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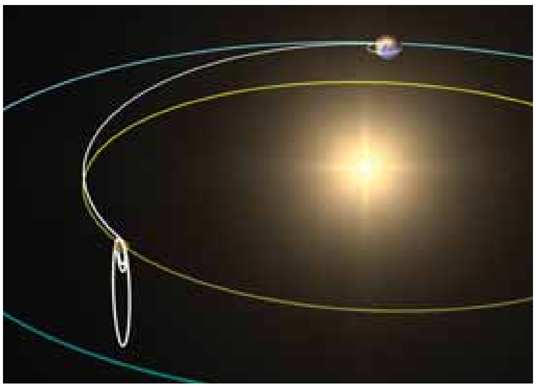

ESOC

European Space Agency
Agence spatiale européenne

Visit the European Space Agency at www.esa.int

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The European Space Operations Centre in Darmstadt, Germany, ensures the development of the ground-segment facilities and services, and the smooth working of spacecraft in orbit. Its control rooms, linked to ground stations all over the world, track and control satellites, issuing commands for spacecraft manoeuvring, carrying out routine systems monitoring and transmitting new payload operational instructions. It is the home of ESA's Directorate of Operations and Infrastructure.

The European Space Agency

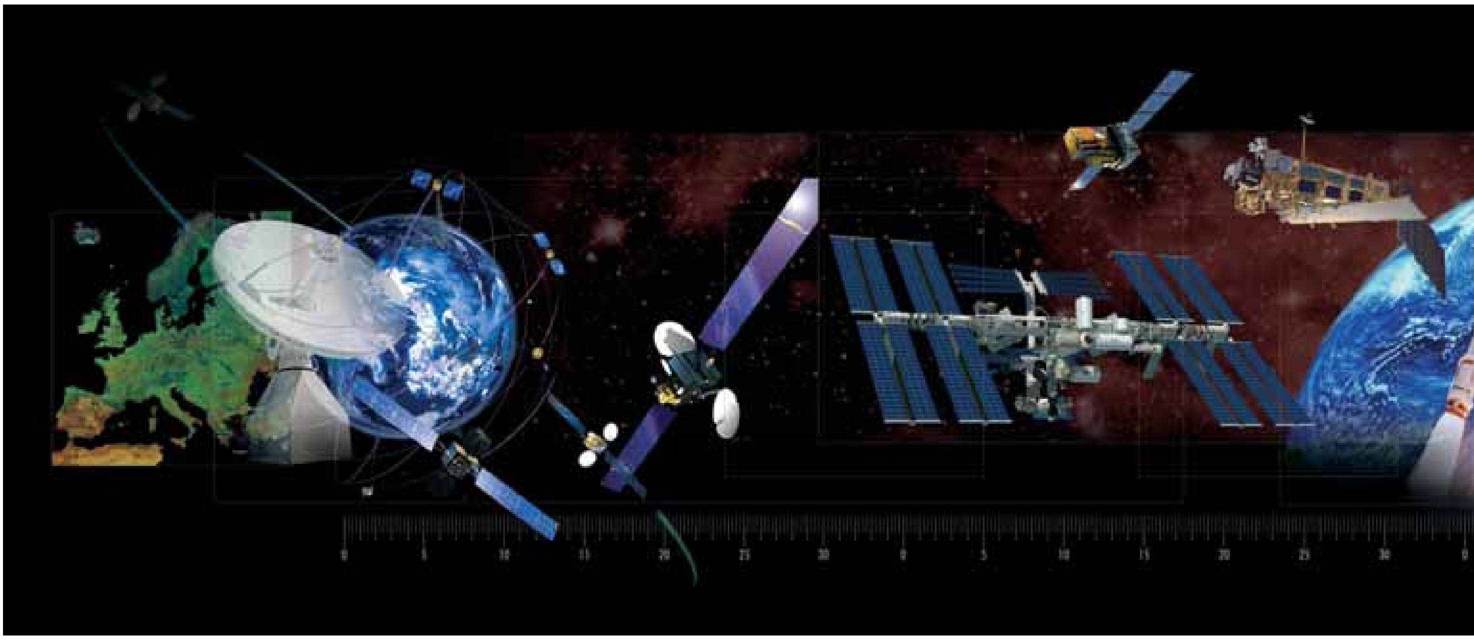
For more than 40 years the Member States of ESA have worked together and pooled their resources to open up new avenues in space exploration, to develop advanced technology and to build a European space industry capable of competing successfully in the global marketplace. The widely acknowledged success of ESA's Scientific, Earth Observation, Telecommunications, Navigation, Human Spaceflight and Launcher programmes is testimony to the high level of competence that has been developed in Europe and the many benefits that have already been brought to our daily lives and the European economy. Space is an essential enabling tool for Europe not only economically but also politically and strategically. Thanks to ESA and to its national stakeholders, Europe has a thriving sector, ready to support the policies of the European Union.

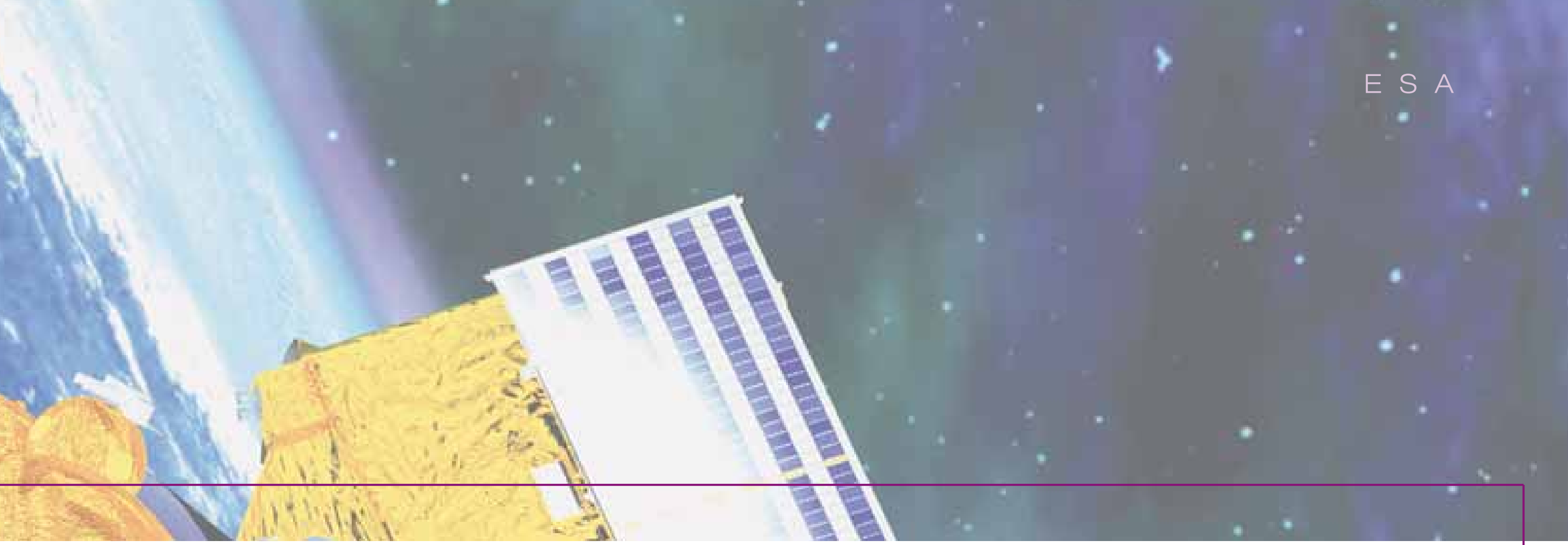
ESA has 17 Member States. The national bodies responsible for space in these countries and in Canada sit on ESA's ruling Council and are its main stakeholders: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

In addition, Canada takes part in some ESA projects under a Cooperation Agreement, and the Czech Republic, Hungary and Romania are participating in the Agency's Plan for European Cooperating States (PECS) programme.

Funding

ESA's activities fall into two categories – 'mandatory' and 'optional'. Programmes carried out under the General Budget and the Science Programme budget are mandatory they include the Agency's basic activities (studies on future projects, technology research, shared technical investments, information systems and training programmes). All Member States contribute to these programmes on a scale based on their Gross Domestic Product (GDP). The other programmes, known as optional, are only of interest to some Member States, who are free to decide on their level of involvement. Optional programmes cover areas such as Earth observation, telecommunications, satellite navigation and space transportation. Similarly, the International Space Station and microgravity research are financed by optional contributions.





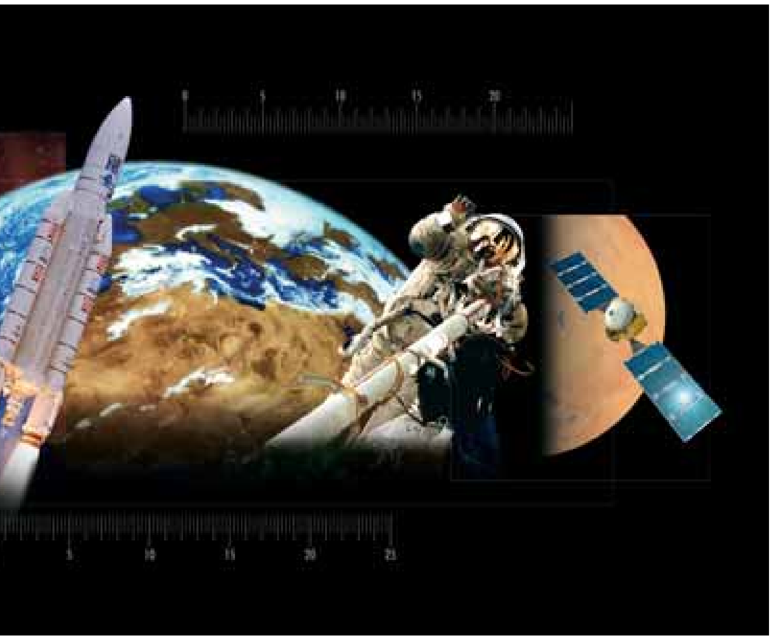
Staffing

There are some 1900 specialists working for ESA and their distribution takes into account not only social and occupational categories, but also gender and the geographical spread of nationalities.

The ESA Centres

ESA has its headquarters in Paris and specialist centres in The Netherlands, Germany, Italy and Spain, liaison offices in Washington DC and Moscow, an office in Brussels for relations in particular with the European Commission, and representation in French Guiana.

ESTEC – the European Space Research and Technology Centre at Noordwijk in The Netherlands is the hub and test centre for European space activities. ESTEC is responsible for the technical preparation and management of ESA space projects. It is the home of ESA's Directorates of Technical and Quality Management; and of Human Spaceflight, Microgravity and Exploration.



ESOC – the European Space Operations Centre in Darmstadt, Germany, ensures the development of the ground-segment facilities and services, and the smooth working of spacecraft in orbit. Its control rooms, linked to ground stations all over the world, track and control satellites, issuing commands for spacecraft manoeuvring, carrying out routine systems monitoring and transmitting new payload operational instructions. It is the home of ESA's Directorate of Operations and Infrastructure.

ESRIN – located in Frascati, south of Rome, Italy, is the ESA Centre for Earth Observation because it manages the exploitation phase of Earth observation missions – acquires, processes and distributes quality-controlled satellite data – and it is the home of ESA's Directorate of Earth Observation Programmes. The centre hosts a number of other activities as well. The project team managing the European Vega small-launcher programme is located here as well as the ESA Telecom Lab. ESRIN is also the central point for ESA information systems activities.

EAC – the European Astronaut Centre located in Cologne, Germany is the home base of the European astronauts who are members of the European Astronaut Corps. The role of the EAC is to prepare and implement astronaut training programmes for a variety of missions, including those for the International Space Station. It also coordinates astronaut training between ESA and its International Space Station Programme partners. The EAC also provides support ranging from public relations assistance to medical monitoring.

ESAC – the European Space Astronomy Centre in Villafranca del Castillo, near Madrid in Spain, hosts the scientific operations for all ESA astronomy and planetary missions, along with their scientific archives. It provides services to astronomical research projects worldwide.

Europe's Spaceport – located in Kourou, French Guiana, lies at latitude 5°3', just over 500 km north of the equator. Its location makes it ideal for launches into geostationary transfer orbit as few changes have to be made to a satellite's trajectory. ESA funds two thirds of the spaceport's annual budget.

The European Space Operations Centre

The mandate of the European Space Operations Centre (ESOC) is to conduct mission operations for ESA satellites and to establish, operate and maintain the necessary ground segment infrastructure.

Mission Operations

Mission operations is the process involving operations planning, satellite monitoring and control, in-orbit navigation, and data processing and distribution, by which the satellite mission objectives are achieved, be they the collection of environmental or scientific data or the provision of a navigation service.

