Chapter 2
Mission Operations

2.1 Mission Operations Preparation

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The success of a space mission depends not only on a properly designed and built space segment and the successful launch via a launch segment. It also depends on the ground segment and successful mission operations, carried out by a team of experts using the infrastructure and processes of the mission's ground segment. Its organization and design as well as the assembly, integration, test, and verification (AITV) are therefore equally important as the respective activities of the space and launch segment. A ground segment thereby comprises a ground system, i.e., infrastructure, hardware, software, and processes, and a team that conducts the necessary operations on the space segment.

This subchapter describes the tasks and activities that are necessary for the preparation of mission operations, i.e., what must be done by whom and in which order to enable mission operations of a particular space mission. It gives the questions that arise automatically when analyzing the requirements of a mission and how these questions are answered with a design based on available resources and respecting project-specific constraints.

It is organized as follows:

- With various examples of past space missions, the reader is first introduced to mission operations preparation in general and why this phase is of eminent importance.

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- The input to the entire phase of preparation or the driving factors that influence the design of the ground segment of a particular mission are explained in Sect. 2.1.2.
- Team organization, i.e., who must do what and when, is described in Sect. 2.1.3.
- Section 2.1.4 describes data, products, and tools required for effective mission preparation.
- The particular activities, tasks, and deliveries are explained in Sect. 2.1.5.
- The final Sect. 2.1.6 treats the proven concept of reviews and, in particular, the reviews that are carried out during the preparation phase.

A general remark shall be given here. The following subsections are to be understood as suggestions on how mission operations preparation can be achieved or how it was conducted successfully in the past. They are by no means a "must do," as each space project may exhibit its very specific demands and boundary conditions which can lead to very different realization concepts.

2.1.1 Introduction with Examples

If being asked what "mission operations preparation" is in plain words is or what it means, one could give the following definition:

> Mission operations preparation comprises all measures related to management, development, test, integration, validation, organization, training, certification, and documentation of the ground segment of a space project. The result of successful mission operations preparation is a ready-for-launch ground segment.

The duration of that project phase can thereby vary considerably. Table 2.1 gives examples of past or current missions and the durations of the operational and the preparation phases. These examples cover a range of various mission types, e.g., Earth-bound satellites in low earth orbit (LEO), medium earth orbit (MEO), or geostationary earth orbit (GEO); interplanetary missions to the Moon, planets, and other celestial bodies of the solar system; and deep-space science missions for Sun observation or the exploration of the outer solar system.

The selected examples show that the definition of a general rule for the duration of operations preparation is nearly impossible. Several, mutually influencing factors contribute to space missions in general and to ground segment systems in particular. These systems are:

1. At least one mission control center (MCC).
2. A ground station network (GSN), via whose antennas the ground segment communicates with the space segment.
3. A flight operations team (FOT), which plans and executes operations of the space segment within its parameters.

Table 2.1 Preparation and total project duration of selected space projects

Mission	Type/purpose	Orbit	Spacecraft lifetime (years)	Preparation (years)
TerraSAR-X TanDEM-X	EO, science	LEO	5+	4
EnviSat	EO, weather forecast	LEO	10	12
GPS	Navigation	MEO	12+	22
Galileo	Navigation	MEO	12+	20
Eutelsat W24	Communication	GEO	15+	2
Grace	Science	LEO	12	3
Voyager 1	Outer solar system exploration	Deep space	3 (primary mission) 52 (power limit)	7
Apollo	Human exploration (moon)	Moon	14d	8
Cassini Huygens	Interplanetary exploration	Saturnian system	20	10
Ulysses	Deep-space sun observation	Deep space	17	5 (excluding delays[a])

[a]With a project start in 1979, ULYSSES was planned for launch in February 1983 (Wenzel et al. 1992) but was delayed to May 1986 and again, due to the Challenger accident, to October 1990

Size, dimension, and complexity of each system depend on a number of mutually affecting parameters and constraints, e.g., mission objectives, technical developments, project phase, schedule, and budget. Striving for an optimal solution therefore inevitably turns into a search for a compromise that is acceptable to the customer. This is the task of mission designers, or, in particular, of those persons responsible for the design of ground segments.

