

History of Meteorological Satellites

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1.1. The beginnings of remote sensing and the conquest of space

For centuries, the atmosphere has remained enigmatic, its movements are difficult to decipher from the ground. Scientists interested in weather, and therefore in meteorology, sought to unravel its mysteries. At first, they could only gain altitude by climbing mountains, loaded with measuring instruments. Later, they operated flying instruments (balloons, kites, planes, rockets, etc.), measuring and recording atmospheric parameters: temperature, pressure, humidity, wind direction and speed. Thanks to on board cameras, it was finally possible to see the Earth from the sky. Among so many other scholars, Pascal, Gay-Lussac, Mendeleïev, Teisserenc de Bort, Bjerknes and Idrac were part of this quest.

On October 23, 1858, Félix Tournachon, known as Nadar, a great photographer and ballooning enthusiast, took the first aerial photograph of Paris from a tethered balloon 80 m high. He can be considered the father of remote sensing. Today, it is unfortunately impossible to get your hands on this shot. In Nadar's footsteps, two years later, on October 13, 1860, James Wallace Black photographed part of the city of Boston from a hot air balloon. This first aerial view taken in America is kept at the Metropolitan Museum of Art in New York. The work is titled "Boston, as seen by eagles and wild geese".

For a color version of all the figures in this chapter, see www.iste.co.uk/phulpin/satellites1.zip.

Satellites for Atmospheric Sciences 1,

coordinated by Thierry PHULPIN, Didier RENAUT, Hervé ROQUET and Claude CAMY-PEYRET.

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It was not until October 24, 1946 that a photograph of the Earth seen from more than 100 km above sea level was obtained using a 35 mm camera on board a German-made V2 rocket at the end of World War II. Taking off from the White Sands Missile Range (New Mexico), it captured the roundness of the Earth and, for the first time, showed cloud cover from space.

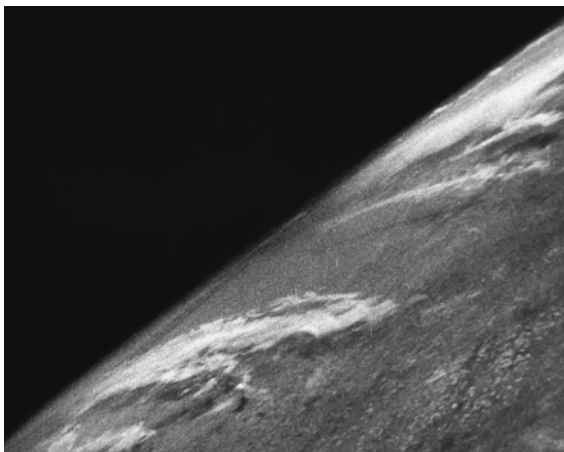


Figure 1.1. *October 24, 1946 – first photo taken from space (source: Wikimedia commons)*

From 1947 to 1950, experiments of this type multiplied in the United States thanks to the V2 rockets, then Aerobee and Viking. They gave rise to a classified report by the Rand Corporation in April 1951 entitled “Inquiry into the feasibility of weather reconnaissance from a satellite vehicle”. This report shows the benefit that future satellites would have in facilitating the recognition of clouds, to delimit air masses, to estimate temperatures and winds, and to help in the drawing and analysis of weather maps at the synoptic scale*.

In 1954, photographs taken from a U.S. Navy Aerobee rocket confirmed the value of images produced from space. The structure of the storm coming from the Gulf of Mexico and the distribution of the associated rains were deciphered, whereas with conventional methods this is not possible.

The International Geophysical Year of 1957–1958 marked the beginning of the Space Age. As early as July 1955, the United States and the Soviet Union announced that they were each preparing an artificial satellite for this event. On the

*See Glossary.

American side, the competition was fierce. The U.S. Navy was a candidate, with its Aerobee and Viking rockets, as well as the U.S. Air Force and the U.S. Army. The U.S. Army had in its ranks Wernher von Braun and his team of German engineers who designed the V2s, who moved to the West at the end of the war. Von Braun outlined his plan to launch the first artificial satellite using the Redstone missile as a launcher, directly derived from the German V2. On this basis, the U.S. Army launched the Orbiter project. As President Eisenhower did not want the first launch of an American satellite to be entrusted to a predominantly German team, the Orbiter project was abandoned in favor of the U.S. Navy's project Vanguard, which was less accomplished than its competitor, and the von Braun team was banned from any attempt to launch a satellite. Vanguard was a fiasco, with nine failures on 14 attempts (including the first two test launches).

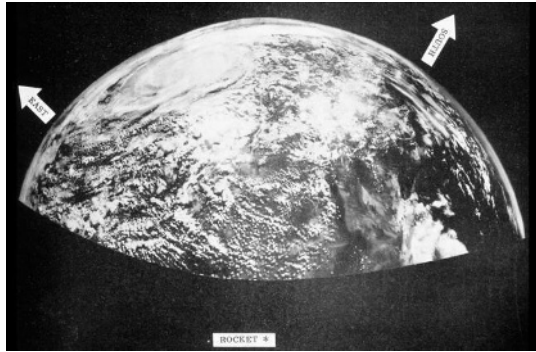


Figure 1.2. *October 5, 1954 – composite image of a storm (source: Wikimedia commons)*

On the Soviet side, Sergei Korolev was developing missiles with increasing capabilities from the V2. On August 21, 1957, the intercontinental ballistic missile R-7 Semiorka made its first successful flight. It was chosen to place the first Soviet satellite in orbit. The launch of Sputnik took place on October 4, 1957 from what would become the Baikonur Cosmodrome (Kazakhstan). Sputnik was an aluminum sphere 58 cm in diameter, equipped with four antennas and weighing approximately 84 kg. Its payload is a radio transmitter whose signal can be picked up by radios around the world. The Americans found this launch traumatic. According to them, it highlighted that the Soviet Union had the technology to attack the United States with a nuclear projectile. The Sputnik crisis triggered a space race between the two parties. The dog Laika went aboard Sputnik-2 on November 3, 1957. The United States then entrusted the Jet Propulsion Laboratory (JPL) and the U.S. Army, therefore von Braun, with the mission to make up for the gap between them and the Soviets. Three months was enough. Launched from Cape Canaveral (Florida) by a

Juno-I rocket on January 31, 1958, Explorer-1 was the first American artificial satellite. Its data led to the discovery of Van Allen belts (torus-shaped regions in space, very dense in energetic particles). In order to bring order to the various initiatives and to pilot space programs and aeronautical research in the United States, the National Aeronautics and Space Administration (NASA) was founded on July 29, 1958.

Verner Suomi and Robert Parent, both from the University of Wisconsin, managed to convince von Braun to board Explorer-7 with the radiometer they had developed. Launched on October 13, 1959 from Cape Canaveral, it was the first satellite associated with meteorology. The radiometer consisted of five bolometers that converted the incident electromagnetic energy flux into heat. Its objective was to measure the radiated power by separating the reflected solar radiation from the radiation emitted by the Earth and its atmosphere. It was the first satellite to provide information on the Earth's radiation budget, which is a still current concern.

1.2. It all began with Tiros-1, the first meteorological satellite

In April 1958, following President Eisenhower's announcement to create NASA, the Department of Defense (DoD) founded the Advanced Research Projects Agency (ARPA), which began to develop a meteorological satellite, before NASA took over its cruising speed. After a historic meeting at the Pentagon, ARPA formed a committee chaired by William Kellogg to define the content of the payload of future satellites. A camera made of a newly developed Vidicon tube was chosen. The main challenge was to be able to take photographs with this camera attached to a rotation-stabilized satellite; the solution was to mount it on the rotation axis. Originally, Kellogg wanted to have three cameras, from the wide-angle camera to the most precise. The latter was refused because of its horizontal resolution of 100 m, which was too detailed and therefore militarily sensitive. This was the beginning of the Television Infrared Observation Satellite (TIROS) program. TIROS was finally transferred to NASA in early 1959.