Monitoring and control starts as soon as the satellite is separated from the launch vehicle, its purpose being to activate the on-board systems for the tasks ahead in the challenging environment of space. Soon afterwards, the payload has to be configured to enable it to play its part in exploiting the mission according to plans based on the wishes of the users. It is a round-the-clock task performed throughout the duration of the mission.

Whenever the satellite is visible from the ground, its health and status are monitored. This task involves the analysis of as many as five thousand telemetry parameters every minute. Operations are effected through instructions sent to the spacecraft in the form of telecommands to change on-board settings or to activate payload equipment. Continuous monitoring is necessary to verify correct execution of up to one hundred commands per minute.

Satellite navigation is the process by which a satellite is brought to and kept in the desired orbit, and by which the required body orientation (attitude) is acquired. It involves determination, prediction and control of the satellite orbit hand in hand with determination and control of the satellite attitude. Changes in orbit and attitude are effected by the execution of often complex manoeuvres under ground control, for example using the satellite's on-board thrusters.

Lift-off of an Ariane-5 launcher

Ground Segment Infrastructure

ESOC has established a comprehensive ground segment infrastructure suitable and ready to support various types of missions, each having different demands, requirements and constraints. This infrastructure encompasses all facilities and services needed for mission operations and includes a network of ground stations around the world, a number of control centres, payload data-processing facilities, spacecraft control systems, simulation systems and communications systems. All ground facilities have to be highly reliable and maintainable: cost-effectiveness in operations is achieved by careful introduction of new technology.

The infrastructure is primarily intended for ESA missions, but is also made available to external agencies and industry. Depending on the type of agreement, ESOC can provide a wide range of services, from consultancy to full mission operations.

Mission Success

The mission operations phase is generally the final and arguably the most critical phase in a space project, during which the return on investment is realised: the return in this case is the quantity, quality and availability of mission products or services. Mission success is therefore gauged by the return of mission products, and by the ability to recover from deficiencies or anomalies in the orbiting spacecraft.

One of the first control rooms for the ESRO-2 mission

Since 1967 ESOC has successfully conducted close to 60 satellite missions, each presenting a different challenge to the operations staff, including:

- science missions in near-Earth, highly eccentric and interplanetary orbits,
- planetary exploration missions in orbit around the Moon, Mars and Venus,
- Earth observation missions in near-Earth orbit,
- meteorological missions in geostationary orbit,
- microgravity missions in near-Earth orbit,
- telecommunications missions in geostationary orbit.

Of particular note are the following missions, for which ESOC had full responsibility:

- The navigation of the Giotto spacecraft to encounter Comet Halley in 1986 was a spectacular success. After surviving the encounter, a gravity-assist swing-by around the Earth in 1990 took Giotto into an orbit in which it was to encounter Comet Grigg-Skjellerup two years later: the operations involved in the hibernation and blind reactivation of the spacecraft are of historic significance.
- The successful execution of the Eureca (European Retrievable Carrier) mission, including the deployment and retrieval of the spacecraft by the US Space Shuttle proved ESOC's ability to control complex rendezvous and docking manoeuvres in space, in close cooperation with another agency (NASA).
- Between 1977 and 1995, ESOC conducted the six European Meteosat missions involving full spacecraft monitoring and control, navigation, payload control, payload data processing, image data extraction, data dissemination and archiving. The service provided to the meteorological community was exemplary in its quality and continuous availability.
- On 14 January 2005, the Huygens mission was completed with the successful descent and landing of the probe on Titan. The scientific data sets returned by the on-board instruments were astonishing and provided the ecstatic scientists and engineers with a first glance into this remote world.
- ESA's Rosetta spacecraft, launched on 2 March 2004, is the first to undertake the long-term exploration of a comet in order to complete the most detailed cometary study ever attempted. The 10-year journey will take it out to about 790 million km from the Sun.

Huygens sends first images of Titan's surface to Earth

Mars Express gathers data from

Satellites are monitored 24h/day, 7days/week, from dedicated control rooms such as this one for Earth Observation spacecraft

Some mission activities for SMART-1 were supported using PDAs

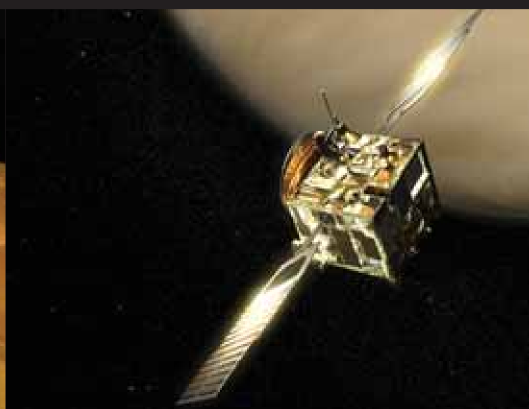
– Both the Mars Express and Venus Express science missions have recorded invaluable data on atmospheric, surface and subsurface conditions of these neighbouring planets. Dedicated control centres at ESOC, responsible for spacecraft operations, collect and prepare the data for distribution to the scientific community.
– The SMART-1 spacecraft successfully demonstrated solar-electric propulsion, using little more than sunlight and ions from 80 kg of xenon gas to travel a complex 100-million km spiral journey to its destination. The mission enabled ESA experts to develop and test innovative ground control systems that ran in a semi-automated mode. Real-time telemetry data and mission planning tools were accessed by engineers via wireless-enabled phones and PDAs, and spacecraft data were distributed via the Internet. The mission ended successfully with a lunar impact on 3 September 2006.

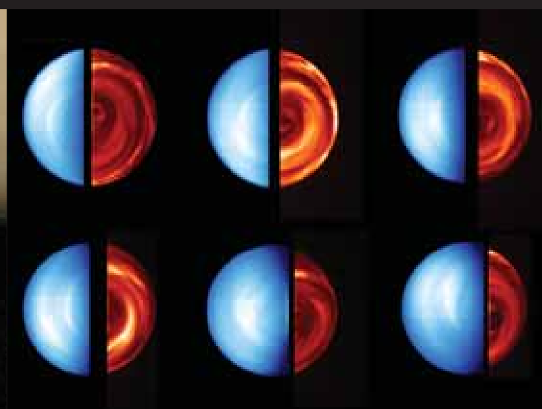
In total, four otherwise doomed missions have been recovered by ESOC, namely TD-1A, Geos-1, Olympus and Hipparcos. Four others were rescued with essential help from ESOC: SOHO, ERS-2, Huygens and Artemis.

The task of operations as conducted from ESOC is now a well-developed discipline involving highly skilled staff in intensive activities both in the preparations phase and in the operations execution phase. The philosophy for the control and operations of various satellites intended to serve the needs of ESA's different spheres of interest is founded on the principles established during more than 40 years' of experience. ESOC is recognised as a leading centre of excellence in Space Mission Operations that is unique in Europe. Conscious of the need to vigilantly maintain its high standards of quality, ESOC has been ISO 9001 certified since 1999.

This extensive expertise allied with the comprehensive and technologically advanced ground segment infrastructure, ensures that ESOC maintains its position as the mission-operations authority for ESA satellites and guarantees that, as such, it constitutes an invaluable resource for the Agency's future space projects.

below and above the Martian surface





Venus Express probing the planet's condition

Preparing the mission

ESOC's involvement normally begins during mission and satellite concept development. This includes the analysis of the type of orbit required, spacecraft design provisions to facilitate the operational tasks and the ground segment facilities required to support the mission. Such involvement continues throughout the assessment phase and the satellite Phase-A studies.

Once a mission has been selected, ESOC is involved in providing operations requirements applicable to the spacecraft Phases-B and C/D; in the formulation of a thorough specification of the ground segment services and facilities needed to support the mission; and in establishing the necessary interfaces for exchange of data and information between the customer and ESOC.

Mission planning requires a team effort

The various units within ESOC then embark on the execution of the preparatory tasks that have to be completed during the period covering the satellite's development, integration and test programme (between three and five years). The culmination of the preparatory phase is the full readiness and availability of all facilities, services and personnel and the 'freezing' of all software systems, hardware and documentation prior to the start of mission operations.

The principal activities to be undertaken by ESOC in the mission preparations phase cover a wide range of disciplines, as described in the following sections.

Mission Analysis

Mission analysis is the term used to describe the mathematical analysis of satellite orbits. This determines how best to fulfil the mission objectives in terms of achievable orbit, launch vehicle, ground station utilisation, operational complexity and lifetime.

These very important aspects are considered by ESOC early in the formative stage of the mission design in close cooperation with the project. The results are then given to the satellite prime contractor as design-driving information. The selected orbit and the derived operations concept have an influence on many aspects of the satellite design, as can be seen from Figure 1.

Different categories of missions require different types of orbit, as shown in Figure 2.

The principal characteristics for each type are as follows:

- Near-Earth orbits (Type 1) have low launch energy requirements and result in short communication distances: they can be reached directly by the Space Shuttle, allowing potential for retrieval and repair. They are, however, subjected to air-drag perturbations and frequent eclipses; periods of direct ground contact are very short.
- Highly eccentric orbits (Type 2) have relatively low launch energy requirements and most of the time keep the spacecraft away from the influence of the Earth. Orbit stability is a potential problem, as is the frequent passage through the Earth's radiation belts.
- Medium-Earth orbits (Type 3) are particularly suited for navigation satellites, typically forming constellations of 24 to 30 satellites distributed among several orbital planes.
- Geostationary orbits (Type 4) are particularly suited for communications satellites, and certain scientific and meteorological applications, but have high launch energy requirements.

Figure 1: Influence of orbit on satellite design
Mission Type will drive: - Launch energy vs. satellite mass - Selection of launch vehicle and orbit injection strategy - Satellite dimensions
Orbit Injection and Control requirements will determine: - Orbit control concepts (mono-bi-propellant/solid fuel) - Number and type of manoeuvres needed - Fuel needed onboard the satellite
Actual Orbit will determine: - Orbital lifetime and stability - Ground station coverage afforded by available stations - Types and positions of attitude sensors - Range of solar input for power generation and thermal control - Eclipse durations and battery requirements - Downlink frequency and RF link margins

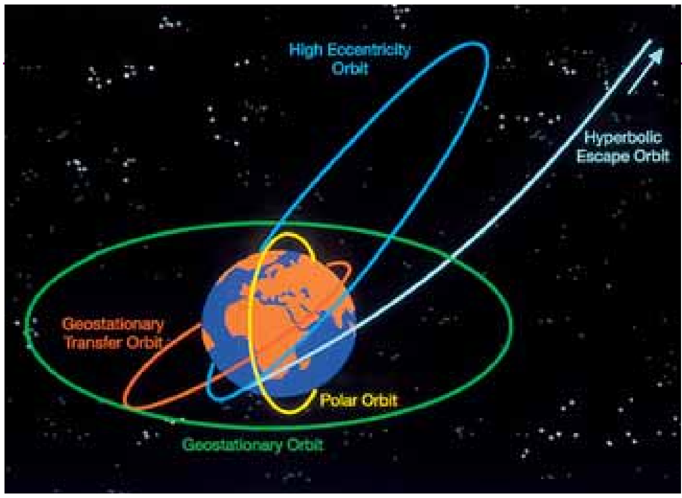
- Orbits near the Earth/Sun libration points (Type 5) can be suited to solar or stellar observation: launch energy requirements are high and communication distances are large.
- Interplanetary orbits (Type 6) have high launch energy requirements (alleviated by gravity-assisted transfer orbits) and tend to result in long-duration missions. Communication distances are very large, as can be the distance from the Sun (which leads to reduced energy for solar power generation).
- Planetary orbits (Type 7) are similar to Type 5: ground station visibility is interrupted by occultation and overall mission complexity is increased.

By no means restricted to selection of the optimum orbit, mission analysis continues throughout the mission-preparation phase, addressing all orbit-related topics, including:

- calculation of seasonal and daily launch windows,
- calculation of mission constraints, including ground-station visibility, eclipse periods, sky visibility and occultations,
- definition of injection strategy and optimisation of orbit manoeuvres,
- performance analysis of navigation system and estimation of propellant budget.

