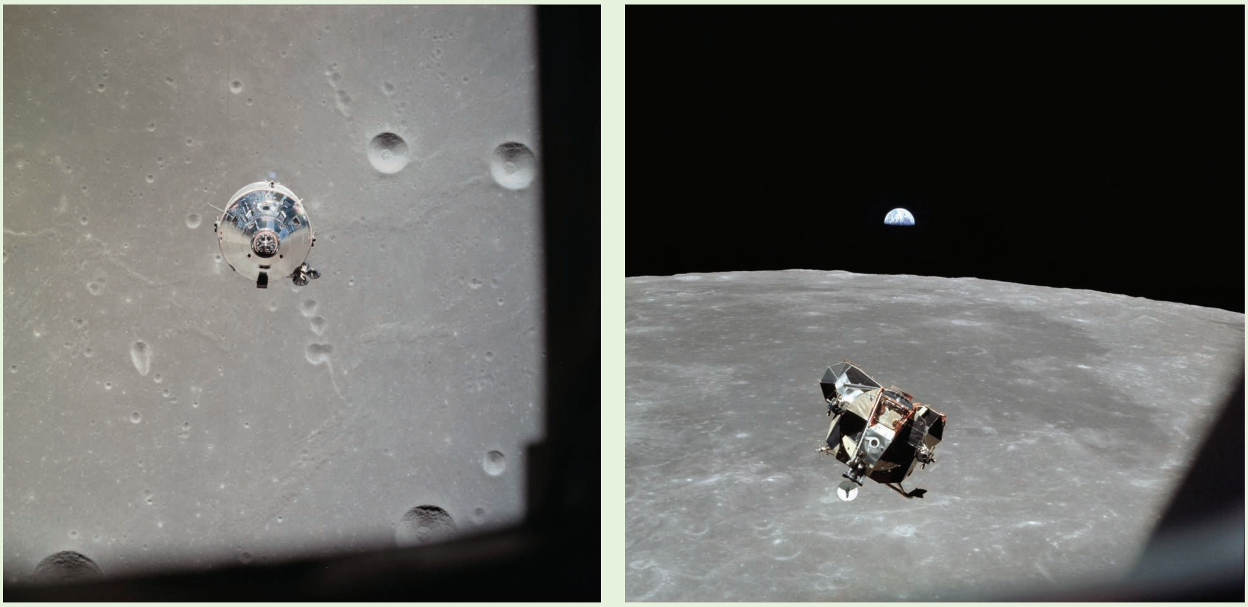
The cost of the program was colossal and weighed heavily on federal finances: with US$20 billion (US$143 billion in 2018 dollars) in the period 1960–1973 (out of US$42 billion of total NASA costs in the same period), landing on the moon involved the largest commitment of resources ever made by any nation in peacetime [9]. At its peak in 1966, NASA's budgets reached US$5.9 billion dollars, i.e., 5.5% of the federal budget.

The implementation of the space programs required the design, building, and testing of new devices, components, and tools that had to be very reliable, light, and often miniaturized. New materials were developed, and new processing techniques were conceived, such as chemical milling and explosion forming. Shielding systems guaranteed protection against radiation and cosmic rays. For the first time, computers were used systematically, in scientific analyses, design, planning, and mission control. At the end, Apollo missions resulted in the concentration of the best technologies available at the time. They spurred advances in several high-tech sectors, many of which are related to IEEE topics, and several were spun off to industrial products.

To allow the astronauts to remain in space for several days, issues of a physiological and psychological nature were addressed, after which a number of medical applications were derived. Space suits and thermal insulation systems suitable for resisting the sidereal cold and the infernal heat of reentry were made with the technology now used in the suits worn by racing car drivers and firefighters. The Pressure Suit Assembly, which was part of the Extravehicular Mobility Unit [10] and protected astronauts walking on the moon, used a Teflon-coated fabric that weighs less than 5 oz/ft^2, is stronger than steel, and is resistant to moisture, temperature, and deterioration, resulting ideally in several present-day applications. Freeze-dried foods are used in military survival gear. Silver ion technology for purifying drinkable water by eliminating bacteria, copper ions, and algae has become an alternative to chemicals such as chlorine and bromine.

If the Passive Seismic Experiments set up on the moon by Armstrong and Aldrin operated for about one month only, the Lunar Laser Ranging experiment is still working. Its first unit was installed by *Apollo 11*, and it measures the distance between the surfaces of Earth and the moon by using laser ranging and retroreflectors capable of reflecting light back to its source with minimal scattering, parallel to the wave's source, even if the angle of incidence is greater than zero. Infrared sensors were used for detecting the temperature. The joystick control was developed to pilot the LM.