In general, the same (or at least similar) activities and tasks have to be done during every space project, although very different mission-specific requirements need to be met. The European Cooperation for Space Standardization (ECSS) issued a set of management and technical standard documents, which shall harmonize management of European space projects. According to this ECSS phase model (ECSS-E-ST-70C), mission operations preparation is covered in the project phases C "Critical Design" and D "Preparation," as shown in Fig. 2.1. They are located between preliminary design and mission execution (see also Sect. 2.2).

The result of successful mission preparation is an integrated, validated, and ready-for-launch ground segment.

A generic example of a ground segment, its subsystems, and the data flows between them is shown in Fig. 2.2. It comprises a GSN of three ground stations and a MCC. The main systems of the MCC are the Ground Data System (GDS), the Flight Dynamics System (FDS), and the Flight Operations System (FOS).

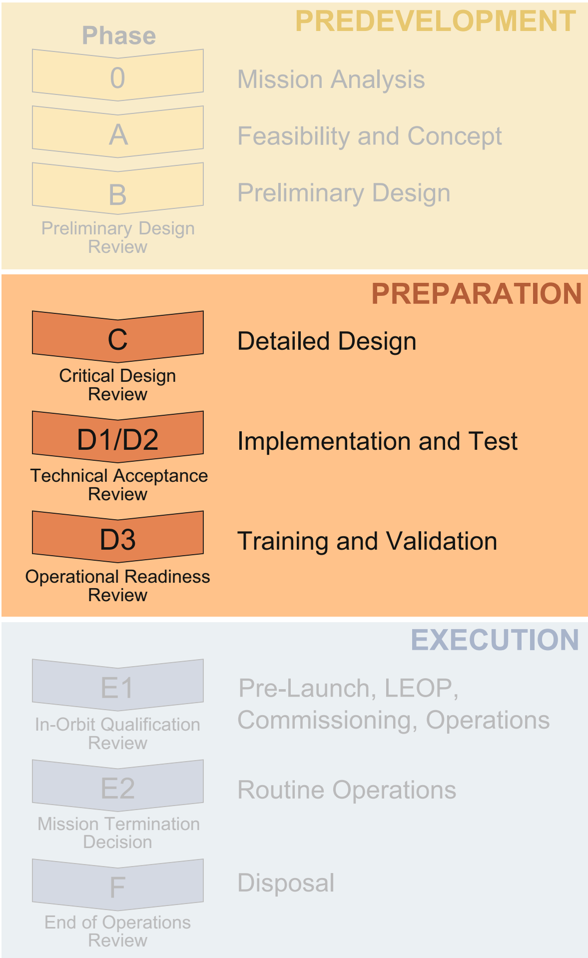

Fig. 2.1 ECSS phase model

2.1.2 Driving Factors

2.1.2.1 Requirements

The specific requirements of a space mission determine the technical design of the respective ground segment. Their formulation should follow the rules of requirements engineering and in particular those set by ECSS (ECSS-E-ST-10C and ECSS-E-ST-10-06C). These are:

- Performance: Requirements shall be described in quantifiable terms.
- Justification: Each technical requirement should be justified together with the responsible entity.
- Configuration Management: Each technical requirement shall be under configuration control.