Figure 2: Types of orbit for different missions

Type	Orbit	Mission type	Spacecraft/vehicle
1	Near-Earth Circular Near-Earth Polar (also Sun synchronous)	Science Microgravity Earth Observation	Spacelab Eureca, ISS ERS-1, ERS-2, Envisat, GOCE, Aeolus, MetOp, Cryosat
2	Highly Eccentric	Earth-Science Astronomy	HEOS, Cluster Cos-B, Exosat, ISO, XMM-Newton Integral
3	Medium Earth	Navigation	Galileo
4	Geostationary	Telecommunications Meteorology Science	OTS, ECS, Marecs, Olympus, Artemis Meteosat Geos, (Hipparcos)
5	Earth-Sun Libration Point	Solar Science	SOHO, Herschel/Planck, Lisa, Pathfinder
6	Interplanetary	Solar System Science	Giotto, Ulysses, Rosetta
7	Planetary	Planetary Science	Cassini-Huygens, Mars Express, SMART-1, Venus Express



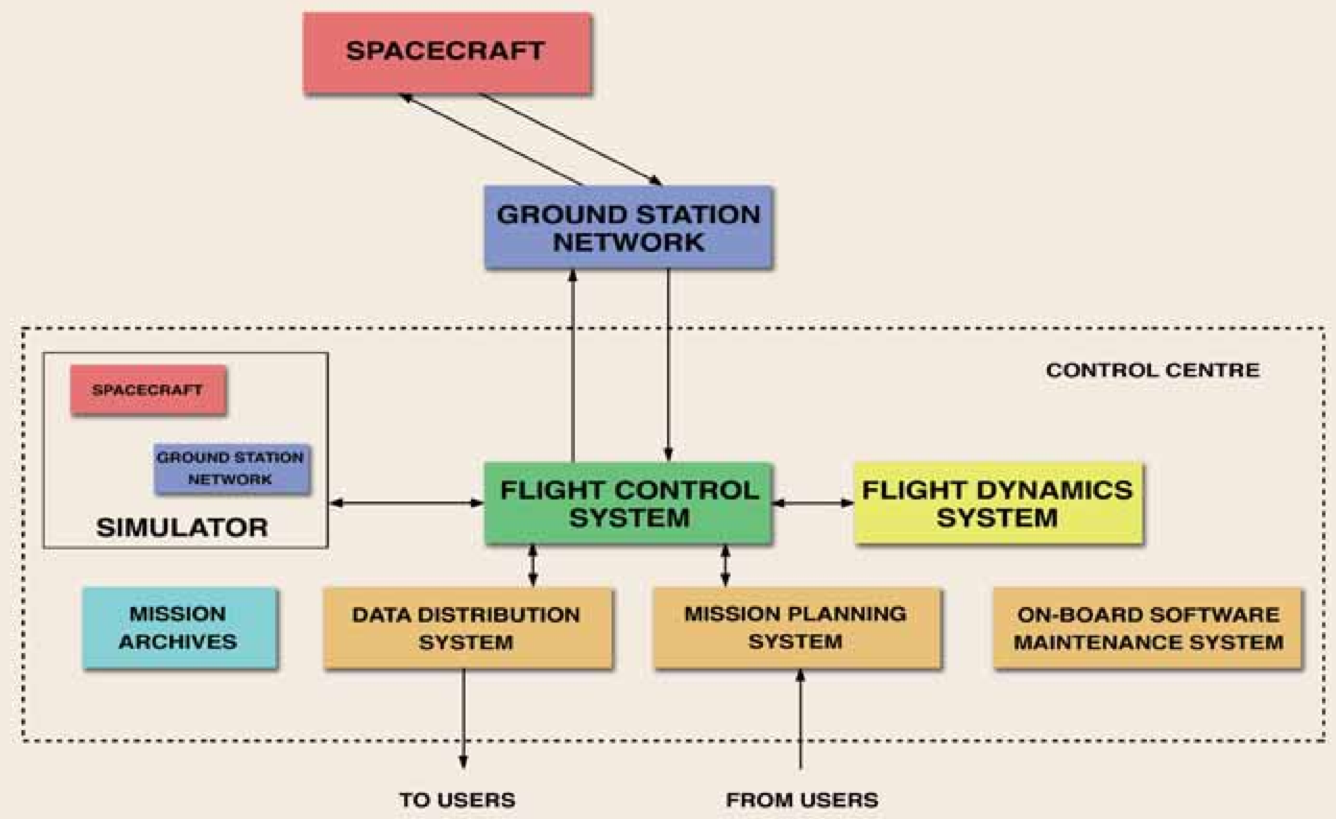
The type of orbit depends on the mission category

These mission analysis tasks are performed with the aid of advanced methods of celestial mechanics, applied mathematics and control and estimation theory. Powerful workstations and a suite of sophisticated software tools and utilities allow in-depth analysis of all aspects of orbits and trajectories. Animated graphical visualisations of particular regions of space, such as the magnetosphere or the radiation belts, or of 3D relationships between the spacecraft, the Earth, the Sun and the planets, are also used to support the analysis and for public relations and educational purposes.

Preparing the Ground Segment

The space segment comprises the launch vehicle and satellite. The ground segment covers all elements, facilities and services needed in support of the mission operations activities on the ground.

Figure 3: Components of a typical ground segment



In the Cluster-2 control room, emergency scenarios are discussed and rehearsed

The major elements of the ground segment to be established include:

- the ground station network to provide the telemetry, tracking and telecommand interface between the Operations Control Centre and the satellite,
- software systems for satellite monitoring and control, flight dynamics, mission planning and data distribution,
- computer facilities to host the software systems and facilities for the maintenance and validation of satellite on-board software,
- the satellite and ground segment simulator,
- Control Centre facilities, including control rooms from which mission operations are conducted,
- communications systems linking all the various elements together.
- the trained Flight Control Team,
- operations plans and procedures, and associated operations databases.

The various components of a typical ground segment are shown in Figure 3.

Operations Preparations

The process of defining the ground segment must go hand in hand with the design and development of the satellite: each mission requires different satellite design characteristics, each of which must have corresponding provisions in the ground segment.

The first step in the process is to formulate the operations concept. This defines the overall scenario for operation and control of the satellite, the payload and the different elements of the ground segment. The detailed specifications for the ground segment will later be based on this work. The different mission phases need to be assessed, as each will place different requirements on the ground segment.

Satellite and payload design information from which ground segment specifications are derived is acquired through the project. The most important source of information in addition to the design specifications, is the satellite user's manual, delivered by the satellite prime contractor. The

The satellite user's manual (shown here for Rosetta and Mars Express) is vital, and a much used source of information

Getting a wave from the antenna maintenance crew

manual provides a thorough definition of the satellite and its subsystems, and defines what has to be done in each mission phase viewed from the operations perspective. It contains sufficient information to enable the operations staff to gain insight into all the internal functions of the satellite and is used to develop the plans and step-by-step procedures to be used by the satellite flight controllers.

The Ground Station Network

The ground station provides the link between the satellite in orbit and the Operations Control Centre (OCC) at ESOC. ESOC has established a network of ground stations (11 antennas) around the world to support ESA missions. Referred to as ESTRACK the network comprises the following locations: Kourou (French Guiana), Maspalomas (Canary Islands, Spain), Villafranca (Spain, 3 terminals) Redu (Belgium), Kiruna (Sweden, 2 terminals), Perth (Australia), New Norcia (Australia) and Cebreros (Spain). The last two, hosting 35 m antennas, are called the European Deep Space Network, which will be complemented with a third station to be built at an American longitude. Each mission has different ground station needs, and some special or collaborative missions call for the services of additional non-ESA stations, like Malindi (Kenya), Svalbard (Norway) and Santiago (Chile), as well as stations belonging to other European agencies or to the NASA Deep Space Network.

Stations at various locations around the world are needed for the different phases of each type of mission. For all missions, it is necessary to have nearly continuous contact with the spacecraft in the first few days of its life (the Launch and Early Orbit Phase, LEOP) so that all the initial critical operations can be performed reliably and, in some cases, so that the spacecraft can be transferred from the injection orbit to an operational orbit.

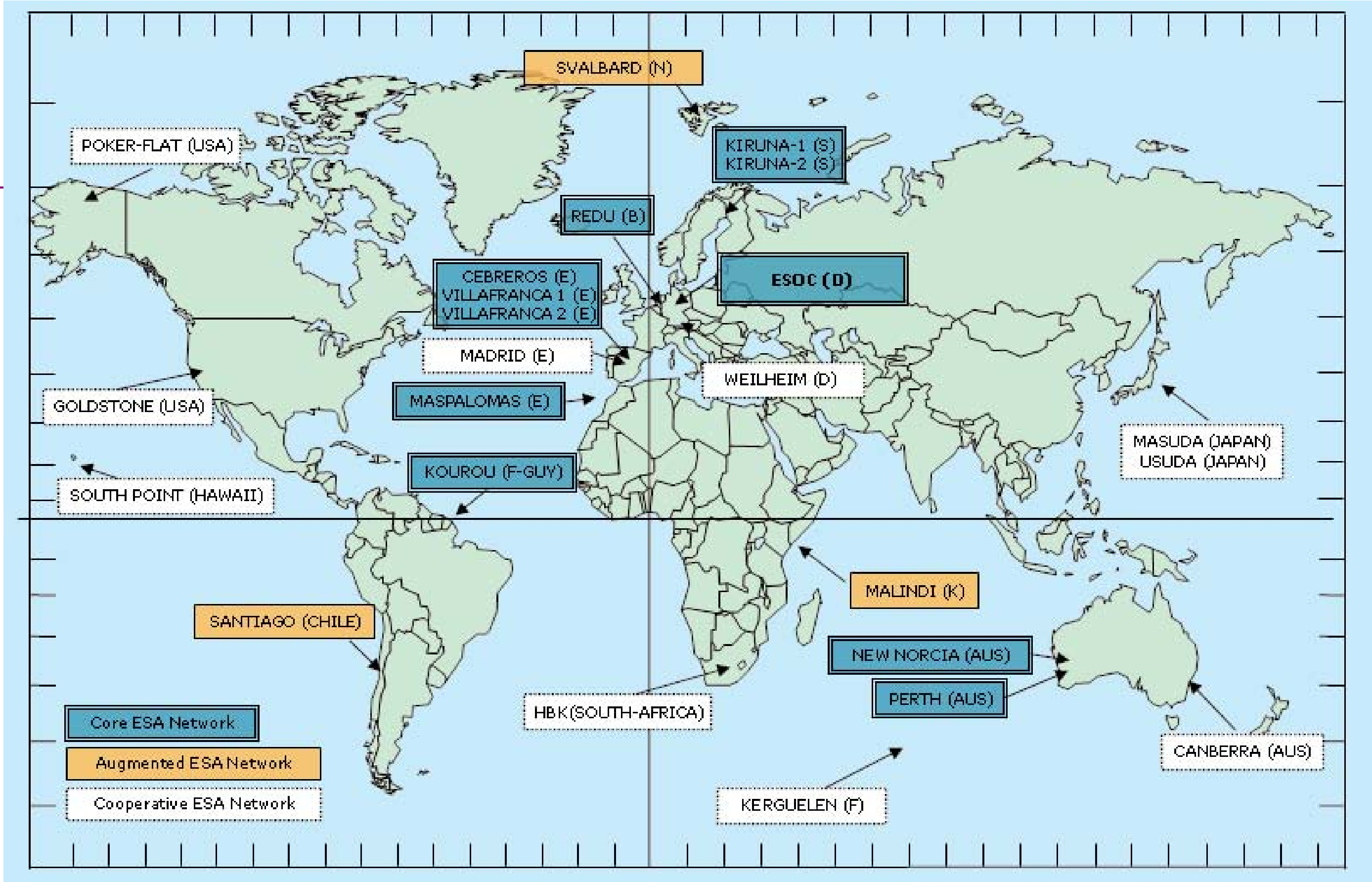
The ESA LEOP stations at Villafranca, Perth and Kourou are ideally placed to provide good coverage, particularly for satellites starting life in a geostationary transfer orbit.

Satellites inserted into polar orbits are best served by stations near the poles, as they see the spacecraft more often than stations near the equator: the ESA station at

Cebreros, Spain

Kiruna, Sweden

New Norcia, Australia

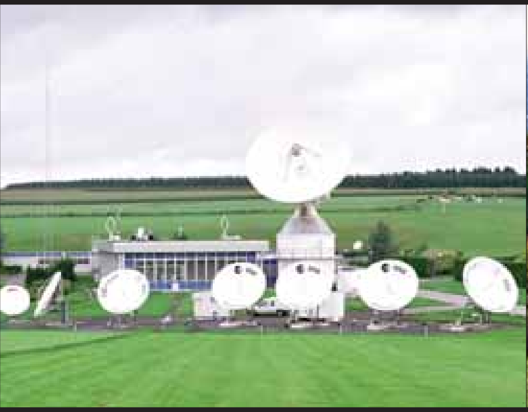


ESA's worldwide network of ground stations

Salmijärvi (Kiruna, Sweden) is particularly suitable. To provide the maximum coverage in the LEOP for polar missions, several stations along the satellite track are needed and additional stations on loan from other agencies are enlisted to join forces.

Ground stations for spacecraft in other orbits are selected with the aim of maximising the periods when the spacecraft is visible from the station. Spacecraft in geostationary orbit, being visible 24 hours a day from points on a particular meridian, pose the least problem, as the station need only be located at or near the appropriate longitude. The ESA station at Redu has been used to serve a number of geostationary missions.