Tiros-1 thus marked the beginning of the space age in meteorology. It was launched on April 1, 1960, early in the morning, from the Cape Canaveral base in Florida, by a Thor-Able rocket. This 122 kg satellite, 56 cm high and 107 cm in diameter, revolved around the Earth at an altitude of 720 km in an orbit inclined at 48.4° from the plane of the equator. It took pictures at scheduled intervals. Its two cameras targeted the same region with different field widths. The first had a wide angle and covered an area of 1,200 km by 1,200 km with a spatial resolution of approximately 3 km; the second was equipped with a zoom for an area of 120 km by 120 km with a resolution of 300 m to 800 m. Each camera had its own tape recorder

and could store up to 32 images. The recorded images were transmitted when Tiros-1 passed over one of the two receiving stations. At the same time, the image being created was sent in real time. The first station was the U.S. Air Force Tracking Station at Kaena Point (Hawaii), the second being the U.S. Army Signal Research and Development Laboratories at Fort Monmouth (New Jersey). At both stations, the images were recorded on film and photographed for immediate processing by meteorologists who carried out nephanalyses. These were forwarded to the Weather Bureau by fax. They generated little enthusiasm among forecasters, since their reading required a little effort to draw a meteorological interpretation. On April 9, 1960, Tiros-1 transmitted the image of a hurricane in the Coral Sea, off the northeast coast of Australia. This was the first of a long series, the hurricanes no longer escaping the eye of the satellites. Tiros-1 only worked for 78 days, falling victim to a power failure after having transmitted, in two and a half months, 22,952 images leading to 333 nephanalyses. On April 27, 1961, Francis Reichelderfer, head of the Weather Bureau declared: "For the first time, Man has a complete view of weather conditions over a large part of the Earth and the data collected by Tiros-1 would have required thousands of weather ships scattered over all the oceans".

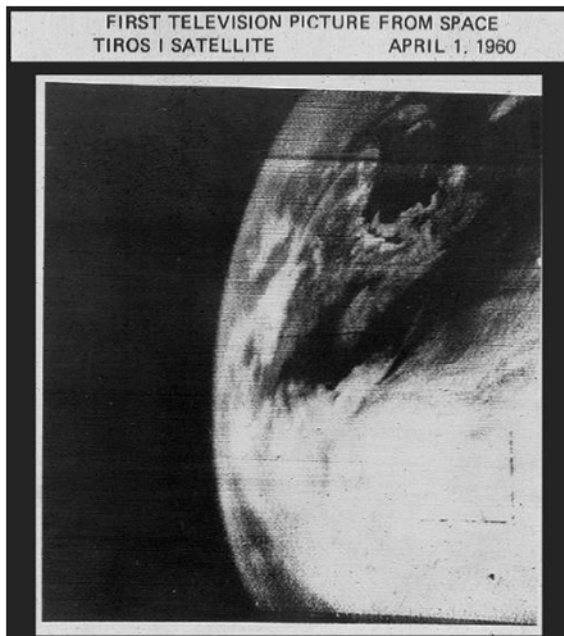


Figure 1.3. *April 1, 1960 – first image of Tiros-1 – Coasts of Maine and Maritime Provinces of Canada (source: NASA)*

Nephanalysis is the graphical interpretation of cloud data on a map. At the very beginning, the interpretation involved analyzing photographs using two basic criteria, the degree of cloud brilliance and cloud shape, in order to plot on a map the outline of the cloudy sectors and the symbols corresponding to the cloud classification and cloudiness. This analysis was significantly improved in 1970 by the use of infrared images, in addition to images of the visible channel. See example in Figure 1.5.

1.3. American meteorological satellites

1.3.1. Polar-orbiting satellites

1.3.1.1. Tiros – 1st generation

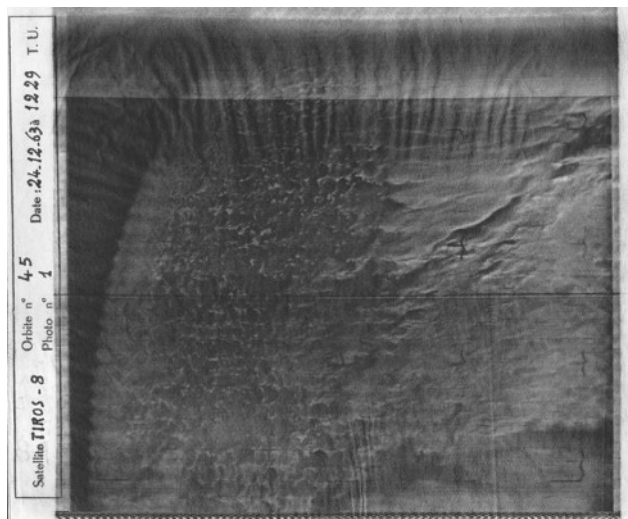


Figure 1.4. December 24, 1963 – first image received in Europe from a meteorological satellite, at the CEMS in Lannion (source: Météo-France)

Ten satellites made up the first series of Tiros, whose launches were spread over five years. Tiros-8 was equipped with automatic picture transmission (APT), real-time image broadcasting, which allowed many meteorological services to receive the images. The cost of a receiving station was low, which allowed many countries to have them. This was the case of the Center for Space Meteorological Studies (CEMS in French), newly created in Lannion by the French National Meteorological Department. Good signal reception assumes that the antenna is

pointed towards the satellite and follows it as it moves. In practice, a readjustment every 30 seconds is sufficient but the tracking is manual by following the position of the satellite using the ephemeris provided by NASA. As a nice Christmas present, the first image of a portion of orbit no. 45 of Tiros-8 was received on December 24, 1963 in Lannion around 12:30 UTC. The CEMS is the first center in Europe to receive an image from a meteorological satellite. The interpretation is tricky and requires a bit of imagination to extract meteorological information! Tiros-9 and Tiros-10, which complete the program, were the first to be positioned in a sun-synchronous orbit.

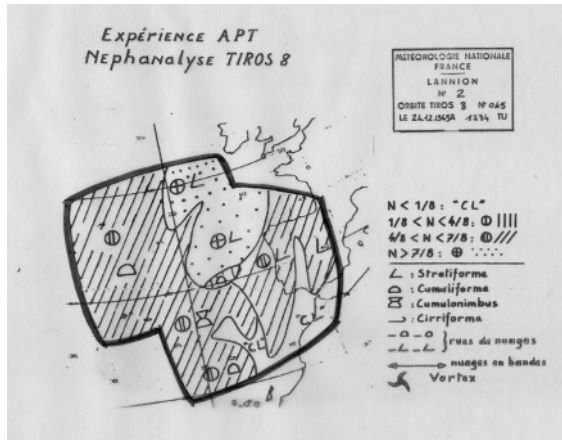


Figure 1.5. December 24, 1963 – nephanalysis performed by CEMS meteorologists in Lannion (source: Météo-France)

1.3.1.2. *Nimbus*

The family of Nimbus satellites, all Sun-synchronous, took over from Tiros. These were seven experimental satellites, designed by NASA, launched between 1964 and 1978. They made it possible to test many instruments, in particular for vertical probing of the atmosphere. The instruments on board varied according to the satellites. In addition to conventional imagers were the high-resolution infrared sounder HIRS**, the infrared interferometer IRIS**, the limb infrared sounder LRIR**, microwave radiometers ESMR** and SMMR**, the spectrometer dedicated to ozone TOMS** and the coastal zone color scanner CZCS**. These instruments were then deployed on operational satellites.

**See Appendix 3.

1.3.1.3. *Tiros operational satellite (TOS) – 2nd generation*

The TOS program included nine satellites named ESSA, named after the administration in charge of the program: Environmental Science Services Administration (predecessor of the National Oceanic and Atmospheric Administration – NOAA). ESSA-1 was put into orbit on February 3, 1966 from Cape Canaveral and carried the same type of Vidicon camera as the last Tiros. ESSA-9, the last of the series, was launched on February 26, 1969.

