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The NewSpace Era

This chapter looks at the history of the space age from its very beginnings, marked in time by the International Geophysical Year (IGY) of 1957–1958 focusing on the event of peak solar activity, and against the backdrop of the Cold War between the USSR and the USA. This period of early discoveries, notably the Van Allen belts, was characterized by rivalry between the two world powers in the space race, with the first man (1961) and woman (1962) in space, and the first man on the Moon (1969). This was followed by a transition toward scientific objectives, such as the observation and collection of data on the Earth's atmosphere for meteorological purposes, and the exploration of the Solar System, in particular with Voyagers 1 and 2, which are still operational outside of the Solar System. This era has been driven by innovation, be it in project management (system approach, V-cycle, etc.) or technology (digital twins, solar panels, digital communications, etc.) to achieve the objectives of space projects driven by space agencies (NASA, ESA, etc.), with a focus on quality and reliability. Initially, satellites were spherical or cylindrical in shape, weighing no more than a hundred kilograms, but by the mid-1970s, they were weighing several thousand kilograms and could reach a weight of up to ten tons.

At the end of the 1990s, visionary entrepreneurs initiated daring projects, including the reuse of space launchers, suborbital flights and exploration of the Moon and Mars. In 1999, two American universities reduced the volume of satellites by inventing CubeSats and nanosatellites. This marked the dawn of the NewSpace era which redefined the space industry and its fields of activity, emphasizing innovation, cost reduction and increased private-sector participation in space exploration and exploitation, as embodied, for example, by SpaceX in the United States (2002) and Rocket Lab in New Zealand (2018).

For a color version of all of the figures in this chapter, see www.iste.co.uk/dahoo/nanosatellites1.zip.

1.1. The space age and its evolutions

The history of space exploration can be divided into four distinct periods. The initial period ran from 1957 with Sputnik 1 to 1970 with the end of the Apollo program. This was followed by the intermediate period from 1971 when military satellites were launched against a backdrop of geopolitical challenges, until the end of the Cold War in the early 1990s. It should be noted that, at the same time, space research experienced a significant boom, leading to major advances in scientific research and influential international cooperation.

At the end of the Cold War in 1991, space exploration evolved in a context of unipolar domination, with the United States in a predominant position. This was the beginning of the NewSpace era, marked by growing private initiative in the space industry (SpaceX, Elon Musk; Blue Origin, Jeff Bezos; Virgin Galactic, Richard Branson). NewSpace brought a new dynamic to the space industry, thanks to reusable launchers and the miniaturization of satellites. The democratization of access to space allows a greater number of operators, including start-ups and research laboratories, to participate in space exploration [NEW 80, LAU 97, POR 98, SID 00, DIC 06, BIG 14].

Meanwhile, a new satellite format, defined as part of an educational project in 1999 at California Polytechnic State University and Stanford University (USA), opened up new prospects for Earth observation. The idea was to imagine, design, implement, test and operate CubeSats (a 1U cube with dimensions of 10 x 10 x 11.35 cm) in space, as part of a three- to five-year university course. This approach represents a new era in the conquest of space [HEI 00, JAN 11, 21, 23], the developments of which are described in the appendix.

1.1.1. *The first artificial satellites*

Although Isaac Newton's work on gravity raised the theoretical possibility of orbiting an artificial satellite from Earth in 1687, it was not until the early 20th century that the theoretical work of Russia's Konstantine Tsiolkovsky and the experimental work of American Robert Goddard confirmed that a satellite could be launched by a rocket.

On October 4, 1957, the Earth's first artificial satellite was launched from the Baikonur cosmodrome by an R-7 Semiorka launcher (a large intercontinental ballistic missile). Sputnik 1 (meaning "satellite" or "companion" in Russian) is a sphere measuring 58 cm in diameter and weighing 83.6 kg. It was the first artificial

object launched into space. For 22 days, it transmitted data on solar winds, the Earth's magnetic field and cosmic rays. These were the first scientific data to be recorded directly from space. It was followed a month later by Sputnik 2, launched on November 3, 1957, with an animal on board, the dog Laïka. The onboard instruments detected radioactivity in the Van Allen radiation belts, but the origin of the signals transmitted was not identified, as they were picked up by nations other than the USSR.

As a reminder, the Van Allen radiation belts (see Figure 1.1)[1] are made up of a high density of energetic particles, originating from the solar wind in a toroidal zone of the Earth's magnetosphere around the magnetic equator. The encounter of these particles with the molecules of the Earth's upper atmosphere manifests itself in the form of polar aurorae.

It took the United States four months to respond and launch its own satellite, Explorer 1, from the famous Cape Canaveral base in Florida on February 1, 1958. This first American satellite was followed by Vanguard 1, launched from Cape Canaveral on March 17, 1958, which became the fourth artificial Earth satellite. Explorer 1's four-month mission also enabled Geiger counters to detect the Van Allen radiation belts. However, it was not until the data recorded by Explorer 3, launched on March 26, 1958, with the first onboard miniaturized magnetic tape recorder, that the riddle of the signals resulting from the presence of the Van Allen radiation belts was resolved.

Vanguard 1 was the first satellite to be equipped with solar cells (six), enabling its second transmitter to operate until May 1964, almost six years after its launch, whereas the mission of the first satellites did not exceed four months.

We should also mention the glorious achievements of the USSR, with the first man in space on April 12, 1961 (Yuri Gagarin) and the first woman in space on June 16, 1963 (Valentina Terechkova); and of the United States with the Apollo program, the first man on the Moon with the Apollo 11 mission and the moon landing on July 21, 1969 (Neil Armstrong, Buzz Aldrin and Michael Collins).

By 1957, space systems and associated missions had become indispensable tools for many disciplines involved in the study and observation of planet Earth and its near and distant environment, as well as the exploration of the near and far Universe [NEW 80, LAU 97, POR 98, SID 00, DIC 06, BIG 14, JAN 23].

1 See: https://en.wikipedia.org/wiki/Van_Allen_radiation_belt.

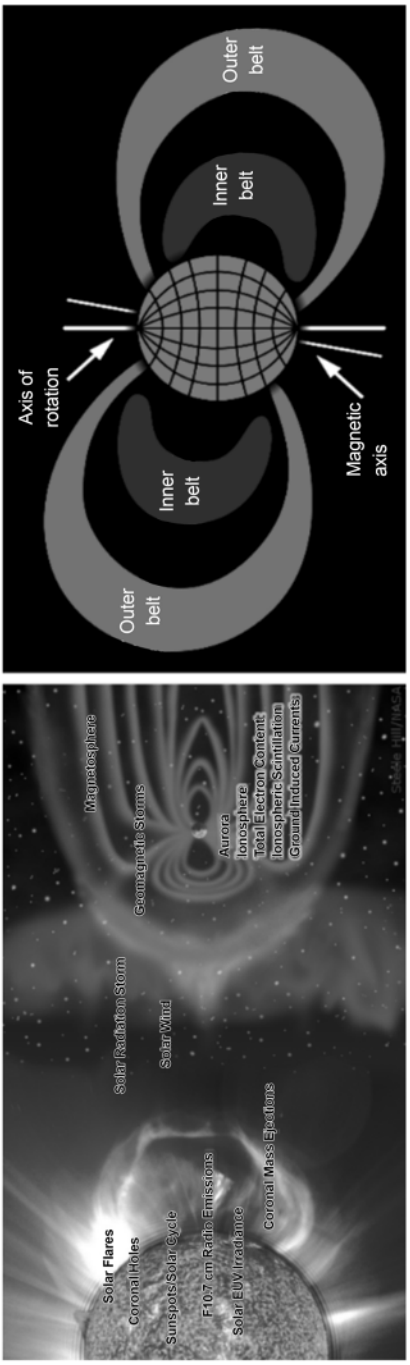


Figure 1.1. *Van Allen belts (NASA)*

1.1.2. *Planet Earth and its near and distant environment*

The formation of ozone holes in the stratosphere above the poles, which, as a result, could no longer sufficiently filter out ultraviolet radiation, or the increase in the greenhouse effect due to a rise in the amount of carbon dioxide in the atmosphere, are just two concrete examples of the benefits of observing the Earth and studying its near and distant environment in targeting the right causes to these harmful effects. Satellites have become indispensable in this field, not only for managing the Earth's natural resources, controlling the environment, protecting people and property in danger, providing meteorological services, studying the climate, space weather, etc., but also for telecommunications, telephony, communication for multimedia applications, navigation, defense, etc.

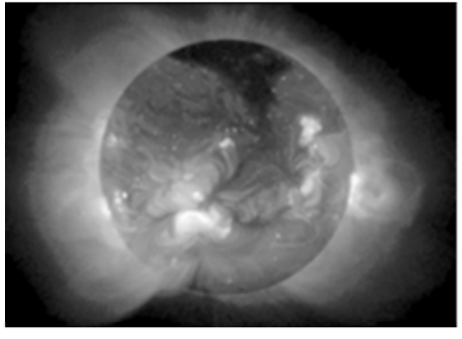
An illustrative example is the series of ten experimental meteorological satellites, Tiros-x (Television InfraRed Observation Satellite), launched between 1960 and 1965 by NASA (the US space agency) into polar orbit to supplement data obtained by traditional ground-based devices and used for weather forecasting. In an international cooperation between CNES (the French space agency) and NASA (the EOLE program), a first PEOLE satellite was also launched in 1970 by the Diamant rocket from the Kourou base in French Guiana, followed in 1971 by the EOLE satellite developed by CNES and launched by NASA from Wallops Island by the Scout rocket. These satellites retrieved meteorological data provided by 500 weather balloons launched from Argentina, drifting from west to east at an altitude of 12,000 m in the Southern Hemisphere on an eight-day cycle [MOR 66, 02, LET 13].

Since then, the analysis of the data collected by various observation instruments has shown that human activities are responsible for modifying the composition and the warming effect of the Earth's atmosphere. In light of the visible and measurable consequences on the ecosystem and climate, it is more than necessary to design instruments that can continuously monitor the state of the Earth's atmosphere by observing its near or distant environment, with quality data to benefit from subsequent analysis and correcting actions.

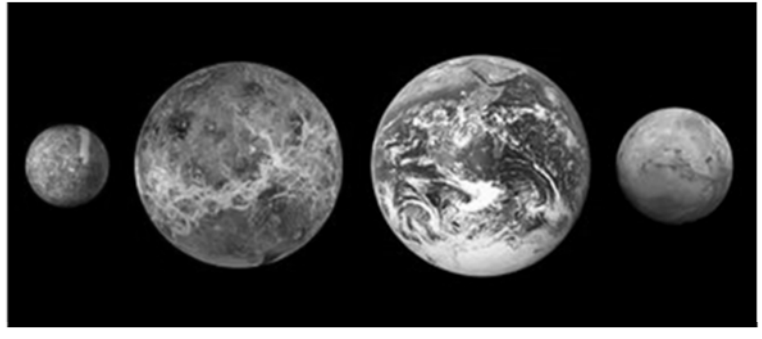
1.1.3. *Exploring the near and distant Universe*

Scientific missions enable us to study the nearby Universe in the solar system – for example, the Sun (see Figure 1.2(a))[2] and the terrestrial planets Mercury, Venus, Earth and Mars (see Figure 1.2(b)) – or the more distant Jovian planets, Jupiter, Saturn, Neptune and Uranus.

2 See: https://en.wikipedia.org/wiki/Sun.



a) The sun



b) The telluric planets

Figure 1.2. *The Sun and the Solar System's telluric planets*

These observation and analysis activities can be carried out either by the study of the Earth from ground-based observatories or the ISS orbital station, or from space systems such as satellites, rovers, probes or orbiters launched to get as close as possible to the objects under study. Examples of the latter include Mars Express and Venus Express, orbiters dedicated to studying the atmospheres of Mars and Venus.

Mars Express (MEX) is the first European planetary mission to the Red Planet, developed in collaboration between LATMOS (formerly the French Aeronomy Service) in France, BIRA-IASB (Royal Belgian Institute for Space Aeronomy) in Belgium and IKI (Russian Space Research Institute) in Russia. Launched on June 2, 2003 by a Soyuz rocket, the 1270 kg orbiter was placed in an elliptical polar orbit around Mars on December 25, 2003, with a pericenter altitude of 259 km and an apocenter altitude of 11,559 km, for a period of 7.57 hours. A measurement and observation instrument, called SPICAM (Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars), has enabled the spectroscopic study of the UV and IR signatures characteristic of the atmosphere of Mars. Dedicated primarily to the study of the atmosphere of Mars, the spectrometer operates in the ultraviolet and infrared ranges [BER 06].

The 1,042 kg ESA Venus Express orbiter was launched on November 9, 2005 by a Soyuz rocket, and was the first mission to apply solar and stellar occultation techniques to the atmosphere of Venus, with the SPICAV/SOIR (Solar Occultation in the InfraRed) instrument. Based on the SPICAM model, the SPICAV instrument (V for Venus) comprises a suite of three spectrometers with a variety of scientific objectives. As for SOIR, it is one of three high-resolution spectrometers on Venus Express, with a new optical design enabling it to achieve a resolution power $\lambda/\Delta\lambda$ = 15,000–20,000 for a volume and mass (6 kg) that are reasonable for space, working in the 2.2–4.3 μm range. This is the highest resolution for planetary space exploration [BER 07, 08].