Any station selected to support mission operations will need to be tailored to suit the individual characteristics of the spacecraft in question, and various parts of the station


Redu, Belgium


Villafranca, Spain


Maspalomas, Canary Islands, Spain

Integral and XMM satellite data are processed from this dedicated control room

Figure 4: Characteristics of a typical ESA ground station

Radio Frequency:	
Antenna diameter	15 m
Transmit frequency S-band	2025 – 2120 MHz
Transmit frequency X-band	7145 – 7235 MHz
Receive frequency S-band	2200 – 2300 MHz
Receive frequency Q-band	8400 – 8500 MHz
EIRP	74 dBW
G/T S-band	29 dB/K
G/T X-band	39 dB/K
Telemetry:	
Normal data rate	up to 1 Mb/s
Maximum data rate	up to 105 Mb/s
Standards supported	PCM and CCSDS packet telemetry
Telecommand:	
Normal uplink rate	2 kb/s
Standards supported	PCM and CCSDS packet telecommand
Tracking:	
Range measurement accuracy	1 m
Range rate measurement accuracy	0.1 mm/s

equipment will be engineered to suit the up- and downlink frequencies, data types and other mission characteristics.

Figure 4 shows the characteristics of a typical ESA S- and X-band ground station. The different ESA stations are listed on the previous page.

Flight Control Systems

The facilities employed within the Operations Control Centre for processing satellite telemetry and preparation of the commands needed to carry out mission operations are broadly termed flight control systems. They comprise the software and hardware systems developed for each mission's requirements. Many elements of these systems may be applicable to a range of missions. The process of defining how best to serve the needs of any new project includes consideration of the re-use of parts of existing flight control systems and the extent to which new features are required. It is especially here that the application of standards in operational requirements for spacecraft design results in savings in the cost of developing flight control systems.

The systems used for the interpretation of telemetry and the generation of telecommand messages are database driven. The satellite prime contractor delivers, in electronic format, the information needed to establish the operations databases (ODB). Error-free creation, validation and maintenance of this information are of paramount importance for reliable spacecraft operations.

The flight control systems are designed to perform a multitude of tasks, examples of which are shown in Figure 5. Of particular importance is the need for high reliability in a real-time environment, quick system response, guaranteed availability of data and clarity of information. Special facilities are included to ensure that all commands are

Computer technology support are essential for mission success

Figure 5: Flight control system components and their functions	
Operations Preparation	Preparations and maintenance of the - Flight Operations Plan (FOP) - Operations Database (ODB) - Mission Planning Database.
Mission Planning	Processing of external planning inputs. Generation and validation of satellite operations timelines.
Network Control	Link control between Operations Control Centre and the ground stations for - Telemetry data - Telecommands - Satellite tracking information.
Spacecraft Monitoring	Telemetry reception from ground station. Space-to-ground time correlation. Conversion of satellite telemetry to engineering values. Limit checking and status monitoring of satellite telemetry. Display of satellite data in graphical or numerical form in real time or fast forward/backward mode. On-line access to historical satellite data.
Spacecraft Telecommanding	Generation of command messages for all types of satellite commands. Online or time-scheduled release of commands to the ground station for uplinking to the satellite. Pre-transmission checking of command contents. Post-transmission verification of commanded actions. Logging and display of command history.
User Facilities	Control of user access using a system of privileges.
On-Board S/W	Maintenance of on-board software for the satellite processors. Validation of the software changes before installation on board.
Data Distribution	Distribution of online and offline data to external users (other Control Centres, Data Centres, Research Institutes).
Performance Analysis	Access and retrieval of all historical satellite data. Offline and periodic analysis and visualisation of user-defined algorithms. Generation of operations reports.

correct before uplinking and to watch for errors in the telemetry. The need to process large volumes of data and to manage complex autonomous on-board systems has placed heavy demands on the flight control systems. These are normally run on high-availability, Unix-based, client/server configurations comprising prime and back-up elements.

Many satellite functions, particularly for Attitude and Orbit Control (AOCS) and On-Board Data Handling (OBDH), are implemented in software resident in microprocessors on board the satellite. If any difficulties arise in the functioning of the satellite, it is often necessary to make modifications to the on-board software, for example to compensate for the degradation or failure of on-board equipment (gyros or other hardware) later in the satellite's life. Having responsibility for mission operations means that ESOC must make provision not only for maintenance of the on-board software, but also for operational validation of the modifications. Changes to the on-board software may necessitate changes to elements of the ground segment: these too must be correspondingly modified and operationally validated in a strict configuration control environment to prevent later errors in operations.

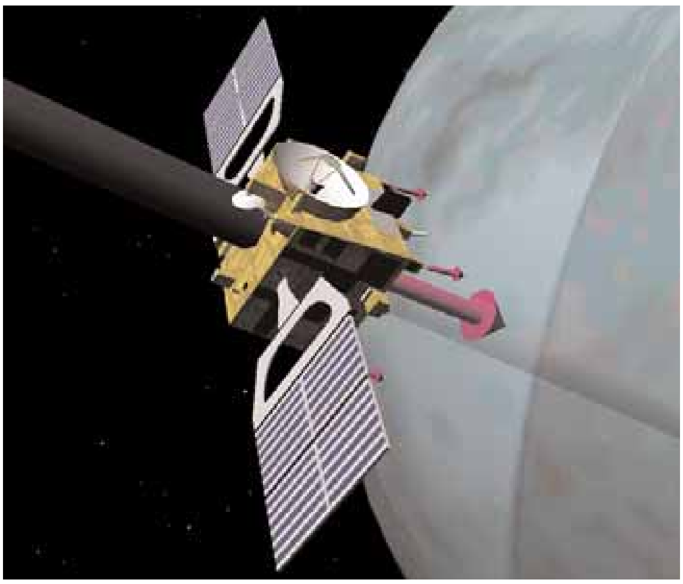
Artist's impression of Rosetta and lander rendezvous with Comet 67P/Churyumov-Gerasimenko

Flight Dynamics Systems

An important aspect of mission operations is satellite navigation, this being the determination, prediction and control of the satellite's orbit or trajectory in space, and the determination and control of its orientation in space, i.e. its attitude. These activities are the domain of ESOC flight dynamics specialists and involve the use of dedicated flight dynamics systems.

In order to achieve the objectives of its mission, each satellite is intended to fly in a predefined orbit. It is the task of the Flight Dynamics Team to refine and put into practice the earlier mission analysis work. One of their first operational tasks in any mission is to determine the characteristics of the initial or injection orbit after the satellite has separated from the launch vehicle and to prepare the information needed to bring the satellite into its final orbit.

The first step is to process tracking data from the ground station and calculate the orbital elements of the initial orbit: detailed knowledge of both the ground station systems and spacecraft systems is needed in this process. It is then necessary to identify how much the achieved orbit differs from the desired orbit and to make the necessary changes to the satellite velocity by performing orbit-correction manoeuvres. The satellite will be equipped with the necessary boost motors and thrusters according to the injection strategy and mission needs.

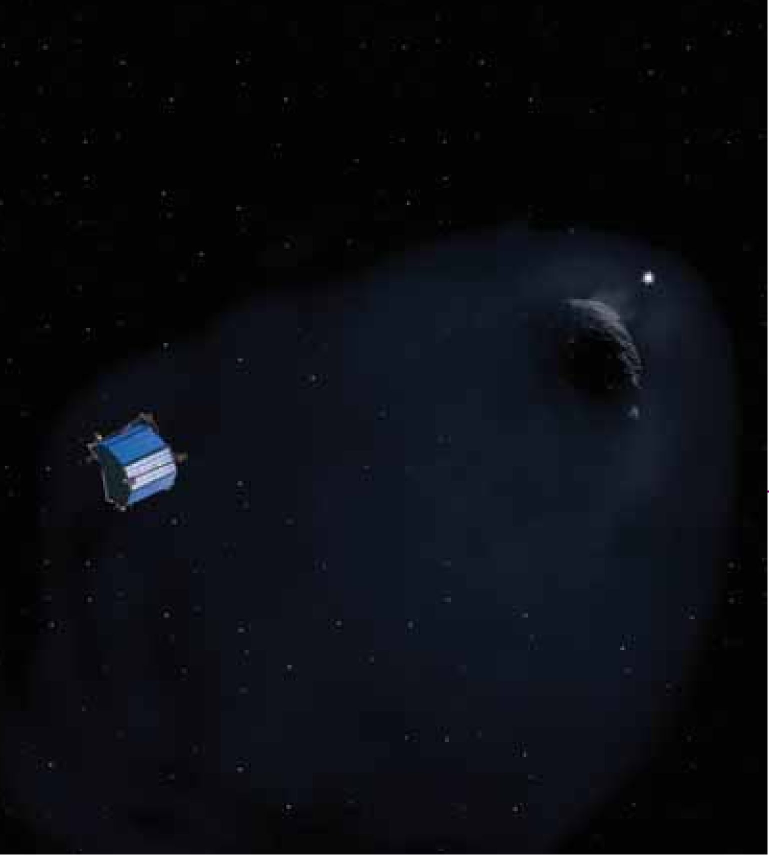


Venus orbit insertion burn

Interplanetary missions may require the implementation of suites of orbit manoeuvres over several years to take them on their journey through deep space to a particular region in space, perhaps swinging by other planets on the way to give the extra boost needed. Missions involving in-orbit docking of one spacecraft to another place high demands on the Flight Dynamics Team and systems.

Orbiting spacecraft are subject to minute perturbations caused, for example, by solar-radiation pressure or resulting from gravitational effects of the Earth, the Moon and the planets. These orbital perturbations add up over time and must be counteracted by regular execution of small orbit-correction manoeuvres throughout the mission. For a geostationary spacecraft, this is known as 'station-keeping' and is necessary to keep the satellite within a specified latitude and longitude 'box' having dimensions of some small fraction of a degree.

The orbit of the European Earth observation satellite, Envisat, takes the spacecraft over the same locations on Earth at regular intervals. At its altitude of about 800 km, the atmospheric drag slowly reduces the height of the orbit and upsets ground track repetition. Since the extent of the drag depends on the density of the atmosphere, it is necessary to take forecasts of solar activity into account in the planning of orbit manoeuvres.

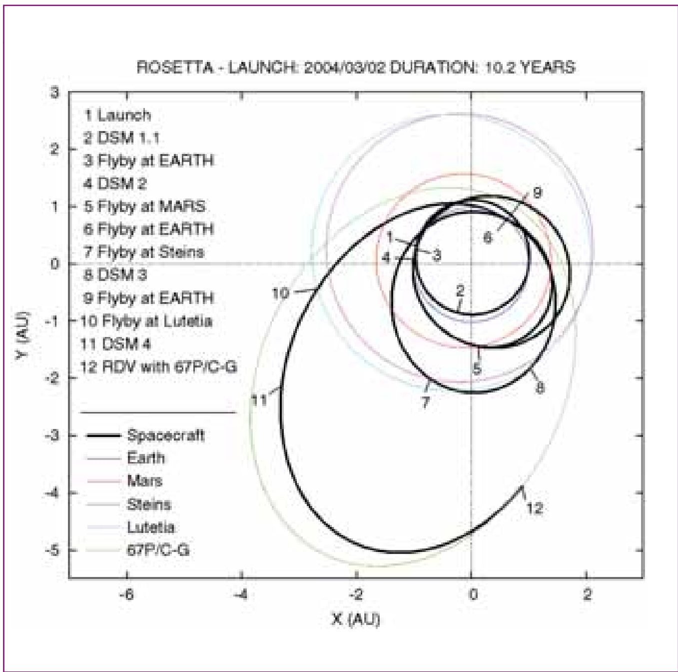


Attitude sensors mounted on board the spacecraft provide information on satellite orientation. Some are designed to identify the relative direction of the Sun or the Earth, some to identify a pattern of stars in the sky (star trackers), and others to measure the rate at which the attitude is changing. Using advanced numerical estimation techniques to analyse this information, the flight dynamics system is able to determine the satellite's attitude to a high degree of accuracy, often within tens of seconds of arc, and to pass the results to users of the satellite data in support of their analysis.

While the satellite trajectory in space must be monitored, it is also necessary to ensure that the satellite body is correctly oriented. Sensitive instruments on scientific satellites must be pointed towards selected stars or nebulae but kept averted from the strong radiation emanating from the Sun or the Earth. It may be necessary to make hundreds of observations of different objects, the satellite pointing direction moving from one to the next in rapid succession. On the other hand, antenna dishes on telecommunications satellites need to be pointed constantly towards the Earth for several years.

Changes to the attitude are effected by means of actuators such as reaction wheels and thrusters on board the spacecraft. The information the spacecraft needs in order to execute each manoeuvre is prepared with the aid of the flight dynamics system and may include thruster firing data, data to adjust the attitude sensors and data to control on-board safety measures, such as Sun avoidance. This information is passed to the spacecraft in the form of telecommands constructed by the flight control system and transmitted by the ground station.