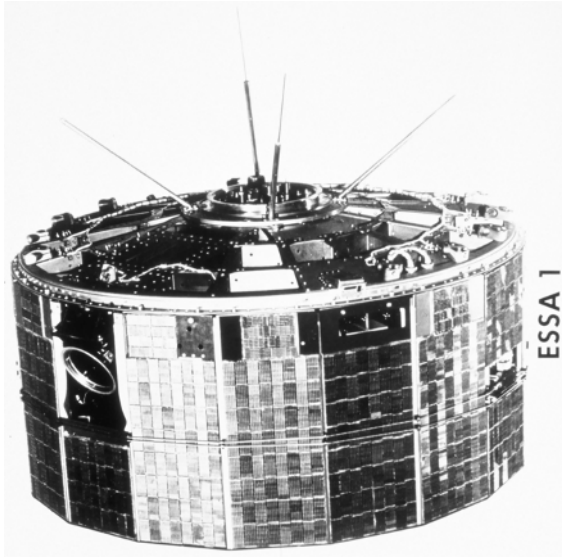


Figure 1.6. *ESSA-1 satellite (source: Wikimedia commons)*

1.3.1.4. *Improved Tiros Operational System (ITOS) – 3rd generation*

Ensuring the continuity of TOS, ITOS was a series of six satellites in flight between 1970 and 1979. ITOS-1, also called TIROS-M, was the first. It was succeeded by NOAA-1. From NOAA-2 onwards, the Vidicon cameras were replaced by a two-channel imaging radiometer, one in the visible spectrum, the second in the thermal infrared (VHRR**). Thanks to this infrared channel, images could therefore be used in the nocturnal part of the Earth. NOAA-2 also carried an eight-channel infrared sounder (VTPR**) whose objective was to measure temperatures at different levels in the atmosphere and the integrated water vapor content.

**See Appendix 3.

1.3.1.5. *From Tiros-N to NOAA-14 – 4th generation*

Tiros-N was the first of a series of 10 satellites (Tiros-N, then the satellites from NOAA-6 to NOAA-14, whose launches span from 1978 to 1994). Launched on October 13, 1978, it carried instruments inherited from the Nimbus, which allowed a major advance in the measurement of atmospheric parameters: a five-channel visible and infrared imager (AVHRR**), an infrared sounder for measuring temperature and humidity (HIRS/2), a microwave sounder (MSU**) and a stratospheric sounder (SSU**). These last three instruments constitute the Tiros Operational Vertical Sounder (TOVS**). All of these instruments are described in Chapter 2.

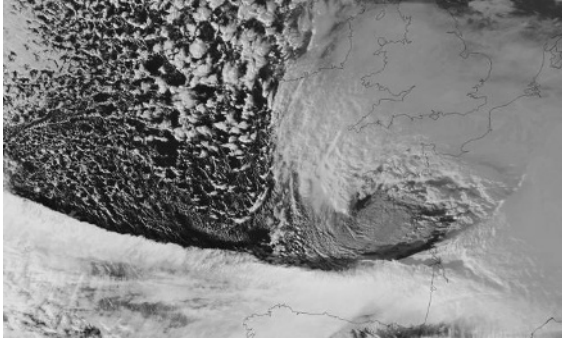


Figure 1.7. *December 27, 1999 at 16:00 UTC – NOAA-14 – image of storm Martin (source: Météo-France). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip*

1.3.1.6. *From NOAA-15 to NOAA-19 – 5th generation*

The objectives of this fifth generation of satellites known as Polar Operational Environmental Satellites (POES) were to provide an uninterrupted flow of imagery data, atmospheric sounding, hydrological and surface information, and ozone observations; to establish a long series of data for climate monitoring and a significant contribution to space weather (with its main objective being to understand the influence of the Sun on the Earth's environment). It was a program under the responsibility of NOAA in partnership with NASA.

With a take-off weight of 2,232 kg, NOAA-15 was put into orbit on May 13, 1998. It carried more efficient instruments than those of the previous generation: the AVHRR/3 imager, the HIRS/3 infrared sounder, AMSU-A** and AMSU-B microwave sounders.

**See Appendix 3.

Thanks to APT and High Resolution Picture Transmission (HRPT) data transmission systems, the fifth-generation NOAA satellites were received by thousands of users around the world. NOAA-19, launched on February 6, 2009, completed the program. NOAA-18 and NOAA-19 were part of a new partnership with EUMETSAT to form the Initial Joint Polar System (IJPS) in which the United States provided afternoon orbit coverage, while Europe ensured the morning orbit with its MetOp satellites.

1.3.1.7. *Joint Polar Satellite System (JPSS)*

JPSS was born from the ashes of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program. The objective of the NPOESS program was to provide, using polar satellites, meteorological, oceanographic, climatic and space data that met the operational requirements of American civilian and military communities. It was canceled in 2010 for budgetary reasons. The civil and military programs are now separate.



Figure 1.8. *Verner Suomi on January 25, 2012 (source: University of Wisconsin)*

JPSS is a series of four satellites and an NPP precursor satellite. The acronym NPP, intended for the NPOESS Preparatory Project, was kept for JPSS under the name National Polar-orbiting Partnership, to which was added Verner Suomi, who was considered the founder of satellite meteorology. This is most often referred to as S-NPP. Scheduled to operate until around 2040, the JPSS satellites are dedicated to the afternoon orbit (see Chapter 8), while the European MetOp satellites carry out the morning orbit.

S-NPP was launched on October 28, 2011 by a Delta II rocket from Vandenberg Air Force Base. Its payload is composed of new instruments, with a 22-channel visible and infrared imager (VIIRS**), a hyperspectral infrared sounder (CrIS**), a microwave sounder for measuring temperature and humidity (ATMS**) and a spectrometer for measuring ozone (OMPS**). These instruments are described in Chapter 2.

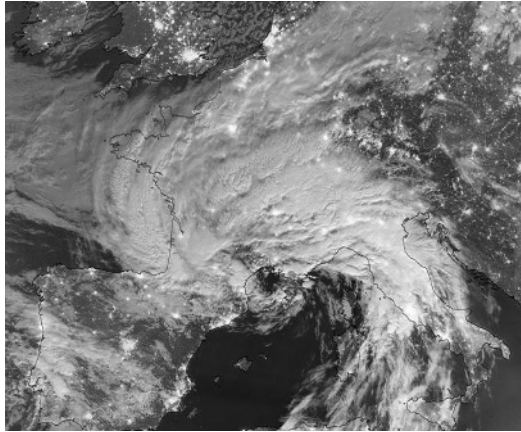


Figure 1.9. May 11, 2020 at 01:29 UTC – Suomi-NPP – day–night channel image (source: Météo-France). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip

1.3.2. Geostationary satellites

1.3.2.1. Synchronous Meteorological Satellite (SMS)

SMS was the first operational series of geostationary meteorological satellites. SMS benefitted from experiments carried out by the Applications Technology Satellite (ATS) program developed by NASA in the 1960s. ATS includes technological and instrumental experiments relating to meteorology. ATS-1, ATS-3,

**See Appendix 3.

and then ATS-6, respectively, carried SSCC**, MSSCC** and VHRR imagers. SMS-1 was launched on May 17, 1974 and was placed at 45° W longitude. It was a 2.30 m long cylinder with a diameter of 1.90 m. It was stabilized by a rotation at approximately 100 rpm. Its main instrument was the VISSR** radiometer with two channels (visible and infrared), which produced complete disk images at a frequency of once every 30 min, with a horizontal resolution of 900 m at nadir for the visible channel. It was followed by the SMS-2, which was launched on February 6, 1975 and was placed at 115° W longitude. These geostationary satellites were a real improvement for meteorologists, owing to their imagery. Each satellite could see almost 40% of the Earth's surface and delivered high-frequency images, enabling quality animations essential for monitoring large-scale phenomena in real time.