1.1.4. *Space activities*

The space sector encompasses a wide range of activities and applications. The main ones are listed below:

1) Scientific research: space plays an essential role in scientific research, enabling us to observe the Universe, study cosmic phenomena, collect data on the Earth, explore the planets, etc.

2) Telecommunications: telecommunications satellites are used for long-distance communications, data transmission, television, broadcasting, cell phone networks, etc.

3) Navigation and positioning: satellite navigation systems such as GPS (Global Positioning System) enable the precise determination of position, speed and time

throughout the world, and are used in many sectors, including transport, logistics and cartography.

4) Earth observation: Earth observation satellites provide invaluable data and images for monitoring the environment, studying climate, meteorology, natural resource management, monitoring natural disasters, etc.

5) Space exploration: space exploration includes sending probes and robots to study planets, moons and asteroids, as well as sending astronauts to explore space and destinations such as the Moon, Mars and beyond.

6) Military and defense applications: space is used in military applications for surveillance, secure communication, intelligence, reconnaissance, etc.

7) Commercial applications: the space sector is increasingly exploited by private companies for activities such as space tourism, satellite launches, telecommunication services, Earth imaging, etc.

8) Education and awareness: the space field also plays an important role in educating and raising public awareness through education programs, exhibitions, events and activities designed to inspire future generations and promote interest in space exploration.

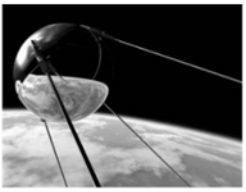
According to Janson, the space era can be divided into three periods since 1957: the first era from 1957 to 1970, the great era from 1971 to 1996 and the new space era from 1997 onward, which can be described as NewSpace [JAN 11, 21, 23].

1.2. NewSpace in the 21st century

Observation sciences and space technologies have followed a trajectory marked by technological transitions and strategic choices for exploration and observation, particularly by the American (NASA) and European (ESA) space agencies. In the initial phase of the 1960s, satellites equipped with the latest technologies were spherical or cylindrical in shape and weighed no more than 100 kg. Since the mid-1970s, however, the design of objects for observation and space technologies has given rise to a diversity of systems – be they satellites, probes, orbiters, rovers or drones – that are increasingly based on a systemic approach to design, sometimes relying on digital twins with weights in excess of a few thousand kilos and sometimes reaching tens of tons.

It was in 1999, outside the decision-making sphere of space agencies or military organizations, that a new era in the conquest of space began. Thanks to an educational project, the first CubeSats – cubes measuring 10 x 10 x 11.35 cm (1U) – saw the light of day in California, inspired by Professor Jordi Puig-Suari of

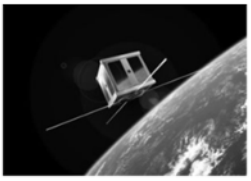
California Polytechnic State University and Professor Bob Twiggs of Stanford University [KIT 94, HEI 00]. The method implemented enabled a complete spacecraft to be designed, deployed, tested and operated in space within a reasonable timeframe, in a three- to five-year curriculum, to train academics with off-the-shelf technologies. The first six CubeSats were launched on June 30, 2003 by Eurockot's Rockot launcher from the Plesetsk site. This educational project democratized the use of small satellites that can be designed in a laboratory for space research programs, and paved the way for a sector of industrial activity in this field. Since 2013, space agencies have shown that the reliability of CubeSat missions can be greatly improved by optimizing design engineering.



1957: Sputnik, already NewSpace

- Small aluminum sphere, 58 cm in diameter
- Weight 83.6 kg
- Four antenna
- Elliptical orbit at an altitude of between 230 and 950 km
- Period: around 98 minutes

→ Satellite temperature?



2003: AAU CubeSat

- 1U cube (10 x 10 x 10 cm^3)
- Weight 1 kg
- 4 antenna
- Orbit: 830 km altitude
- Period: 101.4 mn
- Images acquired with a 1.3 Mpixel Cmos detector, with a resolution of 120x120 m per pixel

→ Diameter of optics?

Figure 1.3. *Satellite evolution between 1957 and 2003*

Figure 1.3 summarizes the characteristics of the satellites designed in 1957, when the space age began, and those of the CubeSats developed in 2003. The diameter of the sphere has been reduced from 58 cm to a cube with sides of 10 cm, which means a reduction in volume by a factor of approximately 100. At the same time, the mass has been reduced by approximately 80, knowing that a cube is easier to build than a sphere. The orbit has moved from elliptical, with an altitude between 230 and 950 km, to circular at 850 km, but with an almost identical period (98 min vs. 104.1 min). The spectral range of observation is wider in range with the CubeSat which, in addition to four antennas in the microwave range, was equipped with Cmos detectors to record images. However, last but not least, the constraints of temperature and optical resolution have yet to be overcome.

NewSpace has been emerging since the 2000s, and a number of new challenges have arisen. The last decade has seen significant advances in space technologies and an intensification of public communication about space. Today, space exploration is

no longer the prerogative of government agencies, but is open to private enterprise, marking the beginning of the NewSpace era. This new space era has brought with it new participants and a deep transformation of the space ecosystem. NewSpace is attracting a great deal of interest, as its dynamic players are injecting new energy and speed into the space sector. This democratization of space has been made possible by the use of innovative reusable launchers and the increasing miniaturization of satellites. These advances, combined with the development of space tourism, the return to the Moon and the exploration of Mars, have rekindled the general public's enthusiasm for space. The conquest of space is inevitably accelerating, with projects for space travel, lunar and martian exploration. The American space agency, NASA, is preparing for an odyssey to Mars as part of its Artemis program. This new space age promises exciting discoveries and major technological achievements, paving the way for a future in which space exploration will play a central role.

Satellites play a major role in the new era of space conquest. A mass criterion is often used to classify satellites, as shown in Table 1.1, in the FAA (Federal Aviation Administration) classification in the United States. In this classification, the first Sputnik 1 satellite was of micro type, as was the first CubeSat of 2003, as shown in Figure 1.3. The Mars Express and Venus Express orbiters were in the category above, medium and mini respectively.

In economic terms, a low-orbit satellite costs between €8,000 and €12,000 per kg to build and launch. Compared with an average cost of €8 million for a medium-sized satellite with a mass of approximately 800 kg, a 10 kg CubeSat only costs €100,000, making it affordable for academic scientific research programs to observe the Earth [CAM 19].

Satellite class	Mass (Kg)
Very heavy	> 7100
Heavy	5401–7000
Large	4201–5400
Intermediate	2501–4200
Medium	1201–2500
Average	601–1200
Mini	201–600
Micro	11–200
Nano	1.1–10
Pico	0.09–1
Femto	0.01–0.1

Table 1.1. *Payloads and specifications*

1.2.1. *Development priorities for the NewSpace era*

A number of areas of development are emerging in this new NewSpace era:

1) *Satellite launches*: this is one of the largest sub-sectors of NewSpace. Satellite launch companies focus on the technology and infrastructure needed to send satellites into near-space and low-Earth orbit.

2) *Internet via satellite*: NewSpace companies focus on improving Internet connectivity through low-Earth orbit satellites, wireless broadband, optical communications and other technologies.

3) *Deep space exploration*: NewSpace companies are developing high-level missions to transport people and goods beyond the Earth's atmosphere to the Moon, the surface of Mars and beyond.

4) *Lunar landing*: NewSpace companies are mainly focused on missions to the Moon, or on construction products and infrastructure for lunar missions.

5) *Industrialization and manufacturing*: these include the development of spacecraft, hardware, propulsion systems, engines, etc.

6) *Earth observation*: imaging, tracking and analysis technologies are being developed to monitor weather, climate, marine data, GPS technology, etc.

7) *Asteroid mining*: these cutting-edge companies are developing technologies to extract water, rare minerals and metals from near-Earth asteroids.

8) *Space debris*: these analyze human-made objects orbiting the Earth. Debris has to be monitored to avoid collisions with satellites and spacecraft, etc.

9) *Space tourism*: access to space for individuals, explorers, etc.

How are research activities faring in the NewSpace era?

1.2.2. *Research development*

The following questions may be asked:

– Is NewSpace leading us toward the privatization of space?

– What kind of legislation and governance will be needed in the future?

– Are we facing a new paradigm (see Figure 1.4)?

This means that, alongside the major standard observation and analysis projects with space agencies (NASA, ESA, CNES, etc.), we need to be able to implement

new systems that are smaller, more efficient, less costly and faster, in an "agile" approach.

This implies greater flexibility, with public–private partnerships and the creation of international networks, to take a new approach to scientific research linked to planetary observation and data analysis.

By way of example, we can cite the spin-offs for scientific research of this new paradigm. LATMOS and OVSQ at the Université Versailles-Saint-Quentin-en-Yvelines have positioned themselves, within the framework of national and international collaborations, on atmospheric observation to provide data for climate studies, as shown in Figure 1.5. They used the CubeSats UVSQ-SAT [MEF 20] and INSPIRE-SAT 7 [MEF 22a] built by these two institutions thanks to Meftah and teams from LATMOS, OVSQ and UVSQ.

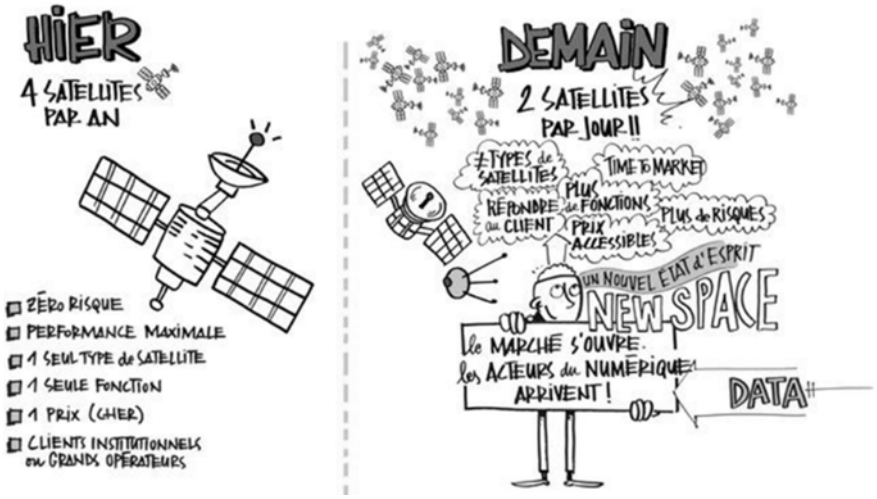


Figure 1.4. *A new paradigm for implementing space programs*

COMMENT ON FIGURE 1.4.– *The figure demonstrates the mass development of satellites by comparing the scale of production between the past and the future. In the past, only four satellites per year were put into orbit, compared to an expected two satellites per day in the future. The figure also compares the characteristics of the old versus new satellites. The satellites of the past have zero risks, maximal performance and there is only one type with one function. They are also expensive and used by institutional customers and major operators. The satellites of the future will be of different types, with multiple functions and carry multiple risks. They will be more affordable in price and open up the market to digital players*.

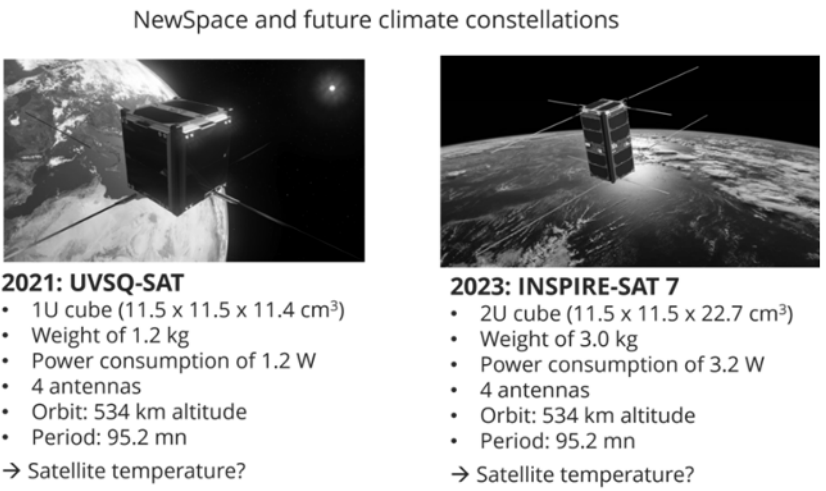


Figure 1.5. *Nanosats: UVSQ-SAT (2021); INSPIRE-SAT 7 (2023)*

1.3. The space system

Engineering is the application of science. Its aim is to convert scientific laws into applied reality, whether for medical concerns or space travel. In the process of designing intelligent objects, the engineer's job is to provide solutions to problems that ultimately have an impact on society. As a result, space programs have been the source of many innovations. They required the application of new project management methods for the manufacture of satellites intended to be propelled into space from launch sites, emphasizing a system approach to the design and manufacture of a satellite or probe [NAS 95, 19, GPG 07, CHI 17, MEF 22b].

Issues such as reliability, logistics, coordination of different teams (requirements management), evaluation measures and other disciplines become more difficult when large or complex projects are involved. This is why the so-called V-cycle method has been used as part of the system approach, as described in section 1.4.

Digital simulation methods based on a digital model of the physical system (the forerunner of the digital twin) were also used in the Apollo programs. The digital twin is a concept of virtual equivalent or dynamic digital representation of a real system.