Flight dynamics specialists prepare the information needed to bring a satellite into its precise orbit



Rosetta's complex set of orbital manoeuvres

The progress in executing manoeuvres is carefully observed in real time to monitor the correct operation of the on-board systems and to ensure spacecraft safety at all times.

Like all intricate systems, the satellite equipment used for attitude and orbit measurement and control must be calibrated. Estimates of sensor alignment, drift and bias errors are needed in addition to estimates of individual thruster performance. As these calibration parameters are likely to vary with time, it is necessary to perform regular calibration activities throughout the mission. Calibration data is also needed to enable records of on-board fuel expenditure to be kept, so that the remaining useful life of the satellite can be predicted.

Figure 6: Flight dynamics system components and their functions

Altitude Determination and Control	Processing of telemetry data Attitude estimation Attitude manoeuvre preparation Angular momentum and fuel budgeting
Calibration	Actuator and thrusters performance and alignment calibration Optical sensor performance and alignment calibration Gyro calibration
Orbit Determination and Control	Processing of tracking data Calculation of orbital elements Prediction of ground station visibility, eclipse times, etc. Preparation of station antenna pointing estimate Orbit manoeuvre preparation Fuel budgeting
Mission Planning Support	Generation of orbit-related planning information Preparation of attitude and orbit-related inputs into mission plans Prediction of angular momentum and fuel budgets
Auxiliary Data Generation	Generation of attitude history data Generation of orbit-related data Generation of spacecraft-related calibration data
Quality Assurance	Independent system validation Supervision of all flight dynamics performance and quality Verification of flight dynamics performance and quality

The Ground Operations Manager waits for 'green' in the Main Control Room of the OCC at ESOC

ESOC's experience in flight dynamics is unsurpassed in Europe and is dependent on the skills of highly trained staff and the development of sophisticated flight dynamics systems. Like other ground segment facilities, the flight dynamics system needs careful preparation and has to be tailored to the requirements of each new mission, a task made easier by the introduction of a mission-independent software infrastructure ORATOS (Orbit and Attitude Operations System). The major components and functions of typical flight dynamics systems are set out in Figure 6.

Operations Control Centre Facilities

In addition to the software and hardware systems established for the performance of mission operations, it is necessary to provide a range of support facilities. This includes the control rooms in the Operations Control Centre and communications networks linking the various internal and external computer systems. The various control room facilities at ESOC include:

– the Main Control Room, used for the conduct of operations in the early phases (LEOP) of a mission (as shown below),
– the Flight Dynamics Room,
– the Project Support Room, in which staff from the project and industry are accommodated while they provide on-site consultancy during the LEOP,
– the Dedicated Control Room, from which operations are conducted in the later routine phases of the mission,
– the Ground Configuration Control Room, where operators oversee and configure the links and systems for data and command routing between the ground stations and the OCC. Ground station operations are remotely conducted from here.

ESOC has also established further specialised control centre facilities at the following ESA sites:

– the Science Operations Centre at the European Space Astronomy Centre (ESAC) near Madrid,
– Redu, located in the Ardennes region of Belgium.

One further important aspect is the establishment of facilities to allow reliable round-the-clock communication between each station in the ground network and the OCC for telemetry, telecommands and voice and data traffic. ESOC has set up and maintains a communications network to complement the ground station network and provides facilities for other communications needs covering, for example, links between the different ESA sites and their working partners in industry, at research institutes and at other Agency sites.

Operations staff rely on a satellite simulator to realistically validate all aspects of satellite operations

Ground Segment Integration and Validation

In order for the whole ground segment to work correctly, a thorough and systematic series of tests must be carried out at all stages of ground segment integration.

This activity extends over a period of many months during the latter stage of the preparations phase. It requires the services of a team of experts in ground segment integration and testing. This team must first define a comprehensive test plan and then execute the plan step by step.

Satellite Simulators

The single most important tool for the validation of the ground segment systems, operational databases and flight control procedures is the so-called 'satellite simulator' (Figure 7). The simulator is itself a sophisticated software system modelling the satellite in such a way that when connected to the flight control systems, it enables operations staff to exercise all satellite operations in a highly realistic fashion.

Developed by the Simulator Group at ESOC, the sources of information for simulator developers are the satellite specifications, the detailed design documents and the requirements documents for on-board software. The simulator is built up around reusable modules, with additional modules to represent the specific features of the mission in question.

The Simulations Programme

The simulations programme is conducted at the end of the preparations phase. Its purpose is to enable all planned operations to be exercised in a realistic environment and for the operations staff to be trained to work together as an efficient Flight Control Team well versed in both nominal and contingency operations.

ESA engineers, scientists and support staff are dedicated to space operations activities...

Figure 7: Major features of a scientific satellite simulator

Element	Modelling
Satellite Subsystems	Fully representative hardware, software, mechanisms, pyros, motors, appendages, etc. Realistic telemetry in all modes Correct command responses
On-Board Software Systems	Hardware emulation Executable on-board software
Satellite Dynamics	Satellite mass properties Attitude manoeuvre execution Attitude sensor fields of view
Satellite Environment	Orbital motion and orbit manoeuvres Eclipse and thermal inputs Ground station and contact periods Star catalogues (including planets)
Network Interfaces	Ground stations Communications
Simulator Control	Faster than real time Operator-injected anomalies Simulator monitoring Command/telemetry replay facility

Typical cases to be exercised include:

- pre-launch phase interactions with the launch site (e.g. Kourou, Baikonur) through to lift-off and spacecraft separation,
- spacecraft separation through to establishment of 3-axis spacecraft control,
- spacecraft attitude and orbit manoeuvres and related calibration,
- spacecraft subsystem check-out,
- instrument switch-on and check-out,
- routine operations, including perigee exit, start of observations, eclipse, perigee entry, etc.

Strong emphasis is placed on the execution of both nominal and contingency operations. Anomalies defined by the Simulations Officer are not known to those taking part, but are injected into the simulation to create the desired realism and to train operations staff in anomaly identification and recovery procedures. Simulations are also a means of proving the mission documentation and operational procedures, and in ensuring that the ground segment performs as required. Such simulations have in the past brought to light satellite design problems that had not been identified in the satellite integration and test programme.

At the termination of the simulations programme and after several years of mission preparations, the Flight Control Team is ready and eager to take on its responsibilities in the execution of mission operations.

Conducting mission operations

Establishing Contact with the Spacecraft

Contact with the spacecraft is necessary for the day-to-day execution of the mission operations and is established when the spacecraft passes over a suitable ground station. A suitable station is one which has been tailored to interact with the spacecraft in question.

Unless it is in geostationary orbit, where it will appear to stay in a fixed position in the sky, the spacecraft will generally rise over the horizon and become visible from the station. In anticipation of the upward path, the station will have moved its antenna in azimuth and elevation towards a direction predicted on the basis of the determination of the orbit. As soon as the spacecraft appears, the station will lock on to its radio signal and start to track its movement in the sky automatically: should the signal be disturbed, the antenna will continue to track according to a predicted satellite path (also derived from the known orbit).

Soon after locking on to the radio signal, the ground station will be able to demodulate and decode the telemetry and route it directly to the Operations Control Centre giving the operations staff the data they need to assess the health of the returning spacecraft. At this point, the ground station transmits a radio carrier signal to the spacecraft: in order to ensure that the on-board receiver locks on to the uplinked carrier and to compensate for the Doppler effect caused by the rapid motion of the spacecraft, the uplink frequency is made to sweep around the nominal value. After the end of this sweep and with confirmation in the telemetry data that

Waiting for post-launch satellite acquisition in the Main Control Room

the on-board receiver is in uplink lock, the ground station is ready to uplink any commands received from the OCC.

All telecommand request messages received from the OCC are checked by the station telecommand equipment and transmitted to the satellite by modulating the RF carrier. While commanding and receiving telemetry, the station may make range and range-rate measurements, to be passed to the Control Centre for orbit determination.

Throughout the period of contact (the pass), the station will continue to track the spacecraft in the sky and provide the telemetry and command services to the OCC. For local safety reasons, the uplink service will be terminated when the elevation of the ground station antenna falls to 5 degrees above the horizon on the downward path. As the spacecraft finally approaches and falls below the horizon, telemetry contact will be lost, marking the end of the pass.

The Launch and Early Orbit Phase

The launch vehicle authority is responsible for the actual launch and management of the launch vehicle carrying the spacecraft into orbit. ESOC takes over responsibility for mission operations at the moment the satellite separates from the launch vehicle in the phase referred to as the Launch and Early Orbit Phase (LEOP), when the first ground contact with the satellite is established.

German Chancellors show their appreciation for ESA's Control Centre

This phase is critical, as activities must be performed under strict time constraints for the purpose of setting up the spacecraft for full operations in orbit and include deploying mechanical parts such as solar panels and antennas, which are normally held in a folded position during the launch. It is also necessary to move the satellite from the launch vehicle injection orbit into the orbit selected for routine operations. Other time-critical operations involve setting up the on-board conditions needed to determine and control satellite attitude and to configure it for the tasks to come.

The LEOP activities are conducted by an extended Flight Control Team headed by a designated Flight Operations Director, who is responsible for direction, coordination and conduct of the mission operations. The Flight Control Team is supported by teams from the project responsible for satellite development and the specialists from industry. This ensures that all necessary expertise is on hand during execution of the LEOP operations.

The Flight Control Team is made up principally of specialists in satellite operations and in flight dynamics who perform their tasks with the aid of workstation facilities in the Main Control Room (MCR) of the OCC, providing round-the-clock support for the duration of the LEOP. The key players in the Flight Control Team include the

Spacecraft Operations Manager, the Ground Operations Manager and the Flight Dynamics Coordinator.

Each manages the activities of a specialised team of fully trained staff in order to conduct all planned operations and to recover from any unforeseen situations arising with the newly operating spacecraft and the associated ground segment.

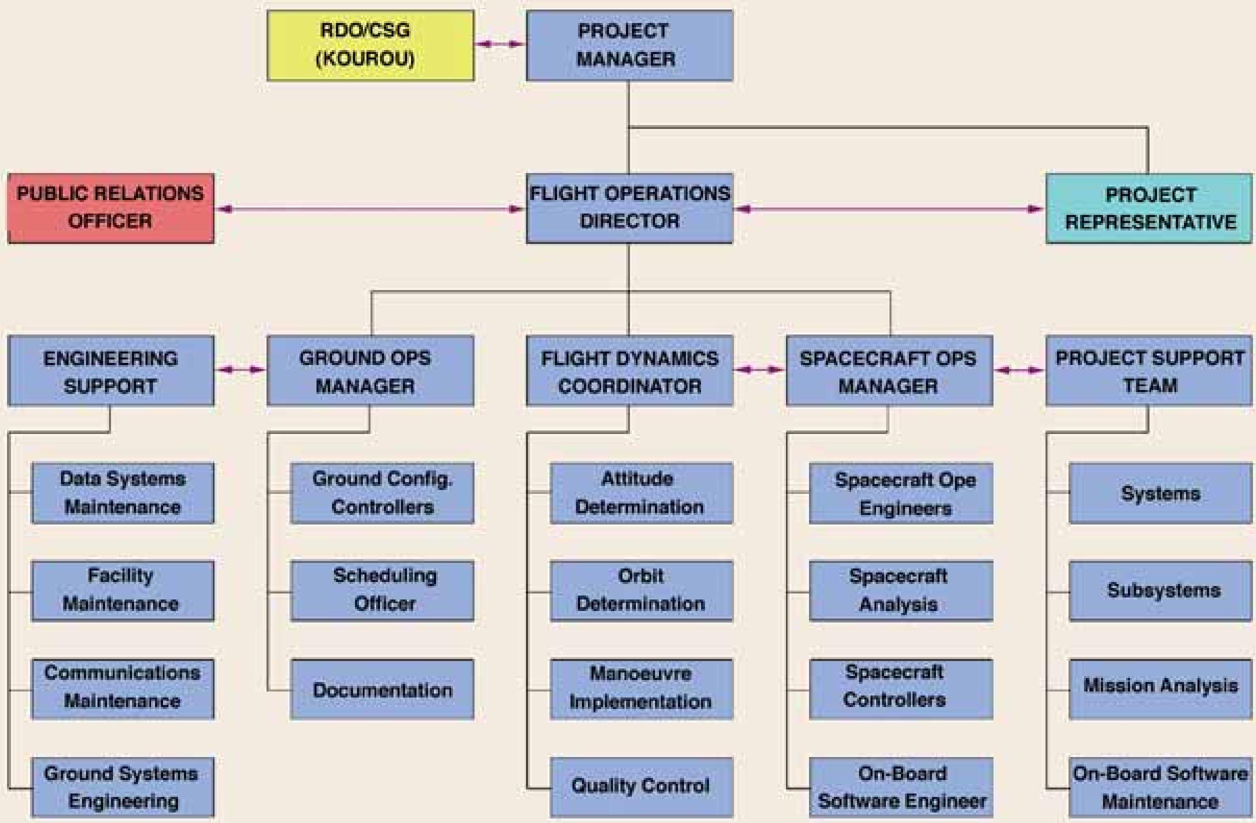
The Flight Control Team is augmented by a range of service support personnel responsible for computer hardware and software, communications and ground station equipment, Control Centre facilities and general services staff. All provide round-the-clock support during this phase. Figure 8 shows the breakdown of a typical Flight Control Team during the LEOP.