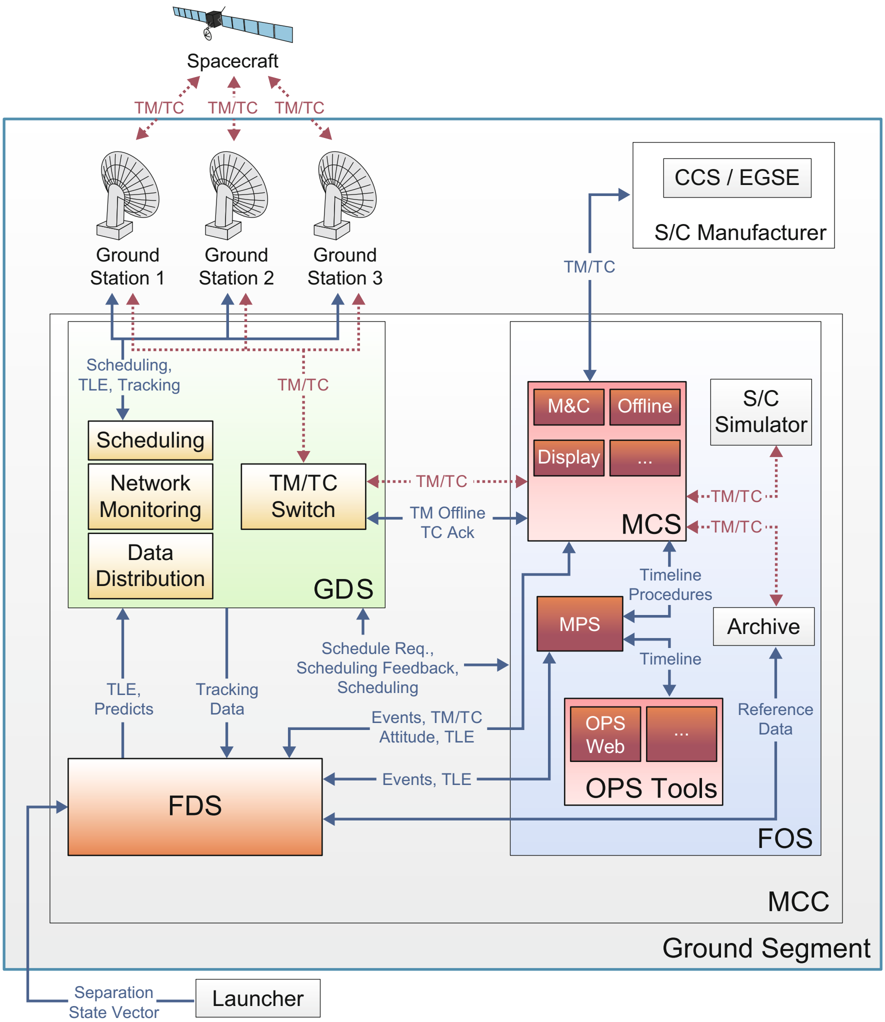

Fig. 2.2 Generic ground segment example

- Traceability: Each technical requirement shall be backwards- and forward-traceable.
- Ambiguity/Uniqueness: Technical requirements shall be unambiguous and unique.
- Identifiability: Each technical requirement shall be identified in relation to the relevant function, product, or system. The identifier shall be unique and reflect the type and life profile situation.
- Singularity: Each technical requirement shall be separately stated, i.e., not a combination of requirements.
- Completeness: Technical requirements shall be self-contained.

- Verification: Technical requirements shall be verifiable using one or more approved verification methods.
- Tolerance: The tolerance shall be specified for each parameter or variable.

These requirements must be analyzed by the engineering and operations responsible (see Sect. 2.1.3) and answered with a detailed design. Ideally, this concept answers each requirement in the best possible way, and its realization takes place within the set project schedule and cost estimate. In reality, however, compromises must be found as otherwise cost and schedule overruns are likely.

Any unanswered or partially answered requirement, i.e., a requirement that is not fully met by a corresponding design, or a requirement whose addressing requires an unjustified high amount of funding, is discussed with the customer. On acceptance by the customer, a temporary deviation or noncompliance to a requirement is documented through a so-called Waiver and thus officially authorized by the customer. A Waiver is, however, not an instrument to document persistent noncompliances, and a requirement alteration should be considered instead.

2.1.2.2 Cost/Funding

Cost-effective design is always required as most projects do not have the funding to develop solutions specifically for a single mission. Nevertheless, the requirements must be satisfied and if several options for realization exist, the one giving the best compromise between risk, schedule, and cost is likely to be chosen.