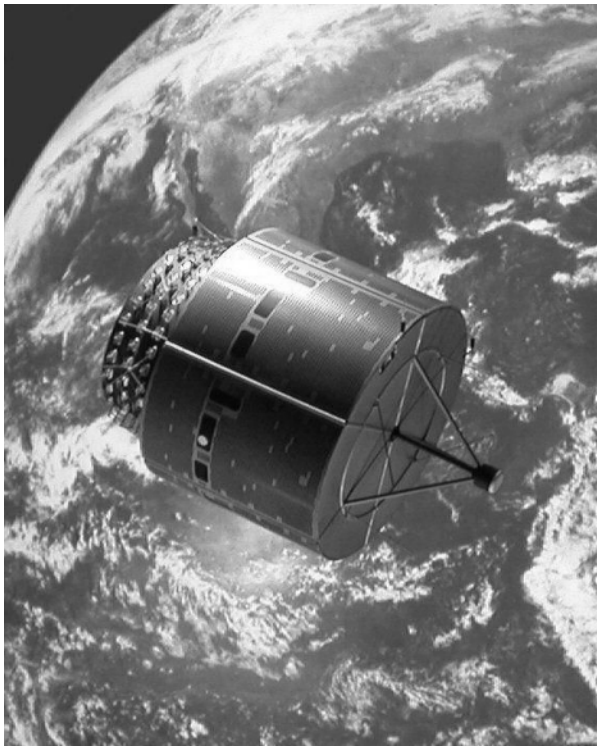


Figure 1.10. Artist's impression of the SMS satellite (source: Wikimedia commons).
For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip

**See Appendix 3.

1.3.2.2. *Geostationary Operational Environmental Satellite (GOES) – 1st generation*

The first generation of GOES corresponds to the satellites GOES-1 to GOES-7. VISSR was the main instrument of the satellites GOES-1, GOES-2 and GOES-3. GOES-1, launched on October 16, 1975 and initially placed at 55° W, was moved several times, changing in longitude. It was even entrusted to the European Space Agency (ESA) on December 1, 1978 and was relocated to the Indian Ocean for a year to participate in the Global Atmospheric Research Program (GARP).

The VAS** instrument replaced the VISSR in and after GOES-4, which was launched on September 9, 1980. VAS has the particularity of combining atmospheric imagery and sounding of temperature and humidity. It was the first sounding instrument on board a geostationary satellite.

To meet the needs of the United States, the GOES system used two satellites simultaneously, one covering the Pacific Ocean (GOES-West – longitude $\sim 135^\circ$ W), the other monitoring the Atlantic Ocean (GOES-East – longitude $\sim 75^\circ$ W).

1.3.2.3. *From GOES-8 to GOES-15 – 2nd generation*

Compared to the previous generation, the stabilization of the platform was now ensured by a three-axis system and the imaging and sounding missions were performed using separate instruments. The imager had five channels and the sounder 19 channels.



Figure 1.11. *August 29, 2005 at 15:00 UTC – GOES-12 – Hurricane Katrina (source: Météo-France). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip*

**See Appendix 3.

GOES-9, launched on May 23, 1995, experienced technical problems from 1997. It was kept in orbit as a backup satellite and replaced by GOES-10. Reactivated in 2003, following the failed launch of the Japanese satellite MTSAT-1, it was moved to 155° E to fill the gap in the geostationary belt before the launch of MTSAT-1R.

1.3.2.4. *GOES – 3rd generation*

Today, it is a new generation satellite that observes the Americas. GOES-R was successfully launched from Cape Canaveral on November 19, 2016. It was declared operational on December 18, 2017 as GOES-16 at 75.2° W longitude. This new-generation program includes four satellites to ensure an observation mission until around 2036. GOES-16 is equipped with the new ABI** imager, which makes it possible to observe the Earth in 16 different spectral bands (compared to five for the previous generation of GOES satellites). The spatial resolution of the images is between 500 m and 1 km for the visible band channels and between 1 and 2 km for the infrared channels. The temporal frequency of the images is increased with full-discs transmitted every 10 min. It even has the ability to scan a targeted 1,000 km x 1,000 km area every 30 seconds to monitor fast-developing hazards. GOES-16 is also equipped with a GLM** instrument, which is an important innovation. This is, in fact, the first operational lightning imager on a geostationary satellite. It complements ground lightning detection networks and anticipates the risk of severe weather, with a rapid increase in the number of lightning flashes being a signal of a sudden deterioration in meteorological conditions.

GOES-17 is located at longitude 137.2° W above the Pacific Ocean. It carries the same payload as GOES-16 but has some cooling issues. As a result, in the infrared, images can be degraded or absent for a few hours at times of the year close to the equinoxes. GOES-18 and -19 will complete the series in future years.

**See Appendix 3.

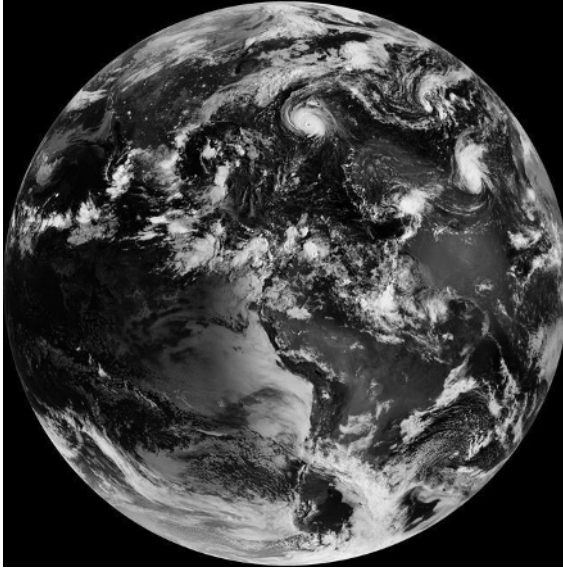


Figure 1.12. *September 12, 2018 at 12:00 UTC – GOES-16 – Geo-color image (source: Météo-France). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip*

1.4. Russian meteorological satellites

1.4.1. Polar-orbiting satellites

In the USSR, the development of the first meteorological satellites was initiated at the request of the military who, during the Cold War, sought to know meteorological conditions across the entire planet for their intercontinental bombers and their war fleet. Soviet strategists do not forget to remind their leaders of all the efforts made by the United States. Convinced, the Soviet government ordered, on October 30, 1961, the development of the experimental network of meteorological satellites, Meteor, assigned to the OKB-586 design bureau in Dnepropetrovsk. In its initial version, the satellite was light enough to be launched by the Cosmos rocket (type 65S3) under development within the same design office. But the OKB-586 played a crucial role in the strategic intercontinental missile program, and its manager Mikhail Yangel decided to transfer the Meteor program, which was considered to be less prestigious, to the Moscow-based VNIEM research institute. This transfer became effective in May 1962.

On April 13, 1963, VNIIEM launched Cosmos-14, an experimental satellite and test platform for on board electrotechnical systems that allowed the orientation and stabilization of future meteorological satellites. The satellite was a cylinder 1.8 m long and 1.2 m in diameter, with two hemispherical ends. The stabilization system consisted of flywheels driven by electric motors. The kinetic energy of the flywheels was damped by electromagnets interacting with the Earth's magnetic field. This system provided a three-axis-type stabilization and oriented the satellite towards the center of the Earth. A similar test flight was carried out almost eight months later with Cosmos-23 and then by the Cosmos-44 prototype. These three satellites, as well as the flights of Cosmos-58, Cosmos-100 and Cosmos-118, were the first stage of development and led to the first Soviet experimental meteorological satellite, Cosmos-122. The latter was launched on June 25, 1966 and transmitted its images to three receiving stations on the ground. These missions and then those of the following satellites (Cosmos-144, Cosmos-156, etc.) paved the way for the first operational meteorological satellite, Meteor-1-1. Weighing 2,200 kg, Meteor-1-1 was put into orbit by a Vostok-2M launcher on March 26, 1969 in an orbit inclined at 81.2° . Its payload consisted of a radiation budget sensor, a television camera and an infrared instrument. This was the first in a series ending with Meteor-1-27, launched into orbit on April 5, 1977.