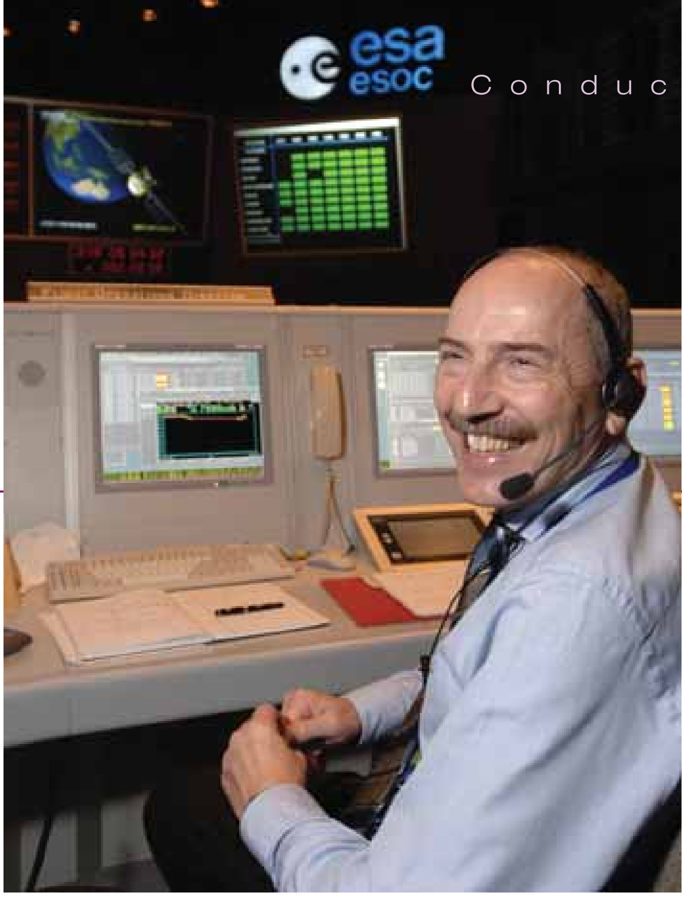
Once the milestones of the LEOP have been passed (i.e. achievement of the required orbit, deployment of satellite appendages and initiation of payload operations), the LEOP is terminated and a reduced operations team moves to the Dedicated Control Room (DCR) for continuation of operations in the subsequent phases of the mission, in which satellite and payload commissioning or even deep-space travel may be undertaken.

Planning Routine Operations

Once the early orbit phases have been completed and the satellite has been fully checked out in orbit, the routine operations phase commences, in which the satellite is operated in the way intended to provide the services or

Figure 8: The Flight Control Team during LEOP





The Flight Operations Manager is thrilled with a successful LEOP of Venus Express

products required. This phase is one in which all activities have to be planned and executed in an orderly and dependable fashion.

The planning process needed depends on the type of mission and the way satellite control is to be performed, but will often involve the formulation of operations plans some weeks ahead of schedule and covering several days at a time. These operations plans must not only take account of requests for the execution of specific tasks, for example radar imaging of a particular region of a planet's surface, they must also take account of the constraints associated with operation of the satellite. These constraints may take the form of limitations on available power under certain conditions, restrictions on available on-board storage of telemetry data, or restrictions on which directions the satellite is permitted to point in as it moves around the orbit. Any conflicts identified in the planning process must be resolved by rescheduling and regenerating plans.

The planning inputs are derived from requests made by members of the user community, by external bodies or by the operations staff themselves. In addition to the user-oriented activities, it is necessary to plan for the conducting of all satellite operations that are needed for orbit and attitude control, satellite health and safety maintenance and any other related operations activities. These must all be incorporated into the overall plan for the whole satellite and for the period in question.

Once the operations plans are established, they must be converted into the appropriate telecommands for uplinking to the spacecraft at the appropriate time.

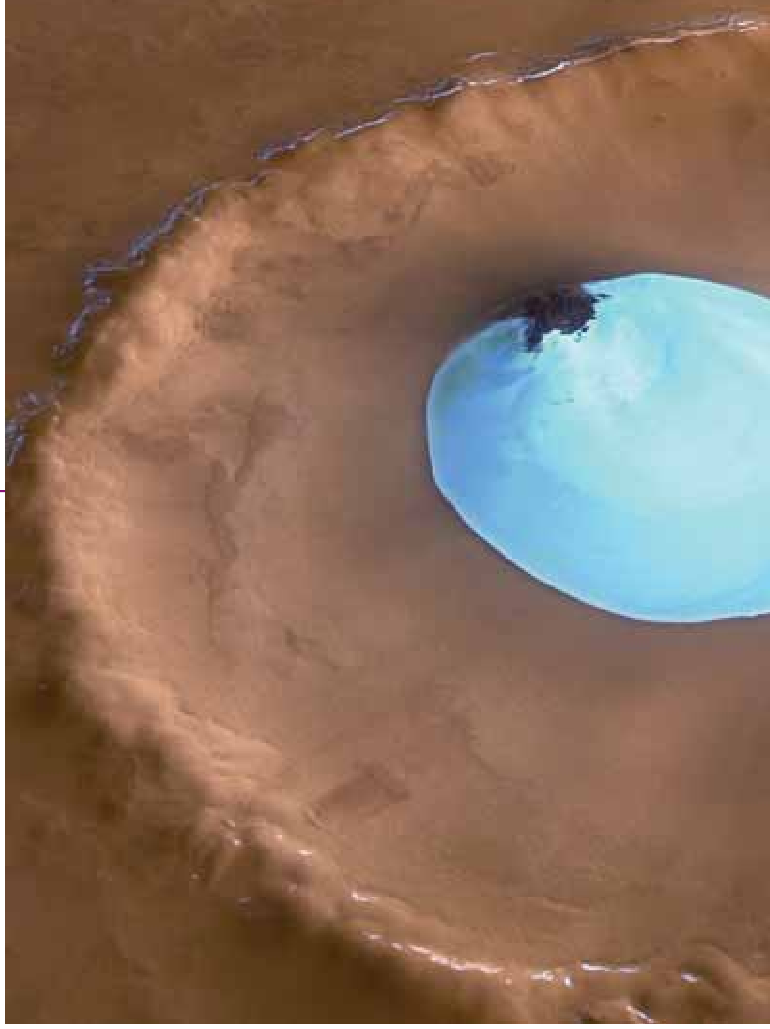
Routine Satellite Operations

Routine satellite operations are conducted by telemetry and telecommand interactions between the Control Centre and the satellite according to the operations concept devised during the satellite and ground segment development phase (Figure 9). The extent of these interactions is dependent on the following:

- the type of mission (Earth observation, astronomical observatory, deep space, etc.),
- the type of orbit (low Earth, highly elliptical, etc.),
- the extent to which ground contact is available (number of stations and visibility afforded),
- the provisions made on board the spacecraft for command execution and telemetry delivery to the ground,
- the complexity of the activities to be performed.

An Earth-resources satellite (such as Envisat) in a low polar orbit is typically only visible for a ten-minute period in each of ten out of fourteen orbits (of 100 minutes each). When out of contact with the ground, such a satellite must be able to execute complex operations and to store the telemetry data on board. In such a case, the Control Centre must define all instructions for the upcoming orbits in advance, in the form of a schedule. The schedule is then loaded on board the

An engineer in the Venus Express control room receives the status report from the ground station



Residual water ice in Vastitas Borealis Crater - as seen by Mars Express

satellite for later timed execution. Each time the satellite passes over a suitable ground station, the Control Centre loads more instructions into the schedule and commands the satellite to downlink the data it has stored since the last pass. The operations concept for such a mission can be characterised as requiring:

- a high degree of operations planning,
- production, uplinking and execution of an on-board schedule,
- storage and dumping of satellite telemetry,
- a high degree of autonomous on-board safety monitoring and control.

A satellite in deep space, on the other hand, may be visible from the ground for up to ten hours per day on some days and perhaps not contactable for days or weeks in between. A further complication is the time taken for commands to reach the spacecraft and for the telemetry to return to Earth; potentially up to one or two hours, travelling at the speed of light. In such a case, the operations concept would be analogous to that for Envisat, employing an on-board schedule and on-board data storage. Such a satellite would also be able to take care of its own safety during the months of deep space flight. This may entail the autonomous switching of heaters to maintain equipment temperatures or the detection of faulty equipment and switching over to spare units. It may even involve an autonomously controlled series of manoeuvres to re-establish contact with the ground after some on-board or ground failure. The OCC's role in this mission would be to prepare all necessary instructions for these and other on-board autonomous functions, involving often complex analysis and modelling. In comparison with the more exotic missions, a satellite in geostationary orbit offering twenty-four hour coverage, permits a much simpler operations concept.

Whatever the concept for satellite operations, the Operation Control Centre's task is to perform all necessary operations according to the mission's needs.

Figure 9: Outline of routine operations for the XMM spacecraft

Start of Pass Activities:
- Acquire satellite telemetry and confirm satellite health and status
- Start the uplink and commerce ranging measurements
- Determine spacecraft attitude with the aid of star tracker data
- Adjust satellite temperatures and monitor telescope thermal situation
- Monitor on-board power situation and charge batteries if necessary
- Set up instruments for start of observations (processor loads)
- Calibrate attitude sensors
- Load instructions for satellite and instrument safety monitoring and control

Science Observations:
- Start sequence of attitude manoeuvres for planned observations (new pointing direction every few hours)
- Change instrument settings for each new pointing
- Monitor satellite attitude and angular momentum
- Perform instrument calibrations
- Switch from one on-board antenna to another in order to keep contact (if necessary)
- Route science data to Science Centre

Before end of Pass:
- Switch instruments into sale mode (to avoid saturation in Earth radiation belts)
- Manoeuvre satellite to safe attitude for perigee passage (to avoid Earth)
- Set up power system for eclipse operation (battery discharge)

Mission Services and Products

The goals of any science or application mission are to make scientific observations or other measurements from space and to analyse and study the results. Final processing of the telemetry data may be the responsibility of ESOC, or an external data centre. It may, alternatively, be the responsibility of a small group of specialists or of individual researchers within the science community. Whatever the final

Figure 10: Examples of mission products	
Mission Product	User or Processing Authority
ERS Synthetic Aperture Radar Images	Fast delivery products: Kiruna Ground Station Final products: P.A.F.s (National centres)
Envisat	Payload Data Segment at ESRIN Principal Investigators in Europe
Mars Express	Payload Support Team at ESTEC Payload Operations Service Team at the Rutherford Appleton Laboratory in Chilton, UK Principal Investigators in Europe and USA
Integral	Science Operations Centre at ESAC Integral Science Data Centre (ISDC) Geneva, Switzerland
Cluster Instrument Science Data	Quick look: Joint Science Operations Centre, UK Final: Principal Investigator institutes in Europe and USA
XMM-Newton	Science Operations Centre at ESAC
Meteosat Images	ESOC (before 1996) EUMETSAT (after 1996)

destination, it is ESOC’s task to provide a maximum amount of good-quality data to users in the form of mission products.

In years gone by, data products were delivered on magnetic tapes by mail. Nowadays, users can receive their data on DVD or across local or international communications links. Users today are able to access product stores via the Internet in order to request and download products of their choice along with the tools needed for product analysis.

Figure 10 gives examples of mission products and the user responsible for final processing.

External Services

The framework of ESOC's third party activities is the 1998 Council Resolution authorising the Director General to offer ESA's spare flight operations capacity to commercial and institutional customers. Services offered by ESOC involve the utilisation of ESA flight operations facilities and/or personnel.

Their main objective is to add value in supporting and responding to requests from industry, often in cooperation with national space agencies such as CNES, DLR or ASI. Although ESOC offers, in principle, spare capacity in providing these services, any additional facilities required for a particular service can be funded by the customer or procured via cooperative agreements.

Quality Management

Ever conscious of the need to ensure customer satisfaction with the services it provides, ESOC has established a process of quality management and continuous quality improvement.

The ESOC Quality Management System encompasses all activities of the Centre, ranging from early negotiation of possible operations services through the whole mission preparations phase, and during the mission operations execution phase, including mission termination.