The first definition was formulated by NASA in its Integrated Technology Roadmap (Technology Area 11: Modeling, Simulation, Information Technology & Processing Roadmap, 2010):

> A digital twin is a multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin [SHA 10].

Let us also note Michael Grieves' definition of the digital twin [GRI 02] as "a set of information constructs that fully describe a potential or actual physical manufactured product, from the micro-atomic to the macro-geometric level".

Finally, we should also mention the implementation of a communication system to collect and transmit data in digital form, whether passive or active. The coupling of this system with the satellite's digital image has paved the way for Industry 4.0. This concerns the automation and exchange of data in manufacturing industries with the additional technology of cyber software, IoT, cloud, and including identification, problem-solving and decision-making (cognitive computing). IoST (Internet of Space Things) is emerging alongside IoT (Internet of Things).

It should also be noted that space activities are particularly focused on data, whether for observation or control, from satellites, telescopes or platforms. These include meteorology, telecommunications (telephone, radio, television, Internet), the GPS and the Internet of Things.

1.3.1. *The system concept*

The noun "system" is used in many different situations. It can be used to refer to air traffic control systems, the solar system or biological systems. The fact that the word is used in so many different ways is an indication of the complexity of the concept itself.

According to the Centre national de ressources textuelles et lexicales (National Center for Textual and Lexical Resources), a definition was proposed in 1552: "A whole whose parts are coordinated by a law"[3].

In Étienne Bonnot de Condillac's 1749 philosophical work *Traité des systèmes* [BON 49], the term is defined as:

> [The] arrangement of the different parts of an art or science in an order in which they all support each other and in which the latter are explained by the former. Those that give reason for the others are called principles.

3 [DET 87]: "I am ready to show you the composition of this System" (author's translation).

According to [DER 75], in general terms, a system is a set of dynamically interacting elements organized in function of a goal. A system can thus be considered as any entity, conceptual or physical, made up of interdependent parts. In other words, it is a set of elements in permanent interaction, organized and open to its environment, to which it must constantly adapt in order to survive (see Figure 1.6).

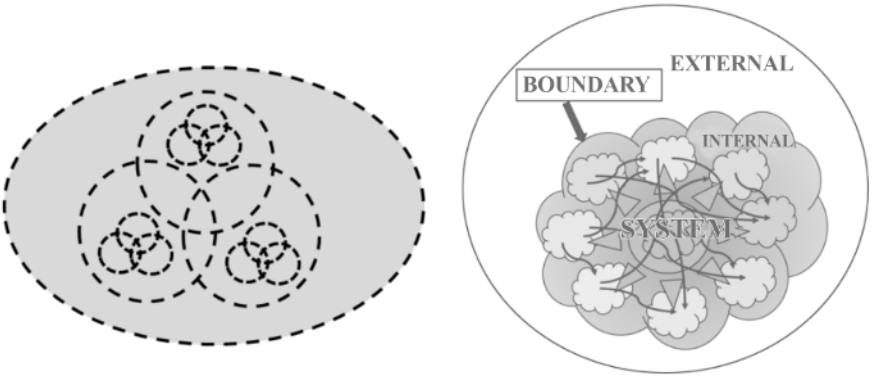


Figure 1.6. *System, subsystems and interrelationships*

A *system* is a set of elements interacting with each other according to certain principles or rules. It is determined by:

– its boundary, i.e. the criterion of belonging to the system (determining whether an entity belongs to the system or, on the contrary, is part of its environment);

– its interactions with its environment;

– its functions (which define the behavior of the entities making up the system, their organization and their interactions).

The system's approach stems from the 1940s encounter between biology and electronics:

– the birth of cybernetics (1948) [WIE 48], with the study of regulation in living beings and machines, and the introduction of the ideas of loop, feedback and regulation;

– a unitary vision of the world expressed by biologist Von Bertalanffy (1950) [VON 50, 68], with open systems everywhere.

The study of systems is carried out within the framework of the system's approach, which follows on from the methods advocated by the Palo Alto school

in the 1950s as well as the work of Gregory Bateson [PIC 13]. The system approach has been the subject of numerous publications and applications, whose non-exhaustive references are given in the appendix [CHU 68, ACK 74, MPH 74, WEI 75, LEM 77, FOR 84, FLO 93, 99, SEN 93, CHE 99, HIT 07, BOA 08, RAM 09, LAW 10, DEW 11, INC 12, 15].

1.3.2. *Designing a space system*

A space system must be considered within the framework of systems engineering, which is also one of the methodological products of space activities in project management. It is an interdisciplinary field of engineering, focusing on the design and management of complex engineering systems throughout their life cycle. Issues such as reliability, logistics, coordination of different teams (requirements management), evaluation measures and other disciplines become more difficult when dealing with major or complex projects. Systems engineering deals with work processes, optimization methods and tools for complex projects. It covers both technical and human disciplines, such as control engineering, industrial engineering, organizational studies, project management, etc. [DAH 21, 22, MEF 22b, 23].

1.3.3. *The two main sectors of a space system*

The space sector can be broken down into two sectors: that of the space vehicle design environment, the “space sector”, and that of the users who implement the vehicle’s functionalities, the “user sector”. In the system approach, these sectors are two subsystems that interact with each other.

The space sector

Space vehicles – satellites, probes, landers, rovers, orbiters – are characterized by their capacity and the type of mission to which they are dedicated. Applications can be scientific, commercial or military. Their definition must take into account all trajectories and orbits followed from launch to end-of-life. The mission-critical part of the spacecraft is called the payload.

The space sector includes the design of satellites from technical specifications. It can be divided into:

– the launch from a site, i.e. the launch center, the launcher and the operations to be carried out from launch into orbit to separation of the launcher from the satellite or probe;

– the operations, including a command and control center with radio links to steer the satellite, and a scientific mission center to process the data.

The user sector

The user sector includes the means for receiving, processing and distributing information associated with the space mission (mission center at one or more sites).

1.4. Implementing a space project

1.4.1. *The initial spatial project and management methods*

The two basic elements to consider when launching a space project are:

– a description of the idea;

– a technological presentation of the idea.

A project's conception and realization is shown in Figure 1.7. It starts with an idea and requires a budget and resources for its realization. The next step is to draw up a schedule and manage its implementation.

Figure 1.7. *Project management*

Project management involves setting up a program to achieve an objective, which is often the design of a product or service.

There are generally three essential stages:

– identifying and describing the project;

– organizing and planning the project;

– monitoring the project and managing discontinuities (or discrepancies) between forecast and actual status.

There are many methods available to help manage a project. The teamwork.com website indicates that there are some 8,462 project management methods.

To implement a space system, it is necessary to use a system approach for decision-making (DM) within the framework of collaborative engineering, in order to meet the requirement of integrating project management (PM) with systems engineering (SE).

The V-cycle is an example. This is shown in Figure 1.8 and is an example of project management. It is based on a cascade model theorized in the 1970s. It allows development processes to be represented linearly, which leads to sequencing in the processes in successive phases from design to realization and validation.

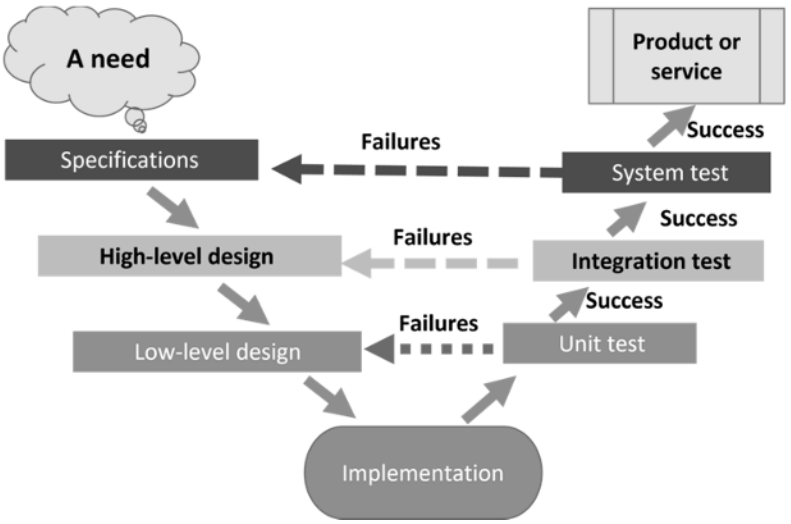


Figure 1.8. *The V-cycle for project management associates a validation phase with each implementation phase*

The V-cycle is a common graphic representation of the system's engineering life cycle, generally applied in the space industry. The left-hand side of the V-cycle represents concept development and the decomposition of requirements into functions and physical entities, which can be organized in the form of an architecture for design and development. The right-hand side of the V-cycle represents the integration of these entities (including appropriate testing to verify that they meet requirements) and their final transition to the field, where they are operated and maintained.

The implementation of a "small satellite" program can also rely on a simplified approach to guarantee the success of a mission, which has to be developed within a limited time (two years). LATMOS implements some of these programs using a simplified organizational structure. The aim is to promote an agile approach while avoiding the vertical management model, which often proves ineffective for rapidly driving a space program from its definition and analysis phase (phase 0/A) through to its exploitation phase (phase E). In this type of program, it is necessary to spur the active participation of the technical and scientific teams throughout the project, thus emphasizing flexibility in the face of possible changes and minimizing the importance of traditional procedures. Despite the simplified organization, a space project is still a complex process that requires meticulous planning, precise coordination and the consideration of numerous variables.

1.4.2. *Key issues from idea to realization*

When undertaking a space project, such as, for example, putting an atmospheric observation system into orbit from a CubeSat, it is necessary to formulate it in a few lines [MEF 23]:

– a description of the idea;

– a technological presentation of the idea.

Then, there are several questions to answer:

– What needs are being met?

– Who are the potential users?

– What is the type of project: experimental, application?

– What resources and budget are required for the program?

– What are the project contingencies?

– How do we obtain financing for the project?

– What do we bring that is new to the table?

– What sets this technology apart from competing technologies?

– What can we do that others cannot?

1.4.3. *Academia and industry*

1.4.3.1. *Academic state of the art*

– Which are the main academic laboratories (on an international scale) working in the project's technological field?

– What do they do exactly?

– What are the competing technologies?

– What are the strengths/weaknesses?

The answers to these questions can then be organized in an easy-to-read summary table.

1.4.3.2. *Industrial state of the art*

– Who are the main manufacturers (on an international scale) supplying the project's technological solutions?

– What do they do exactly?

– What are the competing technologies?

– What are the strengths/weaknesses?

1.4.4. *Questions and steps once the project is defined*

Once the project has been defined, the following questions are usually answered:

– What is it?

– Who is involved?

– How do we do what needs to be done?

We can then, for example, break down the space system into subsystems, such as:

– NewSpace launcher;

– satellite;

– transfer and landing vehicles;

– rover.

To carry out this project, we can then form four groups with a leader for the themes linked to each subsystem:

– a NewSpace launch group;

– a satellite group;

– a transfer vehicle and landing gear group;

– a rover group.

This is the approach adopted in the UVSQ-SAT (2021), INSPIRE-SAT 7 (2023) and UVSQ-SAT NG (2025) projects mentioned above [MEF 20, 22a, 23].

A system's complexity is motivating new approaches to their design, grouped together under the term "systems architecture". System architecture is a conceptual model of a system that describes its external and internal properties and how they are projected onto its elements, their relationships and the principles of system design and evolution.

Figure 1.9 shows an example of a satellite operation center linked to the space sector. The purpose of this device is to control the satellite and receive data from it. It is often associated with a scientific mission center, which enables the data to be processed. Figure 1.10 shows an example of a "project" breakdown. The space sector of this program is broken down into two segments: space and ground.

Every project is based on a stated objective, which requires programming of the tasks to be carried out, identification of the services to be called upon and the expected results. In the case of the design of an artificial satellite of the CubeSat type, the various phases can be summarized, as shown in Table 1.2.

As an example, we give a comparison of the procedures to be followed with regard to the different phases named by ESA and NASA, as well as the documents to be compiled in Table 1.3 [NAS 95, 19, ESA 09].