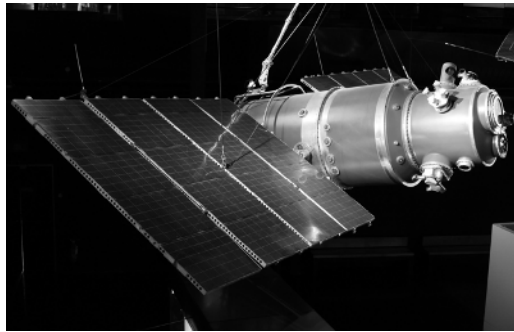


Figure 1.13. *Model of the Cosmos-122 satellite at the Air and Space Museum, Paris-Le Bourget (source: Wikimedia commons). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip*

The early 1970s saw the gradual demilitarization of Soviet meteorological satellites. In December 1971, the government decreed that space resources could also be used to meet civilian needs. This decision paved the way for the development of the Meteor-Priroda series of satellites. The first specimen, Meteor-P.-1 (also called Meteor-1-18) was launched on July 9, 1974 from the Plesetsk cosmodrome. It was a three-axis stabilized satellite weighing 3,800 kg. The

third satellite in the Priroda series, Meteor-P.-3, put into orbit on June 29, 1977, became the first Sun-synchronous satellite, at an altitude of 630 km and an inclination of 98°. It mainly included two multispectral scanners working in the visible and near-infrared domains for imaging, an infrared interferometer and a microwave sounder to obtain temperatures at different levels in the atmosphere. The sixth and final satellite in the series was launched on July 10, 1981.

At the end of the 1960s, the second generation of Meteor satellites was considered. Despite the technical problems encountered, it resulted in the launch of Meteor-2-1 on July 11, 1975, the first of a series of 21 satellites. Among the four instruments on board, the payload of the Meteor-2 satellites included an instrument consisting of three television camera-type sensors that took measurements in the visible and infrared spectra. Cloud cover information was thus obtained during the day and at night. An infrared sounder was used to reconstruct atmospheric temperature and humidity profiles. Two or three satellites, whose passage times were spaced out, made up the nominal Meteor-2 network, guaranteeing high-frequency observations. Hurricanes, storm cells and vast forest fires no longer escaped forecasters. The satellites stored and then released their data as they passed over the main stations in Moscow, Novosibirsk and Khabarovsk, but data could also be received in real time by autonomous receiving stations. There were about 50 of them across Soviet territory, allied countries and even at sea. In May–June 1978, the icebreaker *Sibir*, equipped with such a receiver, attempted a pioneering voyage across the ice-covered Arctic Ocean, from Murmansk to the Bering Strait. Meteor imagery was crucial in locating areas where the ice was thinnest, allowing the ship to travel at speeds of up to 22 knots. The last in the Meteor-2 series was put into orbit on August 31, 1993 from the Plesetsk site using a Tsiklon-3 launcher.

The development of the Meteor-3 program began in the early 1980s. It was a series of meteorological–environmental satellites of the USSR RosHydroMet agency. The system comprised six polar-orbiting satellites. The main objectives of the Meteor-3 program were to obtain information about:

- cloud cover, snow on the ground and sea ice;
- the vertical distribution of temperature and humidity in the atmosphere;
- radiation in near-Earth space.

Meteor-3-1 was placed in orbit on October 24, 1985. With some additional instruments, Meteor-3-6 took off from the Plesetsk Cosmodrome on January 25, 1994.

Delayed due to funding problems, the Meteor-3M polar-orbiting satellite program spans the period 2001–2033. Overall responsibility for the program is given to RosHydroMet, with Roscosmos being responsible for the space segment. They are Sun-synchronous satellites equipped with numerous instruments. Among these are (on the Meteor-M N2, launched July 8, 2014):

- two radiometers for a high spatial resolution imaging;
- a 2,670-channel infrared interferometer for atmospheric temperature and humidity sounding, ozone profiling and greenhouse gas detection;
- a microwave radiometer to reconstruct temperature and humidity profiles, even in the presence of clouds, and to collect information on precipitation.

On November 28, 2017, the launch of Meteor-M N2-1 ended in failure. After taking off from the Vostochny Cosmodrome near Tsiolkovsky in Siberia, the Soyuz-2.1b rocket encountered a problem during the separation of its third stage, leading to the loss of the satellite which probably crashed into the North Atlantic Ocean. According to Roscosmos, it was due to a bug in the algorithm of the navigation software. Some blame it on human error: a poor configuration that does not take into account the location of the new Vostochny Cosmodrome instead of Baikonur. The situation caused a commotion and made it to the highest level in the government.

Meteor-M N2-2, launched on July 5, 2019, did not experience the same setbacks and reached its Sun-synchronous orbit at an altitude of 821 km.

1.4.2. Geostationary satellites

As far as geostationary satellites are concerned, GOMS-1 (also called Electro-1) was the first Russian experimental satellite. The program began in the early 1970s for a planned launch in 1979. Various problems related to the payload and software development, and then to the break-up of the Soviet Union, delayed the program. Fifteen years later, GOMS-1 was finally launched on October 31, 1994 from the Baikonur Cosmodrome in Kazakhstan. It carried a main instrument: the imaging radiometer with two channels (visible and thermal infrared). It sent images every 30 min from longitude 76.5° E.

Following the GOMS-1 experiment, the Russian government entrusted the company NPO Lavochkin with the development of a new family of geostationary satellites called Electro-L, who inaugurated a new platform. These were three-axis stabilized satellites with a 10-channel imager as the main instrument. Their spatial

resolution was 1 km at nadir for the visible spectrum channels and 4 km for the infrared channels. The first satellite in the series was put into orbit on January 20, 2011 at 76° E. It was followed by two other satellites in the series, launched in 2015 and 2019.

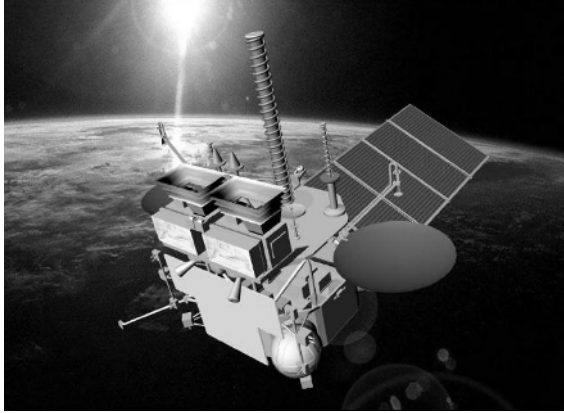


Figure 1.14. Artistic view of the satellite *Electro-L* (source: ESA). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip

1.5. European meteorological satellites

1.5.1. The Meteosat saga

In the 1960s, France, the United Kingdom, the Federal Republic of Germany, Italy and other European nations embarked, on their own initiative and in a dispersed manner, on space activities. Thanks to its National Center for Space Studies (*Centre national d'études spatiales*, CNES), created on December 19, 1961, France became the third world power, after the Soviet Union and the United States, to have access to space by putting into orbit, with its own launcher, its first satellite on November 26, 1965. Asterix was launched from Hammaguir, Algeria, using a Diamant-A rocket. Little by little, the idea of a European collaboration germinated and gave birth to two organizations with complementary objectives: the European Space Research Organization (ESRO) and the European Launcher Development Organization (ELDO), which were operational from 1964. However, it was not until the creation of the European Space Agency (ESA) that European space activities really took off. The convention creating ESA was signed on May 30, 1975 by 11 Member States. As the successor to the ELDO, ESA supports the development of European launchers. Ariane-1 made its first flight on December 24, 1979.

Pierre Morel had the idea for the Météosat project around Christmas 1968 when he and his colleagues from the CNRS Dynamic Meteorology Laboratory were participating in a balloon launch campaign in the middle of the Australian desert. He remembered the ATS-1 geostationary satellite and Verner Suomi's idea to place a 15 cm aperture telescope there. Like its operational successors, ATS-1 provided an animated view of atmospheric circulation from its position nearly 36,000 km away, fixed relative to Earth. Taking up Pierre Morel's idea, CNES is enthusiastically studying the possibility of launching a geostationary meteorological satellite as part of the World Weather Watch and as part of the GARP of the World Meteorological Organization (WMO) to complete the belt of geostationary satellites.