The procedures within the quality management system address contractual activities, ground segment development cycle, anomaly identification and resolution and reporting.

ESOC achieved full ISO 9001 certification in November 1999 and is committed to a programme of continuous self-evaluation and improvement.

Beyond the nominal mission

Recovery from Unexpected Events

It is the task of the Operations Control Centre to maximise mission return and to ensure the safe and reliable conduct of all mission operations. Not all operations progress smoothly, however, and in the harsh environment of space unexpected events sometimes occur. Considerable effort is invested in the preparations phases to minimise possible sources of failure, both on the satellite and in the ground segment, and to prepare procedures and plans for recovery if they occur during the mission.

Using automated features of the flight control systems, operations staff monitor for unexpected events in the satellite telemetry as it arrives at the OCC. The status or values of all important telemetry parameters are checked against a set of predefined limits, and audible alarms will sound if any out-of-limit value is found. The out-of-limit value may simply indicate a slowly increasing temperature of little concern, but it may equally indicate a serious on-board equipment failure, such as an error in the execution of a command or the malfunctioning of a microprocessor.

For every alarm raised, the spacecraft controllers will identify the anomaly and take the necessary recovery actions, using procedures defined in advance. They will have been regularly trained in recovery from anomalies (using the satellite simulator), so they will know how to spot them and what to do. If a new recovery procedure needs to be devised for a complex unforeseen anomaly, it will be developed and exercised on the simulator before the operation is attempted on the spacecraft itself.

Hardware failures on board can result in a need to change the way the spacecraft operates, for example if a gyro fails to provide attitude rate information. In such instances, it may be possible to compensate for the failure by redefining some of the on-board control algorithms and defining new on-board software to do the job. All changes in the on-board software will be fully validated – again with the aid of the simulator – before being loaded on board.

Anomalies are not restricted to the satellite, the ground segment is also subject to occasional errors and failures. The operations staff must be equally well versed in recovery from failures in the ground equipment, such as the ground station antenna motor or data links to the ground station, as well as damage caused by the weather (electrical storm, wind, flood). The first concern in such circumstances is to ensure that the spacecraft is not in danger and to resume normal operations as soon as possible, by means of backup equipment.

In rare cases, the unexpected event turns out to have a major impact on the ability to continue with the mission as

ESOC experts have rescued/redefined several satellite missions

Mission impossible?

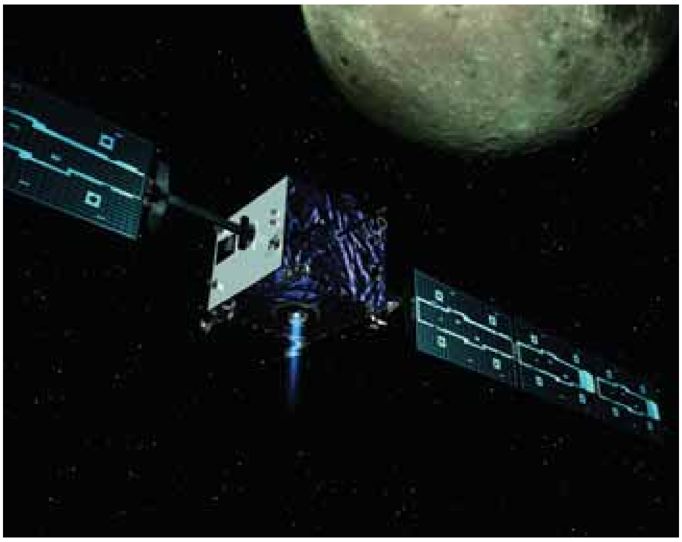
originally foreseen, and it becomes necessary to embark upon a major recovery effort, identifying new ways of rescuing the satellite or defining a means of salvaging the mission. Time is of the essence here, as the spacecraft can degrade further while the rescue plan is being developed. ESOC has been faced with and has met such challenges several times in the past.

Satellite Rescue

One of the many missions for which ESOC has had a successful recovery is the telecommunications satellite Olympus. Within 2 years after launch, premature degradation of the spacecraft made its operation (from the Italian Space Agency site in Fucino) increasingly more complicated. Due to a series of anomalies, the spacecraft unexpectedly began to tumble and to drift out of contact with the ground. Within one week there was virtually no telemetry, no telecommand capability and only marginal, fluctuating power.

ESOC was called upon to establish a rescue plan: a team of some fifty operations and satellite specialists was assembled to devise and implement what was to be a very complex plan. The services of additional ground stations (including those of CNES and NASA) were drafted in and ESOC

Engineers redefine Giotto spacecraft for a second comet encounter



The SMART-1 mission was terminated by a planned and controlled crash into the Moon

facilities were expanded to assume mission control. After weeks of intensive and extremely critical operations, and after the uplinking of several thousand telecommands, the spacecraft was moved back to its nominal orbit and soon afterwards resumed normal operations. ESOC had been able to bring the crippled spacecraft back to life!

Mission Redefinition

Hipparcos, a scientific satellite dedicated to extremely precise measurements of star positions, distances and space motions, was launched in August 1989. The transfer-orbit operations proceeded smoothly until the moment when the apogee boost motor was instructed to ignite. Owing to a failure in both pyrotechnic chains, ignition failed to take place and the spacecraft was unable to move out of its transfer orbit. Consequently, a significant proportion of the Hipparcos flight operations had to be rewritten.

The implementation of a revised mission allowed scientific data collection to start less than four months after launch. At first, the data recovery rate was about 50%, but this later increased to 65% after the optimisation of operations procedures. Despite the successive failure of four of the five gyroscopes and numerous other anomalies, largely attributable to the severe radiation levels, the Hipparcos mission lasted four years – 18 months longer than had been foreseen for the original, nominal mission. Plus it had accomplished all its scientific goals.

In the case of Giotto, ESOC was faced with the challenge of defining a second comet encounter mission for an already orbiting satellite. Launched in July 1985, the scientific spacecraft was designed for a nine-month interplanetary journey to a high-speed fly-by of Comet Halley. This mission was successful and, contrary to expectations, the satellite survived the hyper-velocity dust impacts around closest approach to the comet. Despite structural damage, radical changes in thermal behaviour, instability in the power control system, a punctured star-mapper baffle and the loss of many autonomous functions, the spacecraft was still operable.

A further mission had not been planned for, so in order to keep most options open, Giotto was placed on an Earth-return trajectory and put to sleep. After four years in hibernation, Giotto was reactivated. Re-establishing communications, an operation never before attempted, had to be achieved blind, with no telemetry and with Giotto at a

ESOC offers services and software to ...

Checking spacecraft software parameters

distance of 100 million km from Earth. Check-out of the spacecraft revealed that about half the scientific payload was still working, but on-board redundancy had been further reduced by two failures of vital spacecraft units.

Comet Grigg-Skjellerup was chosen as the next target, being the best compromise between scientific interest and operational feasibility. ESOC took Giotto on to make the first-ever Earth gravity-assist swing-by for a spacecraft returning from deep space. It was put into hibernation a second time, survived extremes of high temperature and was reactivated again two years later. At the second encounter, in July 1992, Giotto approached to within 200 km of the cometary nucleus and once again yielded more unique and valuable scientific data.

... the scientific community, academia and industry

Mission Termination

A spacecraft is designed to fulfil the mission objectives for a defined period of time, ranging typically from two years to ten years or more.

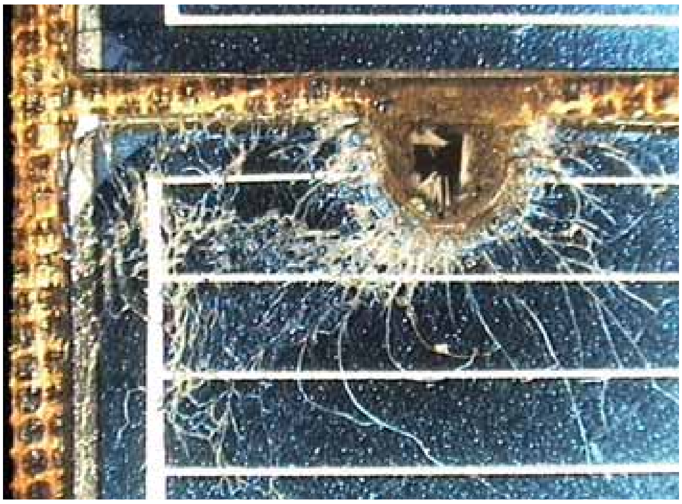
Mission operations will continue while the spacecraft and its payload are fulfilling the mission objectives. If the resources needed on board (power, fuel) become depleted, or if failures of on-board equipment occur, making operations more and more difficult, then mission termination has to be considered.

In some cases, mission termination can be unexpected and dramatic, but normally termination is planned. Quite often, a series of end-of-life tests is performed, for example on spacecraft mechanisms. If possible, the spacecraft is boosted several hundred kilometres into a so-called graveyard orbit where it poses less of a risk to other orbiting satellites or to the space environment. For the OCC, a mission is deemed to have terminated when ground contact with the spacecraft is finally and permanently terminated, whatever the fate of the spacecraft.

ESOC expert services

Space Debris

Space debris is a term used to describe the ever-increasing amount of inactive space hardware in orbit around the Earth. It is the collection of burnt-out launch vehicle upper stages, dead or inactive spacecraft, ejected boost motors, solid rocket motor slag particles, intentionally released objects, fragments from satellite and rocket stage explosions, and surface degradation products. Their size ranges from automobile dimensions or bigger down to microscopic dust. Space debris is becoming a serious concern to current and future missions, with steadily growing collision risks for active spacecraft, especially in densely populated low-Earth orbits (LEO) below 2000 km altitude, and near the geostationary ring (GEO) at an altitude of about 36 000 km.



A solar panel of the Hubble Space Telescope was damaged by debris

In order to alleviate the problem, it is now common practice at ESA and other space operators to apply space debris mitigating measures. Launch-vehicle and satellite designers are becoming 'debris conscious' and are endeavouring to reduce to a minimum the debris produced once their vehicle or satellite enters space. ESA has adopted the policy of moving each geostationary spacecraft at the end of its useful life into a disposal orbit at least 300 km above the geostationary ring. In low-Earth orbits ESA monitors close fly-bys of their operational satellites with known objects. If a high-risk, close encounter is predicted, the spacecraft are manoeuvred out of the way. This was done several times for ESA's remote sensing satellites, and it is done about once per year for the International Space Station. To assess the effectiveness of such mitigation measures, ESA has generated the DRAMA tool (debris risk assessment and mitigation analysis).

ESA maintains a database (DISCOS) on all trackable, unclassified space objects since Sputnik-1. Their current on-

20 000 km/hr high-velocity impact

10 000 (10+cm) debris objects

Delta tank 'fell' to Earth

orbit population comprises about 13 000 items, of which only 5% are operational spacecraft. The size of these objects ranges from about 10 cm in low-Earth orbits to about 1 m in the geostationary ring. DISCOS contains full orbit histories, launch, mission and object data for more than 29 000 objects so far registered by the US Space Surveillance Network.

For space objects which are too small to be observed, mathematical models are necessary to predict their numbers, their evolving concentrations in space and time, their relative velocities, and the resulting collision probabilities with operational spacecraft. ESA has developed the MASTER model (meteoroid and space debris terrestrial environment reference) to meet such requirements. It is supported by a tool for long-term stability analysis of the debris environment as a function of future launch traffic and mitigation policies (DELTA), and it is further supported by a tool to validate the MASTER model against available measurement data (PROOF).

Another concern results from the re-entry of large space objects into the Earth's atmosphere. So far, almost 70% of all known man-made space objects have followed this natural evolution of an orbit. Most of these objects burn up completely. For large ones, however, between 10% and 40% of their mass can reach the ground and may pose a risk to the population. Special software was developed (SCARAB) to predict the re-entry break-up, burn-up, and fragment dispersion. Well-known high-risk events of this type were the re-entries of Cosmos 954 in January 1978 (a Russian spacecraft containing a nuclear reactor), Skylab in July 1979 (a 75 ton US space laboratory), Cosmos 1402 in February 1983 (another Russian spacecraft containing a nuclear reactor), and Salyut-7/Kosmos 1686 in February 1991 (a 40 ton Russian space station). In such cases, ESOC was involved in the analysis and prediction of the time and location of re-entry so that the authorities of ESA Member States could be advised in time.

Space debris research activities within ESA, and cooperation with European and international partners, are coordinated by ESOC's Space Debris Office. Research activities are concentrating on ground-based observations and *in situ* measurements, debris and meteoroid environment modelling, hypervelocity impact tests and protection concepts, and space debris mitigation measures. The latter issue is also addressed (with ESA representation) at the Inter-Agency Space Debris Coordination Committee (IADC), at the United Nations, at ISO, and at the European Cooperation for Space Standardization (ECSS).