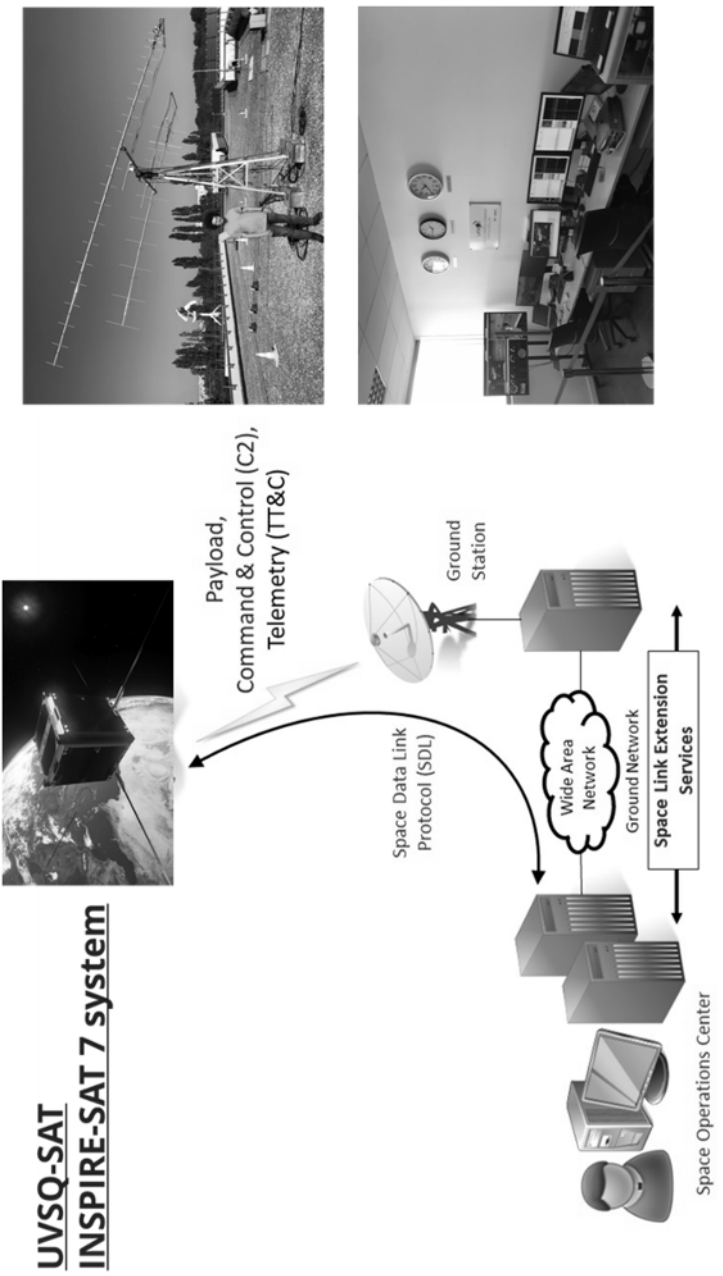


Figure 1.9. *Example of a satellite command and control center (applicable to UVSQ-SAT and INSPIRE-SAT 7 space missions)*

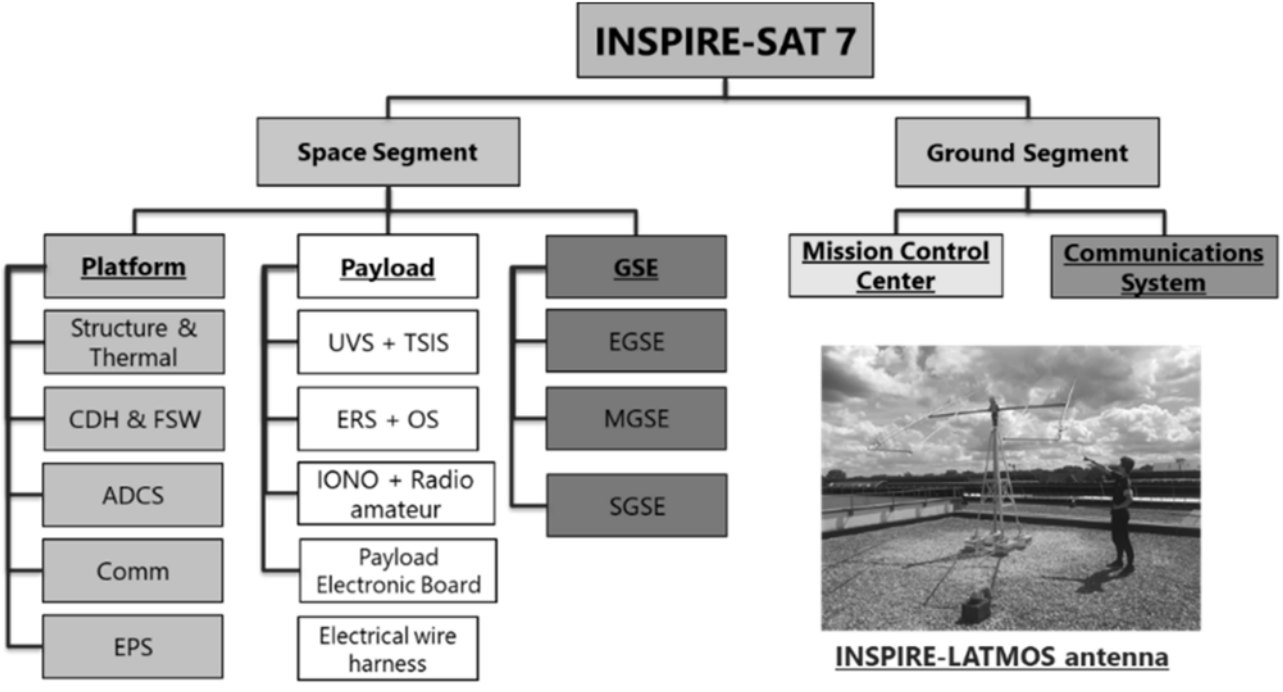


Figure 1.10. *INSPIRE-SAT 7 subsystems and interrelationships*

Phase	Process
0	**Analyze the mission**: define the objectives and list the various parties involved.
1	**Feasibility study**: carry out initial feasibility and sizing studies.
2	**Define preliminaries**: select technical solutions; study solutions and assess the feasibility of each one by identifying cost, operational, scheduling and organizational constraints.
3	**Define the project in detail**: express and finalize requirements and confirm the technical feasibility of the chosen solution based on the results of the studies.
4	**Carry out and qualify the project**: manufacture or acquire the space system and test its various components to qualify their performance.
5	**In-orbit phase**: satellite launch and constraints to be met with the launch organization and the first connection with the satellite in orbit.
6	**Operational phase**: data acquisition and satellite control.
7	**Service withdrawal phase**: close the project.

Table 1.2. *Design phases of a CubeSat nanosatellite*

Phase	ESA	NASA
0	Mission Analysis/Requirements Analysis (MDR)	Design studies (MCR)
1	Feasibility study (PRR)	Feasibility study (SRR-MDR)
2	Preliminary definitions (PDR)	Preliminary design (PDR)
3	Detailed definitions (CDR)	Final design and manufacturing (CDR-SIR)
4	Production/Qualification Test (AR)	System assembly, Integration/Testing (SAR-ORR)
5	Launch	Launch
6	Operation	Operations

Table 1.3. *ESA/NASA phases in satellite design*

COMMENT ON TABLE 1.3.– *MDR: mission definition review; PRR: preliminary requirements review; PDR: preliminary definition review; CDR: critical design review; AR: acceptance review; MCR: mission concept review; SRR: system requirements review; MDR: mission definition review; PDR: preliminary design review; CDR: critical design review; SIR: system integration review; SAR: system acceptance review; ORR: operational requirement review.*

1.5. Building a spacecraft

1.5.1. *Spacecraft subsystems*

A spacecraft such as a satellite or an orbiter is generally decomposed into two sub-assemblies [MEF 22b].

The *platform* (bus) is a device designed to support one or more payloads. It must provide the resources needed for proper operation under the required conditions.

The platform's main functions are:

– supporting structure and mechanisms;

– thermal control of equipment;

– propulsion and in-orbit attitude modification systems;

– energy storage and distribution;

– in-orbit attitude control to modify vehicle orientation and telemetry;

– remote control and vehicle location with a GPS device;

– onboard data processing, storage and management.

The *payload* is the set of elements designed to fulfill a scientific, commercial or military mission.

These are generally measuring or observation devices that collect data in line with the mission objectives, such as:

– the telescope;

– the spectrometer with the different UV, VIS, NIR, MIR, IR channels;

– the antennas;

– the LiDAR;

– the radiometer.

Examples of payloads are shown in Table 1.4. Their functions and the type of orbit associated with their observations are briefly described.

Payloads	Functions	Orbit type
Telescopes → Newton-type telescope → Two-mirror telescope (Cassegrain, Ritchey-Chrétien) …	Mirror telescope for small-field observation (a few degrees) and high spatial resolution (a few arcs) → Sun	Low orbit Heliosynchronous Geostationary
Radiometers → Measurement of emitted, diffused or reflected luminous flux	Imaging and radiation balances	Low orbit Heliosynchronous Geostationary
Lidars → Doppler (for speed measurements) → Pulsed (for distance or concentration measurements)	Measurements of concentrations, temperatures, species detection (water vapor, CO_2, etc.), velocity	Very low orbit Balloons Planes
Spectrometers → Vertical → Imager	Vertical atmospheric sounding or multi-spectral imaging	Low orbit Geostationary

Table 1.4. *Payloads and main functions*

1.5.2. *Example of an optical payload*

Optics is used in a wide range of instruments, such as altimeters, gyrometers, optical telecommunication and metrology systems, atomic clocks for service equipment, and equipment for observation and measurement in scientific experiments.

Onboard instruments are part of the satellite or orbiter payload. Figures 1.11 and 1.12 show examples of payloads for optical measurements using the Sun as a light source. The optical diagram of the space mission telescope is shown in Figure 1.11(a). It is a Ritchey–Chrétien telescope (specific Cassegrain) designed to eliminate the optical aberration known as "coma". This space telescope acquired images of the Sun in the UV, visible and NIR wavelengths from June 2010 to mid-2014. Figure 1.11(b) shows the optical diagram of the SOLSPEC instrument. This is a Czerny–Turner spectrometer (double monochromator) that operated on board the International Space Station. This instrument measured the solar spectrum between 165 nm and 3,000 nm over approximately one solar cycle (from 2008 to 2017). Figure 1.12 shows a schematic diagram of a space radiometer. This design corresponds to that of the DIARAD instrument, which has been used on several space missions. In particular, it was used on board the SoHO solar and heliospheric observatory, which was launched into orbit in 1995 – and is still operational today. The aim of the DIARAD radiometer is to measure the total solar irradiance at the top of the atmosphere. This measurement is of major interest, as it enables us to track the evolution of solar flux over time.

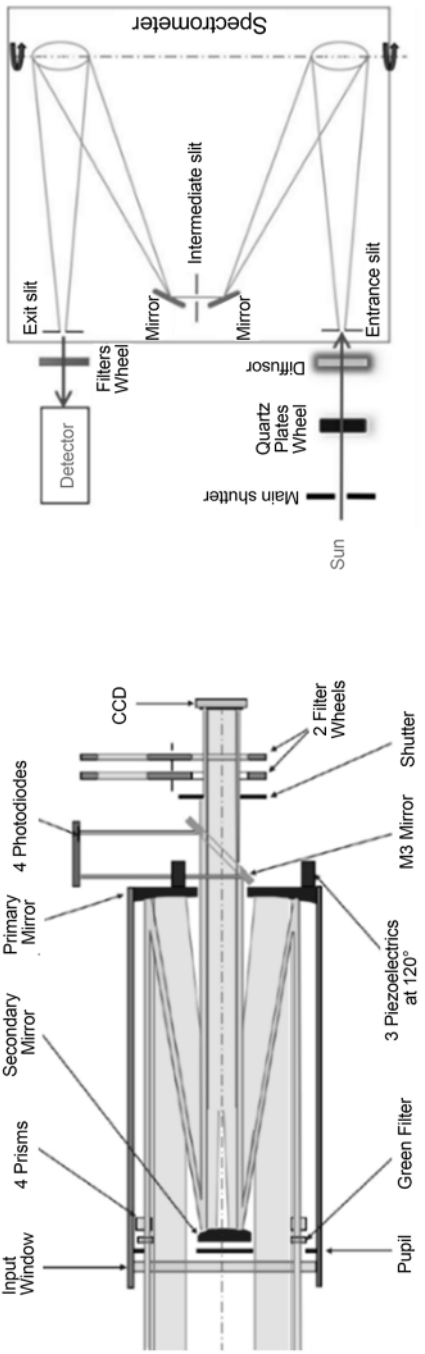


Figure 1.11. *Space instruments for observing the Sun.*
a) Ritchey–Chrétien telescope. b) Czerny–Turner spectrometer

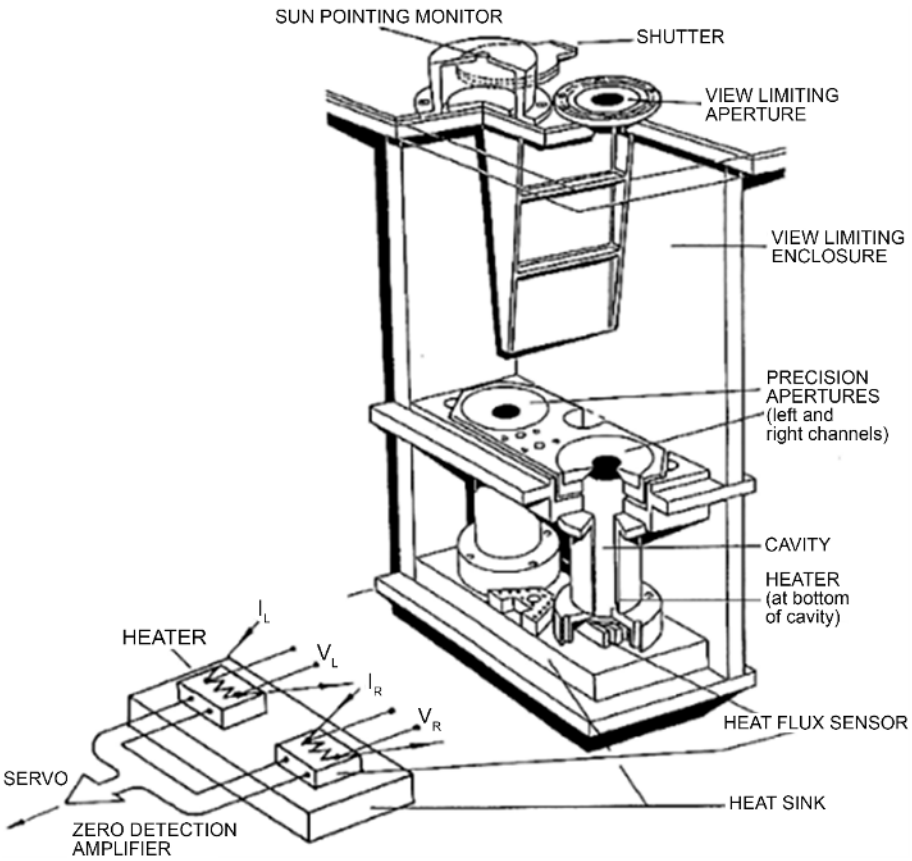


Figure 1.12. *Radiometer used to measure total solar irradiance*

Figure 1.13 shows an example of a LiDAR dedicated to the observation of atmospheric parameters. This is a ground-based laser remote sensing system based on a remote measurement technique that analyzes the properties of a beam of light reflected back to its transmitter. This device is installed at the Dumont-d'Urville base on Petrels Island, a few kilometers from Antarctica. This instrument can be used to measure aerosols, cirrus clouds and polar stratospheric clouds. Ground-based measurements are particularly interesting. They can be coupled with observations from space.