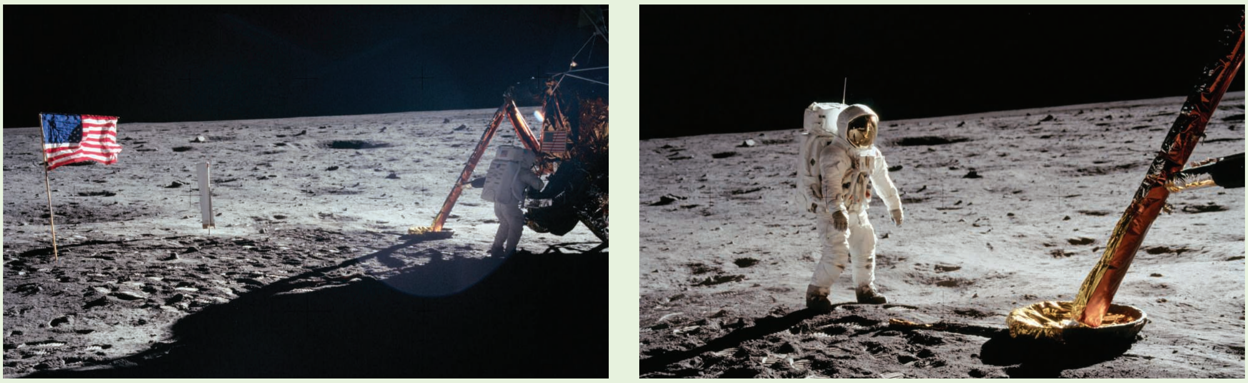
Communications with the spacecrafts were ensured by a network of stations distributed all over the world



(a) (b)

NASA

FIGURE 2 – (a) The CSM *Columbia* photographed from the LM *Eagle* in lunar orbit during the *Apollo 11* mission. (b) The LM *Eagle* after liftoff from the moon, before docking with CSM *Columbia*. Beyond the moon, a half-illuminated Earth hangs over the horizon.



(a) (b)

NASA

FIGURE 3 – *Apollo 11* on the moon, 21 July 1969. (a) Neil Armstrong works at the LM. Photographed with the mission 70-mm Hasselblad camera. (b) Buzz Aldrin photographed by Neil Armstrong near the leg of the LM *Eagle*.

NASA

FIGURE 4 – The stainless-steel dedication plaque left on the moon with the LM's descent stage.

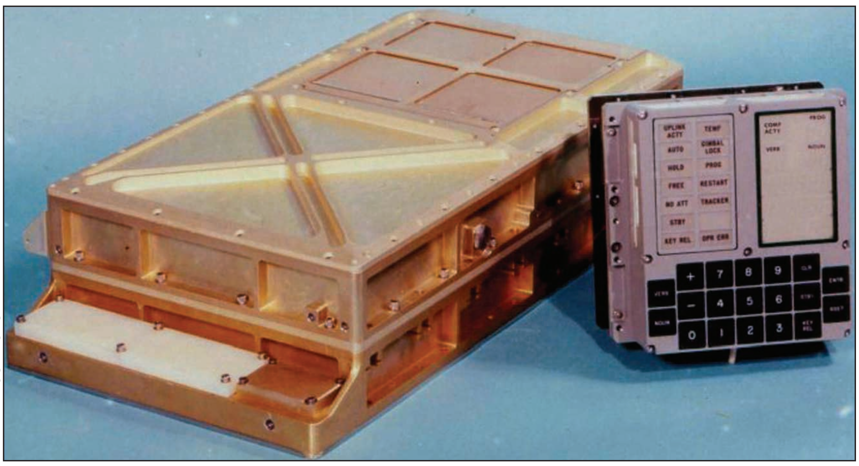
and even in orbit. Noise-reduction techniques were developed for improving audio-video communications. *Apollo*'s CSMs and LMs carried the Apollo Guidance Computer (AGC), developed at the Massachusetts Institute of Technology, to provide computation capability and assistance for guidance, navigation, and control of the spacecraft [12] (Figure 5). It used a special read-only memory consisting of wires woven through small cores and a smaller read-write magnetic core memory. The size of its memory appears incredibly small now: the original 4 K words of fixed memory and 256 words of erasable memory (each with a 16-b length) were increased up to 36 K and 2 K, respectively, during the program. More notably, the AGC was one of the first computers to use integrated circuits, which were developed after the first working prototype made by Jack Kilby at Texas Instruments in 1958 [13]. Integrated circuits were pivotal to obtaining relatively powerful, light, and low-consumption computers. The technology evolved into microchips a few years later. The AGC preceded home computers based on such chips in the late 1970s, such as the Apple II, TRS-80, and Commodore PET.

NASA developed advanced cordless technology, which is now used in a wide variety of lightweight rechargeable tools, from electric screwdrivers to drills to vacuum cleaners, as well as surgery instrumentation and precision instruments. Photovoltaic (PV) cells were used in the Passive Seismic Experiments set up by *Apollo 11* to measure moonquakes. PV cells remain pivotal power supplies for satellites, space stations, and orbital telescopes, while having evolved into a viable alternative for reducing carbonized energy production on Earth. Practical fuel cells were first employed in manned space missions, with the early proton exchange membrane type by General Electric used in *Gemini 5* and 7–12; the alkaline type by Pratt and Whitney employed in the *Apollo* CSM, *Apollo/Soyuz*, and Skylab; and those by the United Technologies Corporation adopted in the Space Shuttle [11]. Fuel cells were ideal for those missions: they combine oxygen and hydrogen to provide electricity efficiently with a high power/weight ratio and also produce drinkable water. They also met the Apollo requirements in terms of reliability, duration, safety, and lifetime. Fuel cells are another emerging technology for decarbonized energy, particularly for electric mobility.