2.1.2.3 Technology/Complexity

Technical complexity influences cost, schedule, and also the general risk of a space project; this is true for the space segment but also for the ground segment. The necessary degree of complexity, however, depends on a number of factors and drivers, with the most important being the satisfaction of the requirements. This is often achievable through different concepts of various levels of technical maturity expressed with nine, so-called Technology Readiness Levels (TRL). The corresponding TRL definitions according to ECSS are:

- TRL 1: Basic principles observed and reported.
- TRL 2: Technology concept and/or application formulated.
- TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept performed.
- TRL 4: Component and/or breadboard validated in the relevant environment.
- TRL 6: System/subsystem model or prototype demonstrated in the relevant environment (ground or space).
- TRL 7: System prototype demonstrated in a space environment.
- TRL 8: Actual system completed and flight-qualified through test and demonstrated (ground or flight).
- TRL 9: Actual system “flight-proven” through successful mission operations.

For each subsystem of the ground segment and for each component, the design must be evaluated for alternatives. These alternatives must then be assessed for their effect on schedule, cost, and risk before a decision on the employed technology can be taken.

This shall be explained with the example of a Mission Planning Subsystem (MPS) of an EO satellite.

Let’s assume this EO mission requires a defined duration from reception of an image order until delivery of the processed image to the ordering customer of less than a defined number of hours or days. Between these two points in time, several activities are to be carried out. These are the planning for the next available contact for the upload of the image acquisition commands, the prediction of the next opportunity for taking an image of the desired spot on the earth surface, the next downlink opportunity, and the processing of the transferred raw image data. If the required maximum duration between order reception and delivery of the resulting picture is 7 days, for example, the necessary activities might be carried out manually or semi-automatically. However, the shorter the required time frame becomes, the more likely the decision for a fully automatic planning systems becomes. The development of an automatically operating MPS is a complex project in itself and requires significant funding and time. It should consequently be developed as a generic system capable of serving multiple missions. For later missions it can thus be handy to use an existing MPS although it has more features than required. The benefit of reusing an existing system is that, due to its higher TRL compared to a new development, test and validation activities are less.

2.1.2.4 Schedule

The project schedule affects the options for the design, implementation, test, and validation of a ground segment in multiple ways. First, if the schedule is tight, i.e., there is not enough time for the development and test of project-specific solutions, proven technologies of higher TRL must be used. This means to reuse existing software, for example, and to accept possible drawbacks from design concepts that have been tailored to a different mission.

Second, the project schedule also influences the validation and training concept. As there is hardly ever sufficient time for training for each possible and foreseeable situation or emergency, the FOT must concentrate on the most severe ones during training phase. Another influencing factor results from due dates of deliveries by the customer. An essential one is the delivery of the spacecraft simulator. It should be as early as possible, which naturally collides with the fact that the spacecraft design is often not finished. For a series of satellites of the same type, e.g., for a constellation of navigation system satellites, this does hold true only for the first one. However, without having a satellite software simulator of adequate fidelity on time, training of the FOT and validation activities are hampered. Consequently, the delivery of this important item should preferably be fixed contractually.

2.1.2.5 Experience

The short version of this factor is "Whatever it is, it requires less effort if you do it for a second time." A company or space center with decades of mission operations experience can approach future space missions of a similar kind easier than a new competitor. The effort is less because many concepts, processes, and tools do already exist in flight-proven configurations. This depends, however, strongly on the nature of the mission; it cannot be generalized because the requirements of space missions can be of considerable difference. Human-spaceflight missions, for example, pose very challenging requirements in terms of safety, and the cost-effective maintenance of a constellation of 20–30 satellites of a global satellite navigation system may have completely opposite ones. Interplanetary deep space missions are different than Earth-bound satellite projects. A control center specialized on Earth observation is therefore not the first choice for a science mission to one of the moons of Jupiter.

Note that experience may contradict the customer requirements considerably. Early feedback of recommendations to the customer is an important task of the control center as it allows looking for different solutions and the reduction of cost and risk.

Besides the general experience also the time since last mission of the particular type plays a role because experience and proficiency reduces with each year of not operating the particular mission type. Ten years after the last mission of a particular type, one can assume the experience is more or less gone or not applicable anymore and must be reacquired, normally with the same effort as if you prepare for a mission type for the first time.