One of the challenges is to develop micro-LiDARs on board satellites to observe scientific variables of interest.

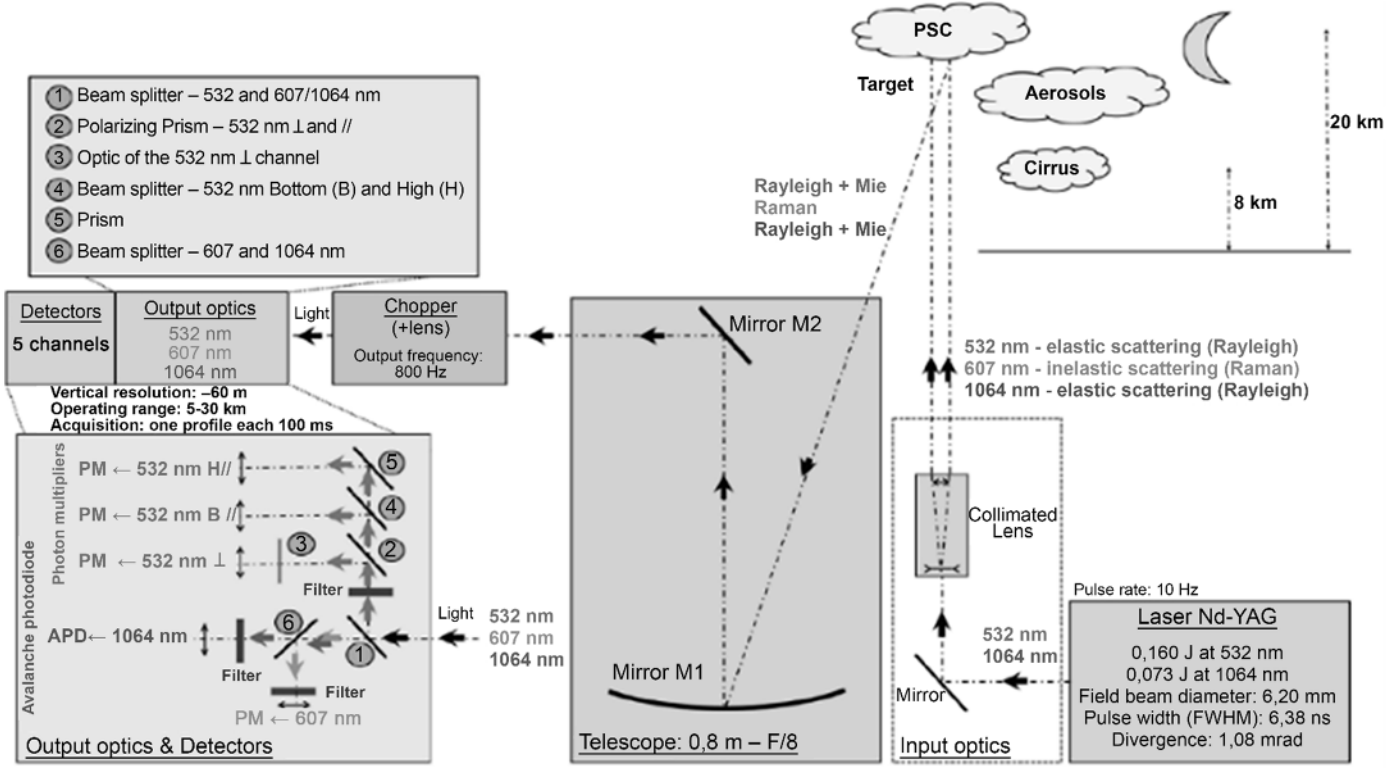


Figure 1.13. *Optical system for LiDAR measurements*

1.6. The digital twin of a space vehicle

The concept of the "digital twin", also known as the "mirror image" of the satellite system, was first proposed in the 1960s during the Apollo program.

NASA's system was used to drive back Apollo 13 (launched April 11, 1970) to Earth:

> Behind the scenes at NASA, there were 15 simulators used to train astronauts and mission controllers in all aspects of the mission, including several failure scenarios (some of which proved useful in averting disaster in Apollo 11 and 13, edla). The simulators represented one of the most complex technologies in the entire space program: the only real things in simulation training were the crew, cockpit and mission control consoles, everything else was an imaginary world created by a bunch of computers, lots of formulas and skilled technicians.

The idea was that if we created a digital representation of a physical object, we could then use it to better understand how it works and eventually control the physical object in its environment, particularly if the latter changes.

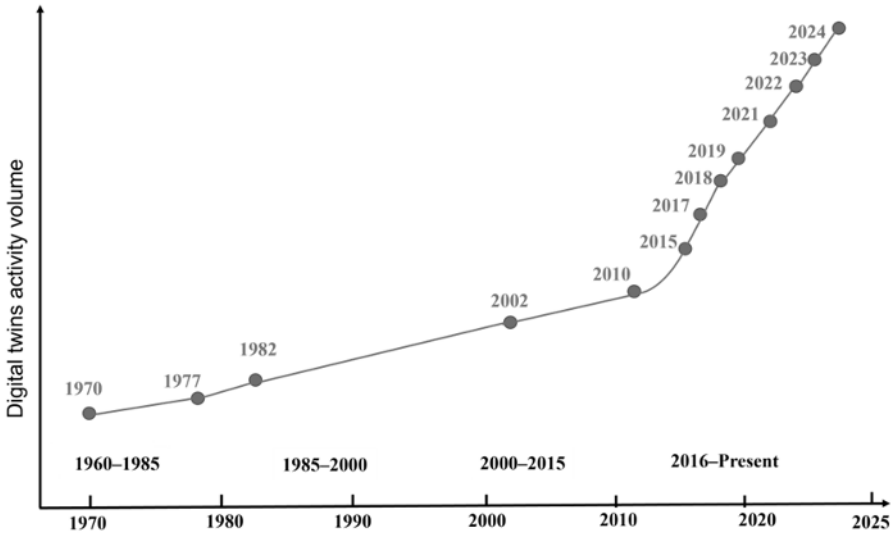


Figure 1.14. *Development of digital twin technology*

Figure 1.14 shows the development of this technology, which originated in the space industry. It has been made possible by the increasing digitization of processes in the manufacturing and service industries in the context of Factory 4.0 – a concept proposed in Germany in 2011 – and the democratization of the Internet of Things (IOT). The term "digital twin" (DT) was proposed by Michael Grieves of the University of Michigan in 2002 in connection with product lifecycle management [GRI 02, 05, 06, 16, GLA 12, DAH 22, 23, XIA 22].

A few dates represent key milestones in the development of digital twin technology:

– 1970: NASA uses matching technology for the Apollo 13 mission;

– 1977: flight simulators with numerical simulations were introduced;

– 1982: Autodesk launches AutoCAD, used to produce 2D and 3D models;

– from 1982 to 2002: AutoCAD became popular and was used in the design and engineering departments of almost all industries;

– 2002: Michael Grieves presents the concept of the digital twin at the University of Michigan;

– 2010: NASA and the USAF (US Air Force) publish articles on the digital twin;

– 2015: general electric "digital twin" wind farm initiative;

– 2017: the digital twin is ranked among the top 10 technology trends by Gartner;

– 2018: major software and industrial companies include the digital twin in their portfolio;

– 2019: the digital twin for rapid qualification of 3D-printed metal components;

– 2021: first international conference on digital twin technologies ICDTT 2021;

– 2022: proceedings of the first digital twin and edge AI workshop for industrial IoT, AIIOT '22;

– 2023: digital twins via data-driven strategies integrating a graphical neural network and IoT data;

– 2024: first international symposium on digital twins for healthcare.

A digital twin can be broken down into parts:

– the physical part, which has the ability to detect, monitor and actuate;

– the virtual or digital part, which has the capacity to link data and store information;

– the data part, which comes from the connection between the virtual and physical parts, and has the capacity to simulate, predict, optimize and delegate tasks to AI agents.

A spacecraft such as a satellite or orbiter is usually broken down into sub-assemblies. Its digital twin is a digital representation of these sub-assemblies. Sensors are implemented on the satellite to supply its digital twin with data in operational mode. This data constitutes in situ information, which engineers can use to analyze operational functions and optimize satellite operation.

Figure 1.15 shows the concept of the digital twin.

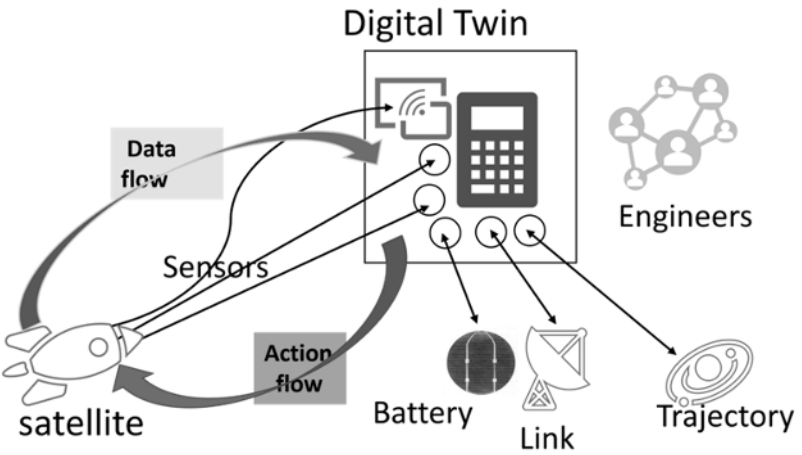


Figure 1.15. *Figure illustrating the concept of a satellite's digital twin*

It also provides useful feedback for future design and operation. For example, engineers can determine which parts wear out first and/or quickly. They can assess under which conditions the battery has to supply a lot of electrical energy and discharge faster. They can optimize the operation of sensors that retrieve information in operational mode for insurance companies and organizations verifying compliance with legal standards. Real-time satellite tracking, for example, can be used to acquire weather data, assess the state of atmospheric warming and track the flow of particles in the atmosphere.

Engineers can use the accumulated data from a large number of these digital twins to refine future satellite designs. They can optimize their performance in a system approach with a feedback effect, as shown in Figure 1.16.

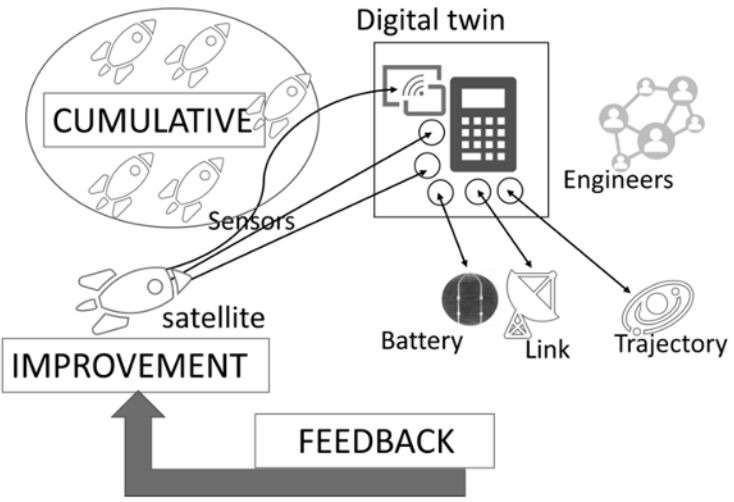


Figure 1.16. *Feedback from the digital twin of a satellite*

A *cognitive digital twin* is a virtual replica of a physical system or process that uses artificial intelligence (AI) and machine learning algorithms to simulate, predict and optimize its performance. Unlike a traditional digital twin, which focuses on monitoring and collecting data from physical assets, a cognitive digital twin is designed to learn and improve from the data collected. It uses advanced analytics and AI to identify patterns, predict outcomes and optimize its performance.