Figure 1.15. *Professor Pierre Morel (source: ESA–CNES)*

For both the French government and Jean-François Denisse, president of CNES, this research mission of the French space agency was not compatible with the implementation of an observation system, such as Meteosat. It was desirable that the National Meteorological Department as well as other European meteorological services actively participated in it. The project was then submitted to ESRO but it

immediately came up against a competing project inspired by British meteorologists, whose satellites had to operate in a polar orbit. After some attempts, the proposal of a coherent Earth observation system took preference over multiple smaller regional initiatives. Meteosat was integrated into the ESRO program on March 23, 1972, before being taken over and continued by ESA. Eight Member States decided to fund the program: Belgium, Denmark, France, Italy, the Federal Republic of Germany, the United Kingdom, Sweden and Switzerland. But what name should this “Europeanized” project bear? MetSat, as proposed by ESRO officials, Geostationary European Meteorological Satellite (GEMS) or Meteosat (anglicized, without the accent but close to the initial name)? It was this third option that was ultimately chosen, delighting the French designers.

The technical design of the Meteosat satellite and its MVIRI** instrument was almost complete when CNES handed over control to the European agency’s project team. It was a three-channel imager (a visible channel at 0.7 μm , a thermal infrared channel at 11.5 μm and an infrared channel in the water vapor absorption band centered at 6.4 μm). The spatial resolution at nadir is 2.5 km for the visible channel and 5 km for the other two channels. The Earth’s disk is scanned every 30 minutes from a satellite stabilized in rotation at 100 rpm. Meteosat is a cylinder 3.2 m high with a diameter of 2.1 m, weighing 626 kg. On this module are the solar panels. It is surmounted by a second cylinder, which is smaller and equipped with antennas.

Produced by the European industrial consortium Cosmos, under the project management of Aerospatiale together with Matra, the Meteosat system comprised three satellites. The first, Meteosat-1, was launched on November 23, 1977 from Cape Canaveral by an American Delta rocket. Its mission was to monitor weather conditions on the Earth’s disk comprising the Atlantic Ocean, Europe and Africa. However, certain technical uncertainties remained, in particular that of the cooling of sensitive parts of the telescope. In order to ensure favorable operating conditions, it was planned to flip the satellite at each equinox. The satellite was oriented upside down when it was put into orbit and the image was taken from south to north. A few months later, with the cooling system functioning nominally and with a sufficient margin, the decision was made to continue without flipping the satellite; an operation that could prove to be tricky. The following Meteosat satellites remained oriented upside down. At present, with the second-generation Meteosat satellites (MSG), the scanning of the disk is always done from south to north, which is a tenacious European peculiarity!

**See Appendix 3.

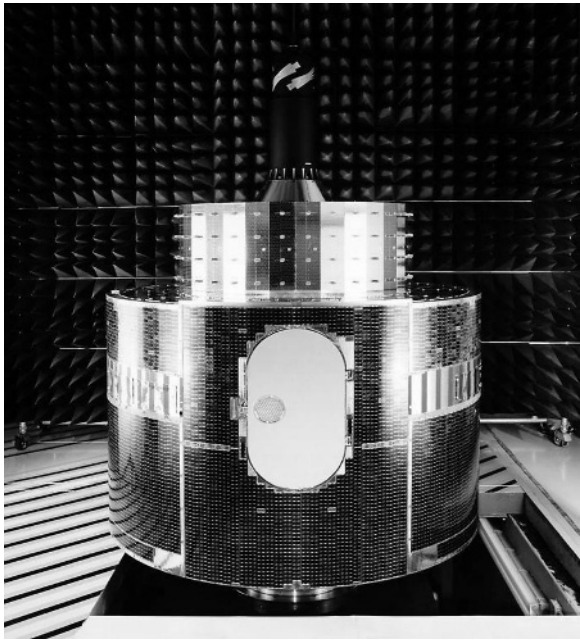


Figure 1.16. First-generation Meteosat satellite (source: ESA). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip



Figure 1.17. December 9, 1977 – Meteosat-1 – first image (source: ESA)

The Meteosat program was qualified as pre-operational. The technical design of the first three flight models was adapted to the provision of an operational service, but no provision guaranteed the continuity of service. This is what triggered the creation of a new European organization. During a long transition period, the solution was found. The provision of a meteorological service from space and its financing were accepted by Europe. The convention establishing the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) was adopted in Geneva on May 24, 1983. It was not until June 19, 1986 and the ratification of the national parliaments that the new organization was actually constituted, with 16 Member States (in 2020 EUMETSAT had grown to 30 Member States). EUMETSAT's main objective was to set up, maintain and run European systems of operational meteorological satellites, taking into account as far as possible the recommendations of the World Meteorological Organization. Meanwhile, Meteosat-2 was launched on June 19, 1981 from Kourou (French Guiana) using an Ariane-1 launcher. It took over from the first Meteosat, which broke down prematurely on November 24, 1979. EUMETSAT entrusted ESA with carrying out an initial operational program of three Meteosats on behalf of its Member States as well as for various countries in Africa and the Middle East. ESA also operated the Meteosat-1 and Meteosat-2 satellites, as well as Meteosat-3, put into orbit on June 15, 1988.

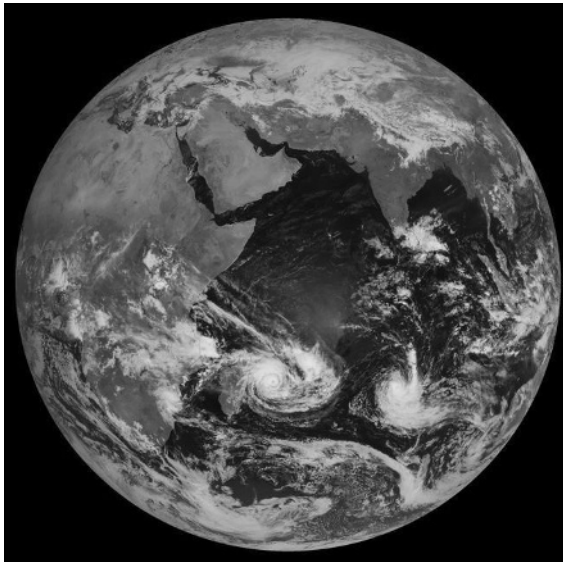


Figure 1.18. February 25, 2007 at 08:00 UTC – Meteosat-5 from its position over the Indian Ocean at 67.5° E longitude – color composition image (source: Météo-France).
For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip

Meteosat-4 was therefore the first model of the Meteosat Operational Program (MOP). It was launched on March 6, 1989. Its main instrument, as for all first-generation Meteosat satellites, was the MVIRI imager. This was followed by Meteosat-5 (March 2, 1991) and Meteosat-6 (November 20, 1993). In 1990, in order to ensure continuity between the MOP and Meteosat second-generation (MSG) programs, EUMETSAT adopted the Meteosat Transition Program (MTP). The MTP included the production of the Meteosat-7 satellite by ESA using spare parts from the MOP, the development of a new ground segment, and the operation of the system by EUMETSAT from 1995. Meteosat-7 was launched on September 2, 1997 to ensure the continuity of Earth's observation from the vertical of the Gulf of Guinea, the main position of the Meteosat satellites, generally ensured by the satellite most recently placed in orbit. It should be noted that Meteosat-3, a satellite that became a backup, was moved to 50° W longitude on August 1, 1991 then to 75° W longitude on February 1, 1993 to fill the gap left by NOAA and the delay in the program of second-generation GOES satellites. As of 1998, Meteosat-5, -6 and -7 were successively moved over the Indian Ocean. EUMETSAT therefore simultaneously carried out two operational missions from two orbital positions. The lifetime of Meteosat-7 was exceptionally long (20 years). The last image it transmitted was on March 31, 2017 at 12:00 UTC. On April 3, 2017, Meteosat-7 set off for a final mission, being placed definitively in a so-called graveyard orbit, about 300 km above the geostationary orbit, where satellites are transferred at the end of their working life. This maneuver, which takes about a week, was carried out successfully.