2.1.2.6 Risk (Also Regarding Launch Delays)

A specific risk analysis must be conducted for each space project, and that analysis must be specific to the respective segments, i.e., also for the ground segment. Risks are primarily w.r.t. cost, schedule, and mission requirements. Naturally, the overall risk for successive mission should be as low as possible; it rarely reduces to zero, though. The minimization thereby results from the reduction of the risk of each system and subsystem to be ready until launch. Preplanned timely buffers and milestones should therefore be part of every project schedule to account for delays in preparation.

Risk reduction is often the reason why aerospace engineering is rather conservative when it comes to employ new technologies. Flight-proven, reliable systems and processes are often given preference before new technologies.

2.1.3 Personnel, Roles, and Responsibilities

The preparation for the operations of a space project requires the organization and assignation of roles and responsibilities. A generic project structure is shown in Fig. 2.3, with the three main branches management, system engineering, and operations engineering. Specific roles are associated to each branch:

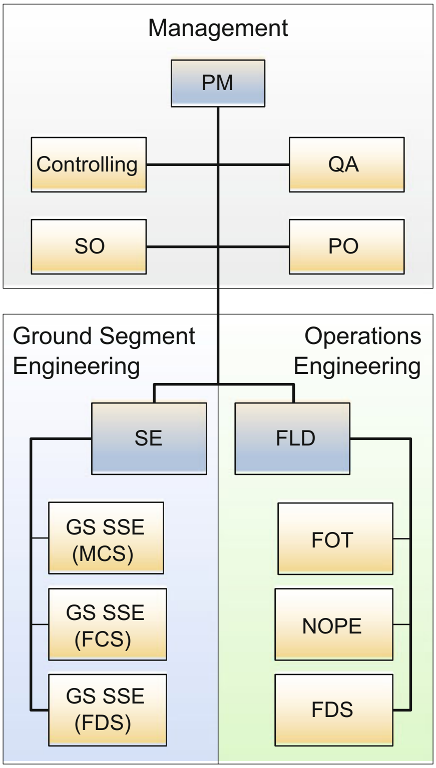

Fig. 2.3 Project organization and roles of a generic ground segment

2.1.3.1 Project Manager

The Project Manager (PM) is responsible for the organization and overall management of the project. He/She is the contact point to the customer and appoints the Flight Director (FD) and the System Engineer (SE). This role is in general given to an experienced engineer who has preferably been either Flight Director or system engineering in an earlier space project. Later, during operations phase, he might take the additional role of the Mission Director (MD).

2.1.3.2 Mission Director

Superior to the Flight Director, the system engineering, and the Lead of the Satellite or Spacecraft Support Team (SST), the MD is overall responsible for the mission execution phase, and, in this function, responsible to the customer once mission operations have started.

2.1.3.3 Flight Director

The FD is responsible for the preparation and the execution of mission operations. He defines size, composition, qualification, and the training concept of the FOT. For this task, he is supported by the simulation officer (SIM). The FD develops the operations concept, formulates technical low-level requirements resulting from that concept, and supervises the FOT during operations. The FD works in close cooperation with the project's System Engineer and reports to the PM.

2.1.3.4 System Engineer

The SE is responsible for ground system engineering and defines the technical concept of a mission's ground segment, which derive from mission requirements. Together and in close coordination with the FD, the SE defines the specification of the ground segment systems and its lower-level components. He supervises the development of new components and adaption of existing ones. He is responsible for the technical implementation of the ground segment, i.e., for integration, test, and validation. In this function, the SE reports to the project manager and supports the FD.

2.1.3.5 Simulation Officer

The SIM is responsible for the planning, organization, execution, and evaluation of the training measures that are required to train the FOT. He reports to the FD and cooperates closely with the SE and the FOT. Common training measures are class room lessons, simulations, and rehearsals. The input of a SIM's work is the required training and skill level, which needs to be defined by the FD. Organizational boundary conditions, such as availability of infrastructure, required data, tools, and specialists, are input for the SIM's planning as well. After an executed training measure and together with the FD, the SIM compiles an evaluation report in which he expresses the success or failure of the particular training measure as well as eventually necessary repetitions or follow-on measures.