1.7. Conclusion

This chapter has covered the space age since its kick-off in 1957, describing its evolution, innovations and development prospects. It traces this evolution over a period of some three quarters of a century up to the NewSpace era, covering the diversity of both its context and its handling through numerous innovations in technologies and methods. The various sources of motivation that are worth noting: from rivalries between different political systems and underlying military activities, to research activities in the quest for knowledge, leading to the development of nanosatellites, or the realization of the dream of space travel and conquest, not to mention the socio-economic activities made possible, such as weather forecasting through more precise knowledge of atmospheric dynamics, data telecommunications for radio, television or the Internet, and the development of new digital-based technologies such as the Internet of Things or digital twins. In this respect, NewSpace and its expectations in terms of economic activities, production,

exchange and consumption should be conceived according to principles of systemic organization integrating humans and their environment. This is the approach developed by Passet in his book *L'économique et le vivant* [PAS 79], for whom the reproduction of the economic sphere cannot be thought of independently of the environment that encompasses and supports it.

1.8. Appendix

1.8.1. *Worldwide satellite development*

As described in section 1.1, Sputnik 1 and Explorer 1 were the first Soviet and American satellites launched in 1957 and 1958 respectively. They were technically classified as SmallSats. With the exception of Sputnik 2 and 3, all of the satellites launched in the 1950s were SmallSats, including Luna 1, 2 and 3 to the Moon's surface in the 1960s. SmallSats continued to be used in many countries for a variety of applications, as the launchers available could not lift heavier payloads until the 1960s.

The USSR's Strela constellation was developed for military communications, while in the USA, Ranger 7, 8 and 9, as well as Lunar Orbiter 1–5, were launched to study the Moon. SmallSats were also used in the Mariner (Mars probes) and Pioneer (interplanetary science) programs.

Countries other than the USA and USSR began launching SmallSats in the 1960s, the first being Canada's Alouette 1 and 2 and ISIS-1, the UK's Ariel 1 and 3, Italy's San Marco 1, France's Asterix and FR-1, etc. Most of these satellites carried instruments for measuring radiation, electric and/or magnetic fields, as well as for telecommunications experiments.

China, Japan, Czechoslovakia and India joined the movement in the 1970s with Dong Fang Hong 1 (173 kg), Ohsumi and Shinsei (24 kg and 64 kg), Magion 1 (15 kg) and Aryabhata (360 kg), respectively. Spacefaring nations considered as small ones continued to launch a few SmallSats, but thanks to increased launch capacities, the USA and the Soviet Union expanded their mission portfolios with larger satellites, such as those for the Viking or Mariner programs in the USA, or the Luna, Mars and Venera programs in the Soviet Union.

SmallSats continued to be used by the major space nations, but in smaller numbers and for more specific missions, such as Pioneer 10 (260 kg) in interplanetary space or Uhuru (141 kg) for X-ray spectroscopy astronomy. In a first case of "piggybacking", a 35 kg PFS-1 "subsatellite" was even superimposed on Apollo 15 and 16 in the 1970s to study the lunar environment [LIN 75].

In the 1980s, other nations began to gain direct access to space with large satellites, such as Bulgaria 1300, a 1,500 kg satellite from Bulgaria, or Morelos 1, a 650 kg satellite from Mexico. The first satellite launched by Israel in 1988, the 155 kg Ofeq-1, was a SmallSat. Most of the nations that had already gained access to space launched large satellites, with a few exceptions such as Japan's 216 kg Tenma, for X-ray spectroscopy astronomy, and Czechoslovakia's Magion program, with a 52 kg satellite.

Large satellites were generally conceived in the 1990s, with a few exceptions such as Japan's launch of Hiten and its Hagoromo sub-satellite, with a total mass of 197 kg, which were the first non-American, non-Soviet satellites to reach the Moon. After that, a growing number of countries took an interest in space. All of them launched SmallSats, including North Korea and Argentina, with the exception of Turkey.

The golden age of satellite design, no longer limited by the launch capabilities of SmallSats, began in the 2000s. Today, most small spacecraft developed are CubeSats (1U CubeSat is a 10 x 10 x 11.35 cm cube), which are standardized nanosatellites (cubesat.org) that were created in 1999 at Stanford and Cal Poly San Luis Obispo universities. The introduction of this standard democratized the transport of such spacecraft in spring-loaded deployers (also known as P-PODs), considerably facilitating access to space for this class of satellites. Similarly, standardized subsystems have emerged that enable a CubeSat project to be built from scratch and launched typically after a maximum of three years of development, with an associated cost of approximately 500,000 USD per unit. Today, CubeSats are used in a variety of programs for scientific, military and/or commercial applications, mainly in LEO, and more recently in interplanetary space too. Scientific spin-offs with SmallSats have been discussed in various groups such as COSPAR [MIL 19], NASA [TAN 21] and the Keck Institute [NOR 14].

SmallSats are currently used for scientific missions in the fields of heliophysics, astrophysics, earth sciences, planetary sciences, astrochemistry and astrobiology.

Examples include heliophysics missions such as MinXSS [MOO 18] and MinXSS-2 [MAS 20] to measure solar soft X-ray spectra, CeREs [KAN 18] to measure radiation belt electron excitation and loss, spectra and microbursts, CuPID [WAL 21] to measure soft X-rays emitted by the solar wind, and Picard to measure total solar irradiance and absolute spectral irradiance [COR 13, MEF 16].

INSPIRE, International Satellite Program in Research and Education, includes several CubeSats in orbit for exploring the ionosphere [EVO 18], studying the Earth's radiation budget (BRT or ERB: Earth Radiative Budget) [MEF 21] and probing the ionosphere [CHI 22]. The CubeSats (UVSQ-SAT and INSPIRE SAT-7) operated by

LATMOS are part of this program. A third French CubeSat, UVSQ SAT NG, has been developed for launch in 2025.

Although military applications are not well documented, in recent years, defense agencies have been acquiring commercial data from SmallSats constellations, showing an interest in such missions. Military SmallSats missions include the ELISA constellation, based on the Myriade platform, which is a constellation of the French military [DAN 19]. The US Naval Research Laboratory Graduate School is also interested in the satellite class, as evidenced by the launch of NPSAT-134 in 2019 for education and technology [SAK 02, 06, NPS 19].

Many publications now rely on imagery data from commercially available constellations such as PLANET (DOVE constellation), such as tropical forest carbon stock [CSI 19] or coral reef assessment [ASN 17]. Spire also provides Earth observations and GNSS-R data to NOAA and NASA [JAL 20].

The number of missions under development is now booming. Capabilities and technologies are becoming ever more advanced, not only in the military field, but also in scientific and commercial applications [KOS 19, JAN 23, SON 24].

1.8.2. *Electromagnetic theory*

This appendix gives a summary of the equations and other theorems essential for understanding electromagnetic phenomena, and in particular for interpreting the existence of the Van Allen belts (see Figure 1.1) and the aurora borealis. Further details on their application can be found in specialized books [MAX 54, BRU 65, FEY 65, LAN 66b, 69, DEB 68, MIZ 72, JAC 98, HEC 05]. For readers unfamiliar with the notions of scalar (one value), vector (three values or three components) and operations on these quantities, please refer to the appendix in Chapter 2 of this book.

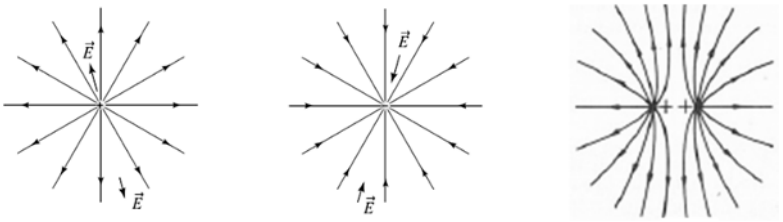
The work of Dufay (1698–1739) and Benjamin Franklin (1706–1790) led to the postulation of the existence of two types of charge, positive and negative. In 1799, Volta invented the battery as a source of electrical energy. In an electrically conductive wire, an electric current can be made to flow, which is the movement of a set of particles carrying an electric charge. These particles are called “electrons”, a term rooted in the Greek word amber. This term comes from Thales of Miletus, who identified the electrification of objects by friction in the 6th century BCE, 600 years before the modern era, or 27 centuries ago. In 1802, André-Marie Ampère (1775–1836) proposed the concept of electric current to explain the discharge of the Volta battery. The study of circuits and currents is one of the phenomena studied in electrokinetics.

Electrostatics is the part of physics that studies phenomena related to static-electrified bodies (positive and negative charges), and magnetostatics is the part of physics that studies phenomena related to moving electrified bodies.

In electrostatics, the space around a point charge Q (unit of charge: coulomb, symbol: C) or a charge distribution (see Figure 1.17) can be assimilated to a polar vector field (see the appendix in Chapter 2) that can act on charged objects. This vector field is called the "electric field" or "electrostatic field" of the charge Q placed in P, whose expression $\vec{E}(M)$ (unit of $\vec{E}(M)$: volt per meter, V/m) at point M is given by Coulomb's law, such that:

$$\vec{E}(M) = \frac{1}{4\pi\varepsilon_0}\frac{Q\overrightarrow{PM}}{\|\overrightarrow{PM}\|^3} = \frac{1}{4\pi\varepsilon_0}\frac{Q\,\overrightarrow{u_r}}{r^2} \qquad [1.1a]$$

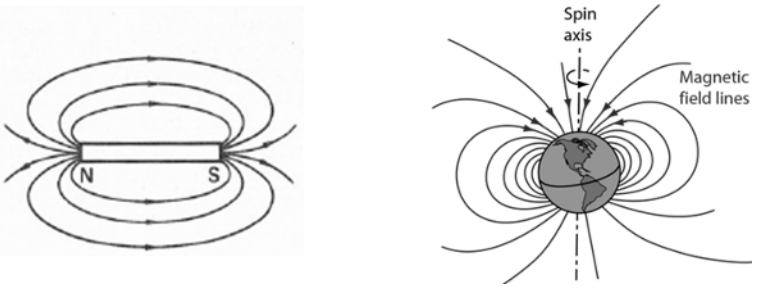
where P is the point where this charge is located, ε_0 is the electrical permittivity of vacuum ($\varepsilon_0 = 8.854\,10^{-12}\ \frac{F}{m}$ or $\frac{1}{4\pi\varepsilon_0} = 9\,10^9\ \frac{Nm^2}{C^2}$) and r is the distance between P and M. The electric field of a charge Q is the force per unit charge around the charge Q. It is a polar vector, so the electric field is parallel to planes of symmetry and perpendicular to planes of antisymmetry.



a) A charge > 0 b) A charge < 0 c) Two charges > 0

Figure 1.17. *Electric field around point charges*

It should be noted that the notion of field was first formulated in magnetism, following the work of Faraday, by determining the properties of a magnet (see Figure 1.18) consisting of a north pole and a south pole. The field lines follow a trajectory from the north pole to the south pole. Unlike electrical phenomena, which are due to the existence of two types of charge, it is not possible to isolate magnetic charges, so every magnetic system has a north and a south pole. Quantum theory, by postulating the existence of spin variables in the quantum domain, has made it possible to explain the physical phenomenon whereby transition elements such as iron, cobalt and nickel lead to magnets, which is not possible with other transition elements. Explanations of these phenomena can be found in works dealing with quantum theory [KEM 37, MES 64, COH 73, LAN 75, SAK 11]. In Chapter 4 of [DAH 16], we have given some background on this phenomenon.



a) A magnet b) The Earth

Figure 1.18. *Magnetic field around a magnet or the Earth*

Any point charge q in space is subjected to a force given by $\vec{F}(M) = q\vec{E}(M)$. Coulomb's law can then be expressed as the force exerted by Q on q, between two point charges, in the following form:

$$\vec{F}(M) = \frac{1}{4\pi\varepsilon_0}\frac{Qq\overrightarrow{PM}}{\left\|\overrightarrow{PM}\right\|^3} = \frac{1}{4\pi\varepsilon_0}\frac{Qq\,\overrightarrow{u_r}}{r^2} \qquad [1.1b]$$

In magnetostatics, the space around a charge or a distribution of charges in permanent motion (see Figure 1.19) can be assimilated to a field of axial vectors $\vec{B}(M)$ (unit of $\vec{B}(M)$: tesla, T) (see the appendix in Chapter 2), which can act on charged objects. This field of vectors is called a "magnetic field" or "magnetic induction field", whose expression $\vec{B}(M)$ at point M for a point charge q moving with velocity $\vec{v}$ at point P (see Figure 1.19(a)) is given by Biot and Savart's law, such that:

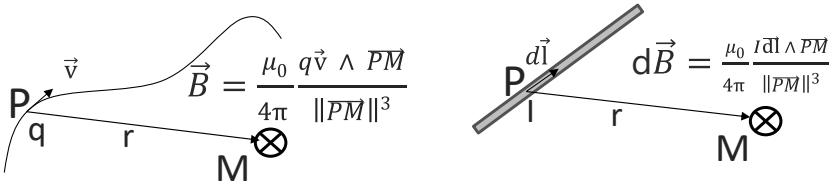
$$\vec{B}(M) = \frac{\mu_0}{4\pi}\frac{q\vec{v}\wedge\overrightarrow{PM}}{\left\|\overrightarrow{PM}\right\|^3} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\wedge\overrightarrow{u_r}}{r^2} \qquad [1.2a]$$

where P is the point where this charge is located, μ_0 is the magnetic permeability of vacuum ($\mu_0 = 1.256\,10^{-6}\ \frac{H}{m}$ or $\frac{\mu_0}{4\pi} = 10^{-7}\ \frac{Tm}{A}$), and r is the distance between P and M. The fact that the $\vec{B}(M)$ field is the vector product between $q\vec{v}$ and $\overrightarrow{PM}$ gives it symmetry properties different from those of the electric field, particularly in a reflection in a plane of symmetry. The magnetic induction field is perpendicular to the symmetry planes and parallel to the antisymmetry planes.