The first model of a second-generation Meteosat satellite, MSG-1, was placed in orbit by the European launcher Ariane-5, which took off from the Kourou Space Center in French Guiana on August 28, 2002. This satellite became operational on January 9, 2004 and was then named Meteosat-8. Four satellites developed by ESA on behalf of EUMETSAT formed the MSG program. Two and a half times larger than their predecessors, they were cylindrical satellites 3.22 m in diameter and 3.74 m long. On take-off, their mass reached two tons, almost half of which is made up of the propellants necessary to put them and keep them in position for the seven years, the time that their mission theoretically lasted. MSG satellites were equipped with new, more powerful and more precise sensors for the continuous observation of the Earth's atmosphere. The SEVIRI** imager was the main instrument of their payload. It was a 12-channel imager in the visible and infrared spectra with a horizontal resolution of 3 km at nadir. One channel, the high-resolution visible (HRV), even achieved a resolution of 1 km. It transmitted images of the Earth's disk every 15 min. When Meteosat-9 became the operational satellite, Meteosat-8 provided a backup, as well as the rapid scanning service (RSS) mission: it scanned

the northern third of the disk, therefore mainly Europe, every 5 min. As for first-generation Meteosats, an MSG satellite was moved above the Indian Ocean, at 41.5° E.

The third generation of Meteosat then emerged. This new program includes six geostationary satellites: four for imaging, MTG-I, and two for sounding, MTG-S, which will be placed between longitudes 10° E and 10° W. In addition to state-of-the-art imagery thanks to the FCI** imager, the MTG satellites have new infrared sounding and lightning detection capabilities onboard. MTG-S satellites also carry Sentinel-4**. This is an instrument dedicated to monitoring air quality within the framework of the European Copernicus program, which aims to bring together all the data obtained from environmental satellites and in situ measuring instruments, in order to produce a global and complete view of the state of our planet. This gives Meteosat satellites a new ability to analyze atmospheric chemistry and identify gas concentrations. The launch of the first MTG satellite will be a major milestone for European meteorology.

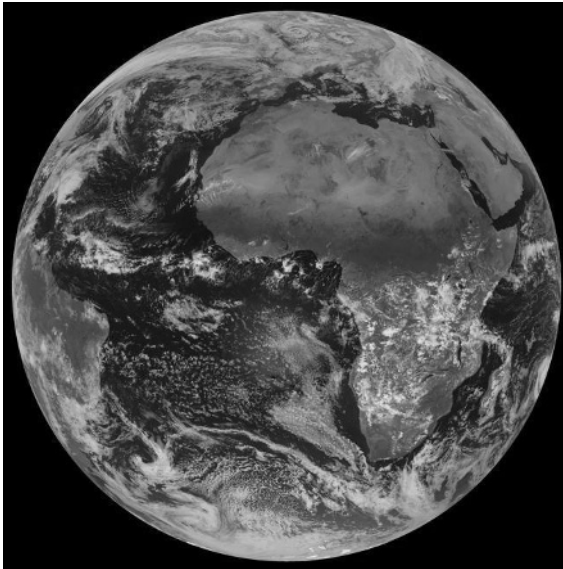


Figure 1.19. December 6, 2011 at 12:00 UTC – Meteosat-9 – color composite image (source: Météo-France). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip

**See Appendix 3.

1.5.2. 46 years after Tiros-1, MetOp enters the scene

Originally, the MetOp satellites were part of an ESA satellite program called the Polar-Orbit Earth Observation Mission (POEM) intended to succeed ERS-1 and -2. The payload must cover the provision of meteorological data and, more broadly, environmental data. In 1992, the ESA Council decided to split the POEM mission into two programs: MetOp for meteorology and Envisat for the environment. MetOp is a family of three satellites. They form the space segment of the EUMETSAT Polar System (EPS) and constitute the European part of a polar meteorological observation system shared with the United States, the Initial Joint Polar Satellite System (IJPS), whose agreement was signed in November 1998. The MetOp satellites occupy the morning orbit, whereas the NOAA satellites occupy the afternoon orbit. This complementarity allows better coverage of the globe.

It was not until October 19, 2006 that MetOp-A took off from the Baikonur Cosmodrome (Kazakhstan) aboard a Soyuz rocket. Once in orbit, MetOp-A came under the control of ESA's European Space Operations Center (ESOC), which placed it in its final orbit, deploying its solar panel and antennas. EUMETSAT then took control of the satellite for the commissioning phase. Lasting six months, it covered satellite verification operations and the scientific validation of the products generated by its instruments. Once this phase was completed, MetOp-A was declared operational and took over the morning service, replacing the American satellite NOAA-17.

The MetOp satellites travel approximately 830 km from the Earth in a quasi-circular, heliosynchronous orbit, known as the "morning orbit" because they cross the equatorial plane at 9:30 am in the descending direction (9:30 pm in the ascending direction). They collect data on all areas of the globe, even at high latitudes, which geostationary satellites over the equator cannot achieve. The images of the polar zones mixing water and ice are spectacular under the low sun. Low orbit is also used to probe the atmosphere in detail in order to collect temperature and humidity profiles, in particular thanks to the IASI** sounder, the result of a collaboration between CNES and EUMETSAT. IASI is an infrared interferometer of unprecedented precision that also collects information on the chemical components of the atmosphere, including greenhouse gases. The MetOps carry numerous instruments including a radar scatterometer, whose main function is to reconstruct wind measurements at the surface of the oceans. With MetOp-A, then MetOp-B and then MetOp-C, the volume of data that fed numerical weather prediction models increased exponentially.

**See Appendix 3.



Figure 1.20. *Artistic view of the satellite MetOp (source: ESA). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip*

Approved by the EUMETSAT Council in June 2010, EPS-SG (SG for Second Generation) is on the horizon, with the planned launch of the first MetOp-SG-A1 in 2023. It is a program comprising six satellites, three “A” platforms which will carry a suite of passive instruments (imagers and sounders) and three “B” platforms with additional instruments, a radar scatterometer, and microwave imagers in particular.

1.6. Elsewhere

1.6.1. Japan

Japan only operates geostationary satellites. Three generations of Himawari satellites (sunflower in Japanese) have succeeded each other since 1977. The first generation, called Geostationary Meteorological Satellite (GMS), included five satellites. It was the result of a partnership between the Japan Meteorological Agency (JMA) and the National Space Development Agency of Japan (NASDA). NASDA was created on October 1, 1969 to develop space technologies and promote the use of space for peaceful purposes. GMS-1 was launched on July 14, 1977 using an American Delta rocket, a few months before the European satellite Meteosat-1. The GMS are spin-stabilized satellites and carry the American VISSR imager with two channels as their main instrument. Like its successors, GMS-1 was positioned at 140° E longitude. The GMS-2 to -5 satellites were successively placed in orbit by a Japanese launcher. GMS-5 saw its VISSR imager have two additional channels (the addition of a channel in the water vapor absorption band and another in the thermal infrared). It was put into orbit on March 18, 1995 and was scheduled to be replaced in 1999 by a second-generation satellite.

The second generation of Japanese meteorological satellites was called Multi-functional Transport SATellites (MTSAT). On May 15, 1999, MTSAT-1 was destroyed during its launch from Tanegashima Space Center. The JMA immediately decided to build a replacement satellite (MTSAT-1R) to extend the life of GMS-5 and negotiated with NOAA on the loan of a satellite. In April 2003, GOES-9 reached its new position at 155° E to replace GMS-5 at end-of-life, while waiting for MTSAT-1R. MTSAT-1R was launched on February 26, 2005. It was a three-axis stabilized satellite with a more efficient imager (JAMI**), equipped with five channels to produce images every 30 min. Its successor MTSAT-2, the second and last satellite of the MTSAT program, launched on February 18, 2006, became an operational satellite in 2010 and captured its last image in 2016.

Himawari-8 and Himawari-9 form the third generation of Japanese geostationary satellites. Himawari-8 was launched on October 7, 2014 and has a new 16-channel AHI** imager. With blue, green and red channels, it makes it possible to produce true color images, which is a notable improvement in particular for the detection of aerosols. It provides imaging in 10 minute intervals up to a resolution of 500 m for its channel at 0.645 μm .