2.1.3.6 Quality Assurance Engineer

The Quality Assurance (QA) engineer is responsible for assuring compliance of the project to internal and external quality standards, i.e., he has to monitor the project from a quality and product control point of view and support the PM, SE, and FD during the entire lifetime of the project. External standards are ISO or ECSS standards, such as ISO 9001 "Quality management," ISO 27000 "Information Security," or ECSS-Q-ST-10 "Product Assurance Management."

2.1.3.7 Subsystem Engineer

A Subsystem Engineer (SSE) is responsible for the operations of a specific satellite subsystem, e.g., data handling subsystem. Sometimes, operations of multiple subsystems are combined; the attitude and orbit control subsystem (AOCS) or the power and thermal control subsystem (PTS) are common examples. A SSE must learn the functionality of the respective subsystem, know the telemetry for monitoring that subsystem, and train to apply the subsystem-specific procedures to control its functions, depending on the current situation and intention. They also work with the Mission Information Database to validate and optimize the performance of the MCS.

Additionally to the SSEs of the FOT, the AIT activities before launch are carried out by ground system SSEs. These are specialists for certain components of the ground system, e.g., networks, infrastructure, communication, server integration and configuration, security, software, ground stations, etc. The primary affected subsystems are the ground data subsystem (GDS), the mission control subsystem (MCS), and the mission data subsystem (MDS). The respective SSEs of these subsystems support the SE and the FD from project phase B until launch.

2.1.3.8 Project Office/Project Officer

A Project Office/Project Officer (PO) might become necessary for bigger projects, as the workload resulting from organization becomes too much to be handled by the PM alone. The PO covers documentation management and team organization and provides general support to the PM, e.g., for the organization of reviews.

2.1.3.9 Controlling

A controller supports the PM on contractual and financial aspects of the project during the entire project lifetime. He provides reports and overviews over the project budget in regular intervals and on demand by the PM.

2.1.3.10 Configuration Manager

The Configurations Manager (CM) develops a project-specific configuration management plan during phase C and supervises the implementation of this plan during subsequent phases.

2.1.3.11 Security Officer

The Security Officer (SO) supports the PM in all security related matters, e.g., access control concepts, encryption, clearances, or classification of documents. This can be of importance for military satellite projects whereas for scientific satellite projects this is practically irrelevant. Whether a project needs a dedicated SO or not is the decision of the PM.

The decision on what role should be assigned to which team member needs to be taken by the PM and is specific for each project. For smaller projects, for example, the PM might not need a dedicated PO for project organization and document management. Furthermore, it makes sense to combine the roles of FD and SE for smaller projects; the corresponding workload of larger projects should, however, be shared between two persons.

2.1.4 Required Data, Products, and Tools

Testing the ground segment with its subsystems and components prior launch requires mission-specific tools and data. The validation of developed flight procedures, for example, is strongly impeded without a software simulator that emulates the spacecraft behavior and its foreseen environment, i.e., the conditions in space. The following tools or deliverables are therefore required for mission preparation.

2.1.4.1 Test Data and Data Generators

Specific sets of telemetry data are required for testing of the Monitoring & Control (M&C) system, including the Mission Information Base (MIB), the processing chains (main and backup), and a potential archiving process. Test data becomes of eminent importance if no satellite simulator is provided. Test data may also be needed for other interfaces like file data deliveries.

2.1.4.2 Spacecraft Simulator

A spacecraft simulator is an essential component for mission preparation but is not always provided by the manufacturer of the spacecraft due to cost or schedule constraints, or both. If this is the case, and no simulator is available to the ground segment, then the ground systems team should be granted remote access to engineering models or the flight model of the spacecraft. Access to the flight model can, however, provide less test and validation options as the spacecraft is still on ground. A high-fidelity software simulator provides a representative model of the spacecraft, the spacecraft subsystems, and of the physics of the spacecraft's environment. The implementation of a satellite simulator can be purely in software but also in combination with real spacecraft hardware, e.g., an engineering model of the onboard computer. Such simulators are called hybrid simulators.