If we consider the magnetic field of a set of charges in permanent motion, such as a current I flowing through a wire (see Figure 1.19(b)), equation [1.2a] shows that the expression of this field is given by the following equation:

$$d\vec{B}(M) = \frac{\mu_0}{4\pi}\frac{Id\vec{l}\wedge\overrightarrow{PM}}{\left\|\overrightarrow{PM}\right\|^3} = \frac{\mu_0}{4\pi}\frac{Id\vec{l}\wedge\overrightarrow{u_r}}{r^2} \qquad [1.2b]$$

where P is the point where the oriented $d\vec{l}$ wire element carrying current I is located, μ_0 is the magnetic permeability of vacuum and r is the distance between P and M.



a) A point charge: q b) A set of charges: I

Figure 1.19. *Magnetic field around permanently moving charges*

In the static regime (independent of time), the work of the electric force from point A to point B does not depend on the path followed, because it is a conservative force. This property can be translated for the electric field by saying that the circulation of the field between two points A and B does not depend on the path followed, meaning that on a closed contour, this circulation is zero (Kirchhoff's second law or loop rule for voltages):

$$\oint \vec{E}(M)d\vec{l} = 0 \qquad [1.3a]$$

It is then possible to postulate the existence of an electric potential V from which the electric field is derived via the following relation:

$$\vec{E}(M) = -\overrightarrow{\text{grad}V} \qquad [1.3b]$$

Just as the electric force of a point charge q in the electric field of a source charge is given by $\vec{F}(M) = q\vec{E}(M)$, we can determine the electrical potential energy acquired by the charge q by the product W = qV.

Electrical phenomena can therefore be interpreted by means of an electric field if electric force is of interest, or an electric potential if electric energy is of interest.

Using the Stokes–Ampère theorem:

$$\oint \vec{E}(M)d\vec{l} = \iint curl\vec{E}(M)d\vec{S} \qquad [1.3c]$$

under static conditions, the property of null circulation of the electric field can be expressed by the following Maxwell equation:

$$\overrightarrow{curl}\vec{E} = \vec{0} \qquad [1.3d]$$

Note that equation [1.3d] is compatible with relation [1.3b], since we have:

$$\overrightarrow{curl}\vec{E} = -\overrightarrow{curl}\overrightarrow{\text{grad}V} = \vec{0} \qquad [1.3e]$$

In the case of the magnetic induction field $\vec{B}$, the magnetic force $\vec{F}$ is expressed differently depending on whether we are considering a point charge moving at speed $\vec{v}$, in which case, the force has the expression:

$$\vec{F} = q\vec{v} \wedge \vec{B} \qquad [1.4a]$$

or depending on whether we consider a set of charges moving in steady state in a wire in the form of a current I, in which case, the elementary force $d\vec{F}$ over an elementary length of wire $d\vec{l}$ has the expression:

$$d\vec{F} = Id\vec{l} \wedge \vec{B} \qquad [1.4b]$$

Expressions [1.4a] and [1.4b] are called Lorentz and Laplace forces, respectively.

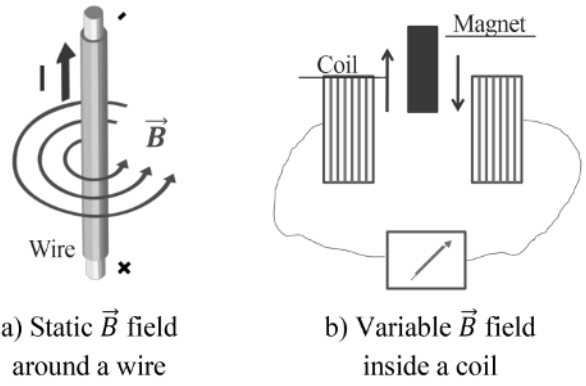


Figure 1.20. *Static and dynamic magnetic fields*

In the case of a wire carrying a current I, the magnetic field lines are circular. By integrating the expression in [1.2] for a wire of length l tending toward infinity, we can show that the expression for this field at point M, at a distance of r from the center of the wire in a perpendicular plane, is given by:

$$\vec{B}(M) = \frac{\mu_0 I}{2\pi r}\vec{u}_\varphi \qquad [1.5a]$$

$\vec{u}_\varphi$ is the unit vector tangent to the circle of radius r (see the appendix in Chapter 2).

If the wire is placed in a magnetic field, the total force on the wire of length l is given by:

$$\vec{F} = BIl\vec{u}_{\perp} \quad [1.5b]$$

$\vec{u}_{\perp}$, the unit vector that gives the orientation of the force $\vec{F}$, is perpendicular to the wire and the field $\vec{B}$.

When the physical situation presents symmetries such as the wire of length l assimilated to a wire of infinite length through which a current I flows (see Figure 1.20(a)), we can use the Stokes–Ampère theorem to show that the circulation of $\vec{B}(M)$ on a closed contour is as follows:

$$\oint \vec{B}(M)d\vec{l} = \mu_0 I = \mu_0 \iint \vec{j}d\vec{S} = \iint \overrightarrow{curl}\vec{B}(M)d\vec{S} \quad [1.6a]$$

where $\vec{j}$ is the current density vector passing through the oriented surface that lies on the closed contour. Note that the current I, which is the amount of charge passing through the surface S per unit time $I = \frac{dq}{dt}$, is also given by the flux of $\vec{j}$ through this surface $I = \iint \vec{j}d\vec{S}$.

Applying this theorem, we can easily show, given the symmetry properties of the magnetic field $\vec{B}(M)$, that its expression is indeed given by equation [1.5a], hence $\frac{\mu_0 I}{2\pi r}\vec{u}_{\varphi}$.

Furthermore, it allows us to show, in the static regime, another Maxwell equation, which is given by:

$$\overrightarrow{curl}\vec{B} = \mu_0\vec{j} \quad [1.6b]$$

In the static regime, it can be shown that this relationship leads to the conservation law of the current density vector $\vec{j}$ (Kirchhoff's first law or junction rule for current) by applying the div operator to both terms of the equation, so that:

$$div\overrightarrow{curl}\vec{B} = 0 = \mu_0 div\vec{j} \Rightarrow div\vec{j} = 0 \quad [1.6c]$$

In the variable regime (time dependent), experiments on the effects of magnetic fields led to the laws of Lenz (1834) and Faraday (1831), which show that when the flux of the magnetic field $\vec{B}$ through a circuit varies (see Figure 1.20(b)), an electromotive force on the mobile charges (the electrons) gives rise to a current that flows through the circuit. The direction of this current is such that it produces a field $\vec{B}$' which tends to cancel out the variation in the variable magnetic field $\vec{B}$.

The Lenz–Faraday law is expressed as:

$$e = -\frac{d\Phi}{dt} \quad [1.7a]$$

where e is the potential difference that gives rise to the current and $\Phi = \iint \vec{B} d\vec{S}$ is the flux of $\vec{B}$ across the surface crossed by the circuit.

Given the relationship between an electric field and the potential difference [1.3a], it is possible to express e as the circulation of an electromotive electric field, such that:

$$\oint \vec{E}(M) d\vec{l} = e = -\frac{d\Phi}{dt} = -\frac{\partial}{\partial t} \iint \vec{B} d\vec{S} \quad [1.7b]$$

This electromagnetic induction phenomenon is used in many applications (motors, generators, transformers, induction plates, eddy currents) and is studied in electrical engineering for its industrial applications. Applying the Stokes–Ampère theorem [1.3c], equation [1.7b] leads, in the dynamic (time-varying) regime, to the following Maxwell equation:

$$\overrightarrow{curl}\vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad [1.7c]$$

which differs from equation [1.3d], valid in the static regime, and is to be compared with equation [1.6b]. To symmetrize the effect of $\vec{B}$ and $\vec{E}$ in a time-varying regime, Maxwell proposed the following equation:

$$\overrightarrow{curl}\vec{B} = \mu_0 \vec{j} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \quad [1.7d]$$

from which it can be shown that visible light is only a small part of a much broader spectrum of electromagnetic waves, all propagating at the same speed as light.

Note that from Maxwell's postulate, we can associate a displacement current with the variation of the electric field as a function of time, such that:

$$\vec{j}_D = \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \quad [1.7e]$$

In a dynamic regime or time varying operation, this current is used to interpret the coupling that can occur between the two plates of a capacitor.

Finally, application of Gauss's theorem allows us to connect the electric field flux $\vec{E}$ across a closed surface to its sources expressed as a charge density, such that:

$$\oiint \vec{E} \cdot d\vec{S} = \iiint \mathrm{div}\vec{E} d\tau = \frac{1}{\varepsilon_0} \iiint \rho d\tau \quad [1.8a]$$

where $\Phi = \oiint \vec{E} \cdot d\vec{S}$ is the flux of $\vec{E}$ through a closed surface, $\iiint \rho d\tau$ is the amount of charge contained within the surface and ε_0 is the electrical permittivity of vacuum.

The volume integral $\iiint \mathrm{div}\vec{E} d\tau$ is the transformed form of the flux Φ by Green–Ostrogradski's theorem. This gives us the first Maxwell equation (Maxwell–Gauss) between the divergence of the electric field and its sources, such that:

$$\mathrm{div}\vec{E} = \frac{\rho}{\varepsilon_0} \quad [1.8b]$$

Given the absence of magnetic charges in volume, we obtain the following expression in the case of field $\vec{B}$:

$$\mathrm{div}\vec{B} = 0 \quad [1.8c]$$

The last expression leads us to postulate the existence of a vector potential $\vec{A}$ (the analogue of the scalar potential V associated with the electric field), such that:

$$\vec{B} = \overrightarrow{curl}\vec{A} \quad [1.8d]$$

Equation [1.8b] shows that Maxwell's postulate [1.7d] leads, by application of the div operator, equation [1.7d] to the following expression for the conservation of electric charge in the form:

$$\frac{\partial \rho}{\partial t} + div\vec{j} = 0 \quad [1.8e]$$

In steady state, equation [1.6c] holds true.

1.8.3. *Light–matter interaction*

In the context of light–matter interaction, electromagnetic waves are used to study a physico-chemical system: molecules, materials, aerosols, atmosphere and environment. The properties and characteristics of matter can be analyzed by making it interact with electromagnetic waves (see Figure 1.21).

Generally speaking, the electromagnetic wave incident on the object under study is generated in a known state using a suitable source and filter system. In space, the Sun is often used as a light source. A detection system consisting of detectors and

suitable filters is used to measure changes in the electromagnetic wave relative to its initial state at incidence. By studying changes in the characteristics of the reflected, transmitted or scattered electromagnetic wave, we can determine the properties of the system under study, or identify it when it is absorbed.

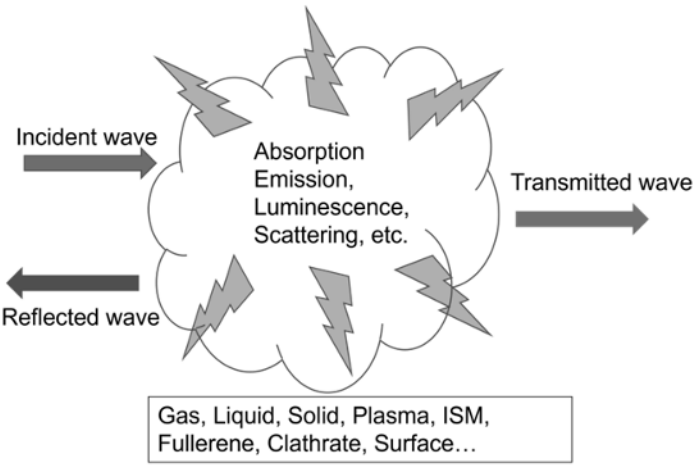


Figure 1.21. *Light–matter interaction*

Maxwell showed that electrical and magnetic phenomena can be described in a vacuum, in the presence of charges and currents, by means of four equations, whose expressions are:

$$\vec{\nabla}E = div\vec{E} = \frac{\rho}{\varepsilon_0} \quad [1.9a]$$

$$\vec{\nabla} \wedge \vec{E} = \vec{curl}\vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad [1.9b]$$

$$\vec{\nabla}\vec{B} = div\vec{B} = 0 \quad [1.9c]$$

$$\vec{\nabla} \wedge \vec{B} = curl\ \vec{B} = \mu_0\ \vec{j} + \varepsilon_0 \frac{\partial \vec{E}}{\partial t} \quad [1.9d]$$

These equations, which achieve the unification of electric and magnetic phenomena, summarize the local properties of the electric field $\vec{E}$ and magnetic field $\vec{B}$ in terms of the sources ρ, the charge density vector, and j, the current density vector, and where μ_0 is the magnetic permeability of vacuum and ε_0 is the electric permittivity of vacuum.