New manufacturing standards were also defined to satisfy the required reliability. Each of the 12 million components of the Apollo rockets and spacecrafts was specified to a 99.9999% reliability. A computerized axial tomography scanner was first used to detect component imperfections. The success of the Apollo program sprang also from the very efficient and innovative coordination of some 400,000 people at its peak, operating in more than 20,000 public institutions, universities, and industrial companies. The new computer-assisted management methods, which had their roots in the German A-4 missile program and in the Manhattan project (although still classified at that time), are among the most important, and least known, legacies of the Apollo program. The experience of the American space programs remains documented in 750,000 technical and scientific reports that are freely available to everyone on the Internet.

Criticism was also directed at the project at that time, claiming that the huge amount of money could be better spent on welfare and for taking care of human needs. Nevertheless, the Apollo program achieved its goals while respecting budget and time limits. From this point of view, it stands as a proof of the American capacity to successfully manage highly challenging projects, such as the Erie Canal, the transcontinental telegraph, railway and telephone lines, the transatlantic telegraph cables, the Panama Canal, the Manhattan project, and ENIAC. Ironically, the program, conceived by Kennedy to demonstrate the superiority of the free-market system, required the organization of tremendous public resources within a unique, vast, centralized bureaucracy [14].

To my eyes, the feat accomplished by Armstrong and his companions 50 years ago deserves one last comment: *Apollo 11* demonstrated how precarious life can be on a celestial body, and thus how precious is the planet we live on.



WIKIMEDIA COMMONS

FIGURE 5 – The Apollo Guidance Computer and its display and keyboard unit.

References

[1] D. Cadbury, *Space Race: The Epic Battle Between America and the Soviet Union for Dominance of Space.* New York: Harper Collins, 2006.

[2] M. J. Neufeld, *Von Braun: Dreamer of Space, Engineer of War.* New York: Alfred A. Knopf, Random House, 2007.

[3] M. Guarnieri, "Seventy years of getting transistorized," *IEEE Ind. Electron. Mag.*, vol. 11, no. 4, pp. 33–37, Dec. 2017. doi: 10.1109/MIE.2017.2757775

[4] P. Seguela and J. Oberg, *Space Probes: 50 Years of Exploration from Luna 1 to New Horizons.* Richmond Hill, ON, Canada: Firefly Books, 2011.

[5] A. L. Jenks, *The Cosmonaut Who Couldn't Stop Smiling: The Life and Legend of Yuri Gagarin.* DeKalb, IL: Northern Illinois Univ. Press, 2012.

[6] C. Burgess, K. Doolan, and B. Vis, *Fallen Astronauts: Heroes Who Died Reaching for the Moon.* Lincoln, NE: Univ. of Nebraska Press, 2003.

[7] J. M. Logsdon, *The Decision to Go to the Moon: Project Apollo and the National Interest.* Chicago: Univ. of Chicago Press, 1976.

[8] C. G. Brooks, J. M. Grimwood, and L. S. Swenson, Jr., *Chariots for Apollo: A History of Manned Lunar Spacecraft. NASA History Series.* Washington, D.C.: Scientific and Technical Information Branch, National Aeronautics and Space Administration, 1979. Accessed on: Apr. 26, 2019. [Online]. Available: https://history.nasa.gov/SP-4205/cover.html

[9] NASA, "Apollo Program Budget Appropriations." Accessed on: Apr. 26, 2019. [Online]. Available: https://history.nasa.gov/SP-4029/Apollo_18-16_Apollo_Program_Budget_Appropriations.htm

[10] K. S. Thomas and H. J. McMann, *US Spacesuits.* Chichester, U.K.: Praxis Publishing, 2006.

[11] K. A. Burke, "Fuel cells for space science applications," in *Proc. 1st Int. Energy Conversion Engineering Conf. (IECEC),* Portsmouth, VA, Nov. 2003, p. 5938. doi: 10.2514/6.2003-5938

[12] E. C. Hall, *Journey to the Moon: The History of the Apollo Guidance Computer.* Reston, VA: AIAA, 1996.

[13] M. Guarnieri, "The unreasonable accuracy of Moore's Law," *IEEE Ind. Electron. Mag.*, vol. 10, no. 1, pp. 40–43, Mar. 2016. doi: 10.1109/MIE.2016.2515045

[14] Lexington, Ed. "Apollo plus 50: The meaning of the race to the moon, half a century after the starting gun," *The Economist.* London: The Economist Newspaper Limited. May 19, 2011, p. 36. Accessed on: Apr. 26, 2019. [Online]. Available at: https://www.economist.com/united-states/2011/05/19/apollo-plus-50.