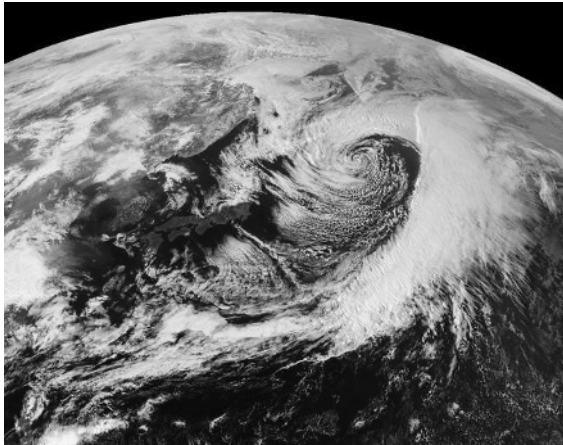


Figure 1.21. *March 6, 2020 at 06:00 UTC – Himawari-8 – Pacific Ocean agitated by a beautiful storm (source: Météo-France). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip*

**See Appendix 3.

1.6.2. China

As early as 1971, the National Satellite Meteorological Center (NSMC) was created within the China Meteorological Administration (CMA) to manage research and operations related to Fengyun (wind and cloud) satellites. Fengyun, abbreviated as FY, refers to all weather satellites developed by the People's Republic of China. FY programs carry odd numbers to denote polar-orbiting satellites and even numbers for geostationary satellites.

1.6.2.1. *Polar-orbiting satellites*

The FY-1 orbiting satellite program, which is the first series of Chinese meteorological satellites, was founded in 1977. The satellites were built by the Shanghai Institute of Satellite Engineering and their payload by the Shanghai Institute of Technical Physics. FY-1A, an experimental satellite, was launched on September 7, 1988 from Taiyuan base. It suffered from several malfunctions: humidity contaminated the detectors altering the infrared measurement, then major attitude control problems led to the loss of the satellite after 39 days in orbit. Its successor, FY-1B, had the same attitude control difficulties but these could be corrected from the ground during the first few months. FY-1B delivered images for about a year thanks to its MVISR** imager with five channels. FY-1C and FY-1D followed with respective launches on May 10, 1999 and May 15, 2002. They benefited from the experience gained and the technical improvements, notably by carrying a new 10-channel imager with a spatial resolution of 1.1 km.

The second generation of Chinese polar-orbiting satellites was called FY-3. This program was the result of collaboration between the CMA and the China National Space Administration (CNSA). Approved in 1998, its development really began in 1999; eight satellites made up the series. The first two were considered experimental. Regular launches, every two years, were planned with equatorial crossing times of orbits around 06:00 (FY-3 E and H), 10:00 (FY-3A, C and F) and 14:00 (FY-3B, D and G). The experimental satellites FY-3A and B were launched on May 27, 2008 and November 4, 2010, respectively. Satellites B, C and D are currently operational. Although their payload was different depending on whether they were morning or afternoon satellites, the improvements are significant compared to FY-1, with increased capacities concerning in particular:

- VIS/IR imagery with spatial resolutions from 250 m to 1 km;
- atmospheric soundings;
- microwave imaging.

1.6.2.2. Geostationary satellites

FY-2 was the first generation of Chinese geostationary satellites. The development of the program began in the 1980s with the first ready in 1994. On April 2, 1994, while the satellite's fuel tank was being filled, a fire broke out, followed by an explosion that killed a technician from the Xichang Satellite Launch Center and injured 31 others. It took three years to build a new satellite with a modified tank. It was therefore on June 10, 1997 that FY-2A was launched. Like Meteosat, it was a spin-stabilized satellite. Its main instrument was the three-channel S-VISSR** imager. It operated in a nominal way until April 1998 when it began to experience transmission problems. Its capabilities were then limited to producing six images per day. The second experimental satellite, FY-2B, was put into orbit on June 26, 2000. These two experimental satellites were followed by six satellites, until FY-2H, which was launched on March 27, 2017 carrying a third-generation S-VISSR imager with five channels.

FY-4 is the next program, consisting of seven satellites. The performance of the FY-4s improved considerably. FY-4A was put into orbit on December 10, 2016. It was considered the pre-operational satellite of the series. It had a 14-channel imager, an infrared interferometer, as well as a lightning imager. The FY-4s are expected to be operational until around 2040.

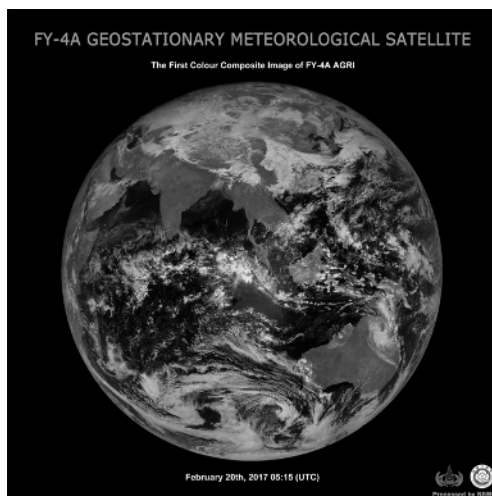


Figure 1.22. February 20, 2020 at 05:15 UTC – FY-4A – first color composition image (source: China National Space Administration). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip

**See Appendix 3.

1.6.3. Korea



Figure 1.23. Artistic view of the satellite Kompsat-5 (source: Wikimedia commons).
 For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip

South Korea began to develop its space program in the late 1980s. On October 10, 1989, the South Korean space agency, Korea Aerospace Research Institute (KARI), was born. The first of the Kompsat polar-orbiting Earth observation satellites was put into orbit on December 20, 1999. It was not until June 26, 2010 that COMS, the first geostationary satellite, dedicated, among other things, to meteorology, was launched. It had a five-channel imager as well as a second imager dedicated to the color of the ocean with eight channels. It was positioned at 128.2° E longitude and produced images every half hour. It was followed by the GEO-KOMPSAT-2A geostationary satellite in 2018.

1.6.4. India

The Indian National Satellite (INSAT) program was created in the 1970s. Four geostationary satellites were planned, positioned around longitudes 74° E and 93° E. These satellites carried both a domestic telecommunications system including television and a weather observation system. Built by the American company Ford Aerospace Corporation, their VHRR imager had two channels. INSAT-1A, the first of the series, was launched on April 10, 1982. The last satellite of the program, INSAT-1D, was deactivated on May 14, 2002 after 12 years of good and loyal service.



Figure 1.24. *Insat-1B in a clean room (source: Wikimedia commons). For a color version of this figure, see www.iste.co.uk/phulpin/satellites1.zip*

The second generation of satellites, INSAT-2, was designed and built entirely by India. Like INSAT-1, the INSAT-2 program had multiple missions: the satellites were used for both telecommunications and Earth observation. It was a program of five satellites. They carried a more efficient imager than that of INSAT-1 (the spatial resolution of the visible channel drops from 2.75 km to 2 km and that of the infrared channel from 11 km to 8 km). INSAT-2A was put into orbit on July 9, 1992 by an Ariane-4 launcher. INSAT-2C was totally devoted to telecommunications. The INSAT-2E payload included a new imager that had a third channel dedicated to water vapor.

At the end of the 1990s, the Indian Space Research Organization (ISRO) signed agreements with NASA and NOAA, and then with EUMETSAT for real-time data exchange. At the beginning of 2000, in collaboration with EUMETSAT, a reception station was installed at the Indian Meteorological Department (IMD) to receive high resolution data from Meteosat-5, located at 63° E longitude.

MetSat-1 was launched on September 12, 2002. It was the first Indian satellite dedicated solely to meteorology. It was positioned at 74.1° E longitude. On February 6, 2003, it was renamed Kalpana-1 in tribute to Kalpana Chawla, a female Indian astronaut who died in the destruction of the American space shuttle Columbia during

its re-entry into the atmosphere. Kalpana-1 had a three-channel imager with a spatial resolution of 2 km in the visible and 8 km in the infrared.

Like its predecessors, INSAT-3A, put into orbit on April 9, 2003, was a satellite dedicated to both telecommunications and meteorology. It carried the same instruments as Kalpana-1 and was positioned at 93.5° E longitude.

We have to wait for INSAT-3D to deal with the new generation of Indian satellites. It was put into orbit on July 25, 2013 from Kourou by an Ariane-5 and was positioned at 82° E longitude. It carries both an imager and a sounder. The imager, which offers full disks every 30 min, has six channels, the visible and very near-infrared channels of which achieve a spatial resolution of one kilometer. As for the 19-channel sounder, its purpose is to reconstruct temperature and humidity profiles.

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