In the MKS system of units, these fields and sources are defined by vector $\vec{E}$ in Vm^{-1}, vector $\vec{B}$ in Tm^{-1}, ρ in Cm^{-3} and j in Am^{-3}.

It can be shown that Maxwell's equations lead to a propagation equation for the $\vec{E}$ and $\vec{B}$ fields in the form:

$$\Delta \vec{F} - \mu_0 \varepsilon_0 \frac{\partial^2 \vec{F}}{\partial t^2} = \Delta \vec{F} - \frac{1}{c^2} \frac{\partial^2 \vec{F}}{\partial t^2} = 0 \qquad [1.10]$$

where $\vec{F}$ represents the $\vec{E}$ or $\vec{B}$ fields.

In electromagnetic theory, Maxwell's equations lead to the same expression for wave velocity c in vacuum in terms of the electrical permittivity ε_0 and magnetic permeability μ_0 of vacuum for all radiations (see Table 1.5). With $\varepsilon_0 = 8.86\ 10^{-12}\ Fm^{-1}$ and $\mu_0 = 4\pi 10^{-7}\ Hm^{-1}$, c is equal to $310^8\ ms^{-1}$ ($2.997924581 0^8\ ms^{-1}$).

The wave front carrying an electric field and a magnetic induction field moves transversely to these fields, unlike mechanical longitudinal waves whose movement is in the direction of the mechanical phenomena (compression–expansion). The energy carried by the wave travels perpendicular to the electrical and magnetic phenomena. The direction of wave propagation is parallel to the direction of $\vec{E} \times \vec{B}$, which is perpendicular to the wavefront. Thus, we define the Poynting vector $\vec{S}$ to represent the energy flux per unit time by:

$$\vec{S} = \frac{1}{\mu_0} \vec{E} \times \vec{B} \qquad [1.11a]$$

expressed in joules per second per unit area: $[J/(s.m^2)]$.

From the electromagnetic energy density, *u* is given by the formula:

$$u = \frac{\varepsilon_0}{2} \vec{E}^2 + \frac{1}{2\mu_0} \vec{B}^2 \qquad [1.11b]$$

and by using the balance equation translating the conservation of electromagnetic energy in a vacuum – for in the absence of matter there is no loss of energy, and therefore no dissipation – we can show that:

$$\frac{\partial}{\partial t} u + \mathrm{div} \vec{S} = 0 \qquad [1.11c]$$

The norm of the Poynting vector therefore represents the instantaneous power carried by the electromagnetic wave across a unit surface, perpendicular to its direction of propagation.

Maxwell's equations show that light is a transverse electromagnetic wave, which can be decomposed into two linearly independent electrical components, corresponding to the polarization of light. It propagates as two mutually coupled vector fields, $\vec{E}$ and $\vec{B}$. Table 1.5 summarizes the different domains of electromagnetic waves. Optics corresponds to the frequency range between 10^{12} Hz (far IR) and 10^{16} Hz (far UV), while the visible spectrum extends from 4 10^{14} to 8 10^{14} Hz.

Field	Associated frequencies
Cosmic rays	10^{14} GHz and above
Gamma rays	10^{10}–10^{13} GHz
X-rays	10^{8}–10^{9} GHz
Ultraviolet radiation	10^{6}–10^{8} GHz
Visible Light	10^{5}–10^{6} GHz
Infrared radiation	10^{3}–10^{4} GHz
Microwaves	3–300 GHz
Radio waves	470–806 MHz
Short waves	54–216 MHz

Table 1.5. *Electromagnetic waves and associated frequencies*

Classically, light–matter interaction can be established using Poynting's theorem, which establishes a relationship between electromagnetic energy, the Joule effect and the flux of the Poynting vector, such that:

$$\frac{\partial}{\partial t}u + \mathrm{div}\vec{S} = -\vec{j}.\vec{E} \qquad [1.11d]$$

where the term $\vec{j}.\vec{E}$ represents the Joule-effect dissipation term in the presence of matter, $\vec{j}$ being the current density vector and $\vec{E}$ being the electric field of the wave.

At the atomic or molecular scale, the process of light–matter interaction is of a quantum nature. In this case, to interpret the photoelectric effect, we must consider that light is made up of energy grains, according to Einstein's corpuscular formulation of light. Each energy grain corresponds to a quantum of energy carried by a photon.

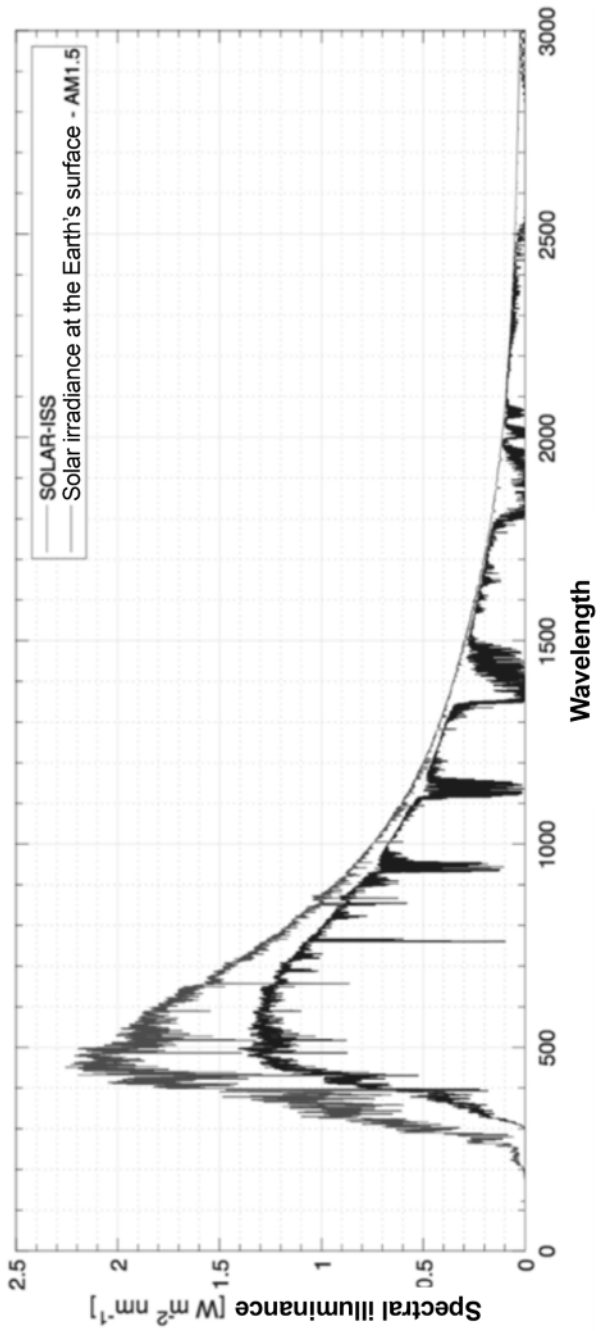


Figure 1.22. *The Sun's emission spectrum and spectral solar irradiance at the Earth's surface ([MEF 18], Solar-ISS, A & A, 2018)*

The energy E of a photon is expressed as a function of its frequency ν, such that:

$$E = h\nu \quad [1.12a]$$

and its momentum p is given by De Broglie's relation (which De Broglie applied to the electron, regarded as a particle, thus giving it wave properties) as a function of its wavelength λ:

$$p = h/\lambda \quad [1.12b]$$

Note that this interpretation a posteriori justifies the method proposed by Planck, who had hypothesized the quantization of matter in terms of oscillators capable of emitting and absorbing light in the form of energy quanta given by the relation $E = h\nu$. Although, after Maxwell's work it had been established that light is a transverse wave made up of an electric field and a magnetic induction field in a plane perpendicular (the wavefront) to its propagation, the quantization of oscillator energy had enabled Planck to interpret the emission spectrum of a black body at temperature T, such as, for example, the Sun (see Figure 1.22), by the following formula:

$$U(\nu, T) = \frac{8\pi h\nu^3}{c^3} \frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1} \quad [1.13]$$

where $U(\nu, T)$ is the spectral energy density at temperature T, h is Planck's constant and k is Boltzmann's constant.

Figure 1.22 shows different solar spectra (at the top of the atmosphere (red) and on the ground (blue)). The top-of-atmosphere spectrum was obtained with the SOLAR/SOLSPEC instrument (see Figure 1.11).

An absorption or emission corresponds to a transition between two energy levels (see Figure 1.23) by the absorption of a photon (induced absorption) or by the emission of a photon (induced or stimulated emission) as proposed by Einstein.

For each frequency range, it is customary to identify a wave by a parameter specific to the field of application, according to the scientific or user communities (see Tables 1.5 and 1.6).

In the energy scale, we use the relationship E = hν, and the electromagnetic wave is characterized by its frequency expressed in hertz (Hz). The wave can also be characterized in terms of its wave number (σ) or in electron volt (eV). A wave can also be characterized by its wavelength, expressed in nanometers (nm), microns (μm) or angströms (Å) on the momentum scale. Figure 1.24 summarizes these different notations.

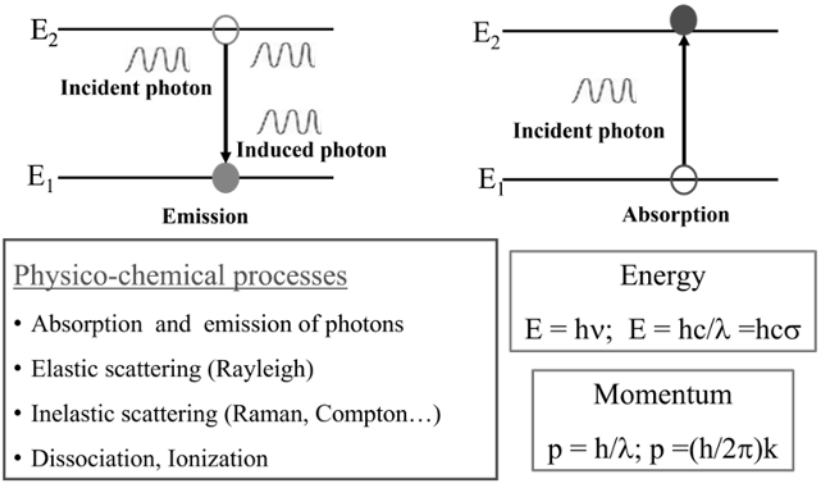


Figure 1.23. *Light–matter interaction, a quantum phenomenon*

Field of application	Associated frequencies
Sterilization	10^{14} GHz and above
Vision	10^{10}–10^{13}GHz
Photography	10^{8}–10^{9} GHz
Radar, microwaves	10^{6}–10^{8} GHz
Satellite communication	10^{5}-10^{6} GHz
UHF television	10^{3}–10^{4} GHz
VHF television VHF, FM waves	3–300 GHz
Radio waves, small waves	470–806 MHz
AM Radio	54–216 MHz
Cancerotherapy	3–25 MHz
RX-ray examination	535–1605 KHz

Table 1.6. *Frequency-dependent use*

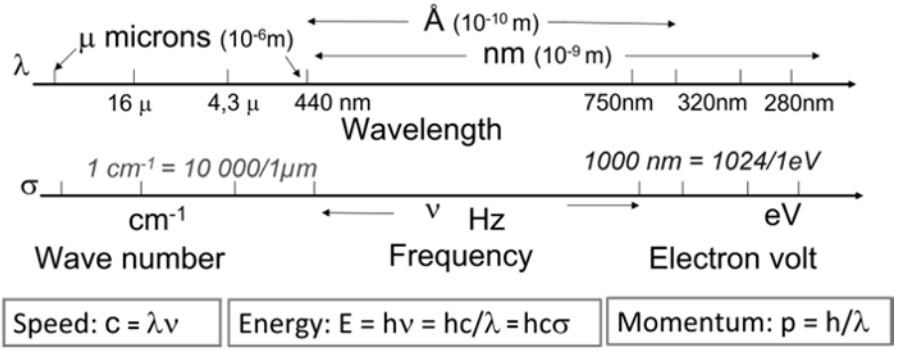


Figure 1.24. *Characterization of light in the electromagnetic spectrum*

The relationship between frequency and wavelength is $\lambda = c/\nu$, where c is the speed of light. In space, we distinguish between the optical and microwave domains, such that:

Optical domain:

– gamma rays → wavelengths < 0.3 Å;

– x-rays → wavelengths from 0.3 Å to 100 Å;

– ultraviolet (UV) → wavelengths from 10 nm to 400 nm;

– visible (VIS) → wavelengths from 400 nm to 700 nm;

– violet (400–446 nm); blue (446–500 nm); green (500–578 nm);

– yellow (578–592 nm); orange (592–620 nm); red (620–700 nm);

– infrared → wavelengths from 0.76 μm to 500 μm.

Radio-electric domain:

– microwaves and radar → wavelengths from 1 mm to 10 cm;

– radios → wavelengths greater than 10 cm.

Electronvolt (eV)	Frequency (ν)	Wavelength (λ)	Wave number (σ)	Temperature
1	2.418 10^{14} Hz	12,339 Å	8065.5 cm^{-1}	11,605 K

Table 1.7. *Scale conversions*