The implementation of effective space debris mitigation measures by all space operators is a pre-requisite to keep the space debris risk within acceptable tolerances, also into the far future.


Galileo satellite system


Galileo constellation


Galileo navigation

The Navigation Facility actively participates in the elaboration and implementation of GNSS exemplary applications

Navigation Office

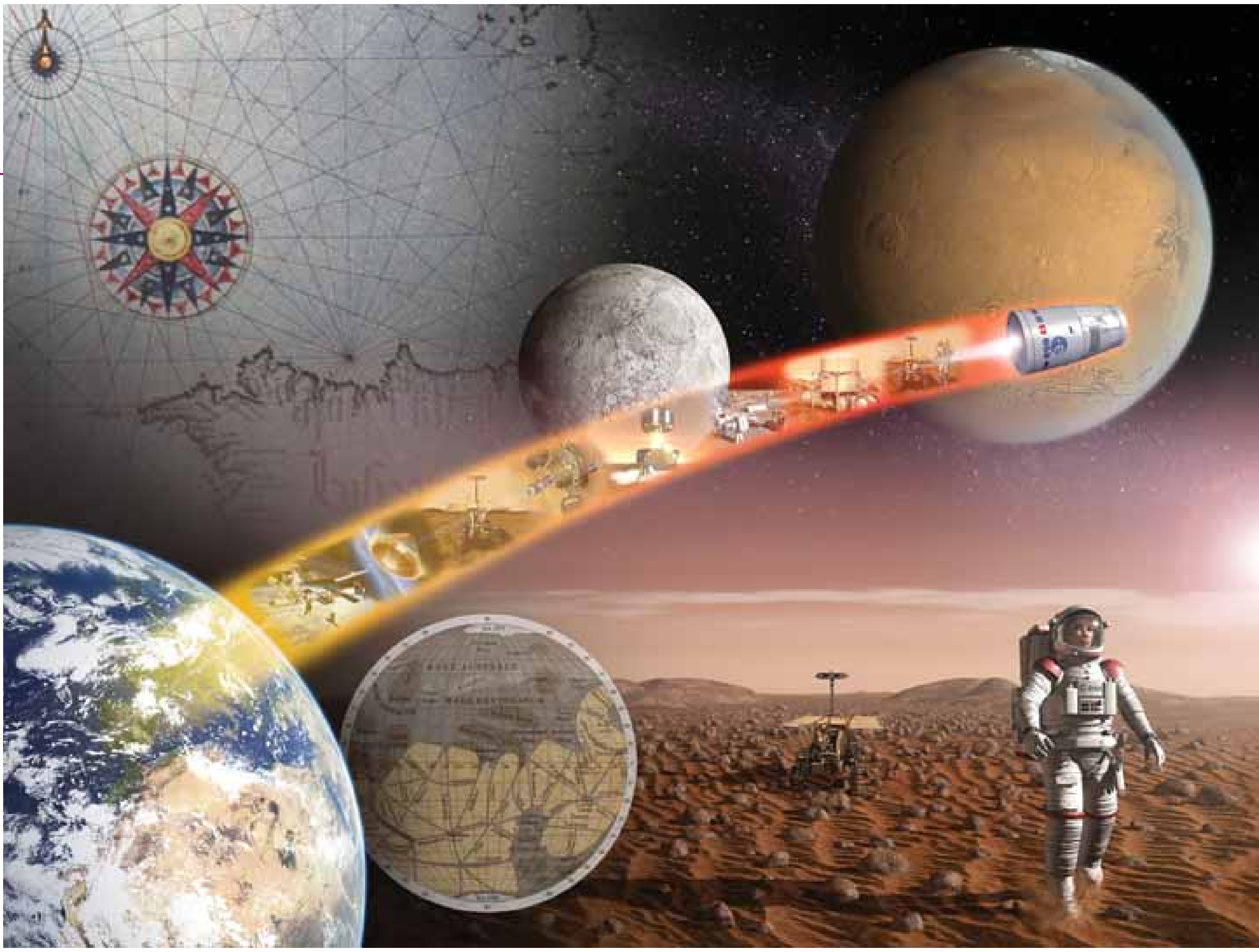
With its Navigation Office, ESOC plays a key role in the emerging field of data products and tools related to Global Navigation Satellite Systems (GNSS) and services. ESOC is paving the way for the implementation and usage of GNSS services mainly through basic data processing capabilities, which are needed to efficiently use GNSS. These capabilities involve the characterisation of GNSS system performance itself (e.g. clock monitoring and offsets or precise ephemerides for navigation satellites). Moreover, the Navigation Office actively participates in the elaboration and implementation of GNSS applications, such as high-precision orbit determination, localisation in space and on Earth, as well as derivative GNSS applications such as ionospheric mapping or atmospheric sounding.

The most visible symbol for these activities is the ESOC Navigation Facility. It joins computer installations, software and communication systems in a modern and efficient work environment. The heart of the Navigation Facility is the 'Tracking and Data Analysis Facility', a set of computer tools to transfer, decompress, reformat and route GNSS satellite data. It is also in the Tracking and Data Analysis Facility, where the dedicated software for GNSS data processing is accommodated, allowing one for example to calculate position and motions of GNSS receivers in space or on the surface of the Earth.

The activities of the ESOC Navigation Office moreover include the set-up, operation and maintenance of a network of ground GNSS receivers, located mostly in ESA's ground stations, but also at sites of other IGS partners.

More specifically, for the future European GNSS Galileo, the Navigation Office is developing prototype facilities, for instance to define and maintain the Galileo Terrestrial Reference frame, and a system for Real Time Navigation (RETINA), which delivers global clock and orbit corrections for navigation satellites in order to enhance the real-time accuracy for the users.

ESOC is paving the way for the implementation and usage of Galileo services



Future robotic and human missions to the Moon and to Mars

Incubation Centre for New Galileo Navigation Applications

In light of the long-standing expertise of the ESOC Navigation Office and of its contracting companies working in the field of satellite navigation in the Darmstadt region, ESA decided to set up a business incubation centre for future Galileo-related navigation applications. Several studies have shown that Europe's future navigation system Galileo will help to develop a tremendous global market for highly accurate navigation and positioning solutions.

In this context, ESA – under its business incubation initiative – and the Hessen Regional Government decided to team up with research organisations, IT companies, consultancy firms, banks and major future Galileo users to launch the 'CESAH' incubation centre. The Centrum für Satellitenanwendungen Hessen (Hessen Centre for Satellite Applications) provides a full range of services in terms of information, application and business incubation/start-up support for future navigation applications (www.cesah.com).

The Exploration Programme

ESA's Human Spaceflight and Exploration Operations Department conducts its studies, special projects and exploration mission operations from ESOC. From carrying out feasibility studies of new missions that are still in the early design phase, to identifying and implementing new technologies and advanced mission concepts, it ensures continued mission success for even the most complex missions of the future.

The Department also provides ground station and operations support to other international agencies and organisations, such as the European Meteorological Satellite Organisation, EUMETSAT, and the new European Global-Navigation and Positioning System, Galileo. Based on the successful operation of ESA's Mars mission, Mars Express, and its advanced technology lunar mission, SMART-1, it is also preparing to operate the next generation of ESA's robotic exploration missions to Mars and the Moon, paving the way for manned exploration missions.

ESA missions supported from ESOC

Name	Purpose	Launch date	Mission Duration (years)	Orbit	Stations/Remarks
ESRO-2	Science	17.05.1968	3	LEO	Redu/Falkland/FBA/Spitzbergen/Tromsø
ESRO-1A	Science	03.10.1968	2	LEO	Redu/Falkland/FBA/Tromsø
HEOS-A1	Science	05.12.1968	7	HEO	Redu/FBA/
ESRO-1B	Science	01.10.1969	2 months	LEO	Redu/Falkland/FBA/Tromsø/Launch vehicle underperformance
HEOS-A2	Science	31.01.1972	2	HEO	Redu/FBA/Spitzbergen
TD-1A	Science	12.03.1972	2	LEO	various
ESRO-4	Science	20.11.1972	2	LEO	Redu/FBA/Spitzbergen/Tromsø
COS-B	Science	09.08.1975	7	HEO	Redu
GEOS-1	Science	20.04.1977	5	GTO	Redu/ODW/NASA
ISEE-2	Science	22.10.1977	10	HEO	STDN OCC at GSFC
Meteosat-1	Meteorology	23.11.1977	8	GEO	ODW
IUE	Science	28.01.1978	18 years/	HEO	Vilspa OCC at Vilspa 8 months (joint NASA mission)
GEOS-2	Science	14.07.1978	6	GEO	Redu/ODW
OTS-2	Telecom	11.05.1978	13	GEO	Fucino/Redu
Meteosat-2	Meteorology	19.06.1981	10	GEO	ODW
Marecs-A	Telecom	20.12.1981	14 years/ 9 months	GEO	Redu/Vilspa
Exosat	Science	26.05.1983	3	HEO	Vilspa
ECS-1	Telecom	16.08.1983	13 years/6 months	GEO	Redu OCC in Redu
ECS-2	Telecom	04.08.1984	9	GEO	Redu OCC in Redu
Marecs-B2	Telecom	10.11.1984	ongoing	GEO	Redu/Vilspa
Giotto	Science	02.07.1985	hibernation	interplanetary	Carnarvon/Parkes/DSN/Perth
ECS-4	Telecom	10.09.1987	ongoing	GEO	Redu OCC in Redu
Meteosat-P2	Meteorology	15.06.1988	7	GEO	ODW
ECS-5	Telecom	21.07.1988	12	GEO	Redu OCC in Redu
MOP-1	Meteorology	06.03.1989	6	GEO	ODW
Olympus	Telecom	12.07.1989	4	GEO	Fucino Only LEOP
Hipparcos	Science	08.08.1989	4	GTO	ODW/Perth/Goldstone
Ulysses	Science	06.10.1990	ongoing	interplanetary	DSN OCC at JPL
MOP-2	Meteorology	02.03.1991	ongoing	GEO	ODW OCC moved to EUMETSAT
ERS-1	Earth Observ.	17.07.1991	9	LEO	Kiruna
Eureca	Microgravity	31.07.1992	1	LEO	MASPAL/KRU Retrieved by Shuttle
MOP-3	Meteorology	20.11.1993	ongoing	GEO	ODW OCC moved to EUMETSAT
ERS-2	Earth Observ.	21.04.1995	ongoing	LEO	Kiruna
ISO	Science	17.11.1995	3	HEO	Vilspa/Goldstone LEOP in ESOC Routine in Vilspa
Huygens	Science	15.10.1997	ongoing	interplanetary	via JPL, Pasadena Joint NASA mission
Teamsat	Technology	30.10.1997	5 days	GTO	Kourou joint with ESTEC
Pastel Payload	on Spot4	24.04.1998	ongoing	LEO	CNES mission
XMM	Science	10.12.1999	ongoing	HEO	Perth, KRU/Santiago (Chile)
Cluster II	Science	16.07.2000			
		09.08.2000	ongoing	HEO	Vilspa
Envisat	Earth Observ.	01.03.2002	ongoing	LEO	Kiruna, Svalbard
MSG-1	Meteorology	28.08.2002	ongoing	GEO	(operated from EUMETSAT)
Integral	Science	17.10.2002	ongoing	HEO	Redu
Mars Express	Science	02.06.2003	ongoing	interplanetary	New Norcia
SMART-1	Science	28.09.2003	ongoing	interplanetary	Vilspa, Maspalomas, Perth, Kourou
Rosetta	Science	02.03.2004	ongoing	interplanetary	New Norcia
Huygens	Science	15.10.1997	7	interplanetary	NASA DSN/(Huygens descent to Titan 14.01.05)
Venus Express	Science	9.11.2005	ongoing	interplanetary	Cebreros
MSG-2	Meteorology	22.12.2005	ongoing	GEO	(operated from EUMETSAT)
MetOp-A	Meteorology	22.12.2006	ongoing	Polar	(operated from EUMETSAT)

Glossary of terms

AOCS	Attitude and Orbit Control Subsystem
CNES	Centre National d'Etudes Spatiales
CSG	Centre Spatial Guyana
DCR	Dedicated Control Room at ESOC
DISCOS	Database and Information System Characterising Objects in Space
D/OPS	ESA Directorate of Operations
EIRP	Effective Isotropic Radiated Power
ESA	European Space Agency
ESOC	European Space Operations Centre
FOP	Flight Operations Plan
G/T	Gain/Noise Temperature
JAXA	Japan Aerospace Exploration Agency
LEOP	Launch and Early Orbit Phase
MCR	Main Control Room at ESOC
NASA	National Aeronautics and Space Administration (USA)
OBDH	On-Board Data Handling Subsystem
OCC	Operations Control Centre at ESOC
ODB	Operations Database
ORATOS	Orbit and Attitude Operations System
PCM	Pulse Coded Modulation
RF	Radio Frequency

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