The early provision of a stable, high-fidelity satellite simulator eases mission preparation, as it allows early checks of the commands and telemetry data. Furthermore, it enables early familiarization of the FOT with the spacecraft in addition to the spacecraft user manual. The creation and validation of flight procedures is a third mandatory activity during mission preparation that profits from early availability of a spacecraft simulator.

2.1.4.3 Mission Information Base

The MIB contains the definition of the commands, the command parameters, the telemetry, and the position of the telemetry data in the downlink data stream. It is therefore an essential input to validation of the M&C software and also for procedure development and validation. In a preliminary version, it should be delivered on time for the validation phase of the ground segment. At the end of this validation phase, the MIB should be final as well.

2.1.4.4 M&C System Software

The spacecraft is monitored via telemetry monitoring and display software and commanded via command software. Together, these software packets combine to an M&C system. It is an essential component of the FOS and is preferably written in a generic manner so that for each mission only adaption is required. This eases validation as only the changes need to be tested extensively. The functionality of the entire M&C system is then validated during validation of the MIB. Simulations and rehearsals are also used to validate the M&C system.

2.1.4.5 Ground and Flight Procedures for Nominal and Contingency Situations

Control of the spacecraft is basically possible through the M&C software and the validated MIB. However, logical work flows, branching, and timing conditions cannot be described with a simple list of commands. A proven concept to mitigate this deficiency is that of using validated procedures. They are developed for ground and for flight processes and increase mission operations considerably as they reduce the risk of operational mistakes. A procedure describes a validated workflow step by step, together with the required initial conditions, the commands to be sent, the expected response of the space segment, timing conditions, and explaining comments. Such procedures are primarily developed for routine operations, e.g., activation or deactivation of an onboard component or subsystem. Nevertheless, it is important to cover also potential contingency situations with respective procedures. The drop into safe mode is a prominent example of a contingency situation, and the respective procedure should describe the analysis and recovery actions to bring the spacecraft back into normal operations mode.

2.1.4.6 Operations Support Tools

A spacecraft must be monitored and operated. The amount of attention from ground, however, depends on the particular mission. There are space projects that are operated around the clock, e.g., human spaceflight missions, and there are satellites with a single ground station contact per day. Operations of each mission therefore need a customized set of operational tools to make operations as robust as possible. Such tools are anomaly tracking tools, Sequence of Events, telephone lists, shift plans, minutes, recommendation handling tools, links to documentation, procedure lists, etc. The tools should be organized such that they are easily accessible from each control room position, like a mission-specific Web page, for example.

2.1.4.7 Project Documentation, E.g., Spacecraft User Manual, Ground Segment Design Description, Operational Documentation

For safe and robust mission operations, the FOT needs to know the functionality of the space segment and must be trained for situations that are typical or likely to occur. This is facilitated through training and technical documentation, which must be available on time, i.e., before training and operational validation phase. The documentation must be accessible during the entire operational lifetime of the space segment.

2.1.5 Activities, Tasks, and Schedule

A number of tasks must be accomplished during preparation for mission operations. Early in the preparations phase, they are primarily of technical nature, e.g., the integration and test of the ground segment systems and components like software, computers, and networks. Later, when technical work is finished, the composition, training, and certification of the FOT becomes the dominating activity. The following description gives a top-level overview of the tasks of each subphase, the required prerequisites to accomplish these tasks, and the expected output of each subphase.

The first of these phases is project phase C, called “Critical Design Phase,” and the finalization of the ground segment design is its content. If technical developments need to begin before phase D, then they will also start already in that phase (long-lead items). Key roles during this phase are those of PM, FD, SE, and QA.

They coordinate design and documentation activities, and, in this role, they are supported by SSEs and specialists, e.g., flight dynamics experts, network specialists, etc. They all use the design documentation from phase B and elaborate the developed concepts to final fidelity. The interfaces are defined completely and respective test approaches and plans are written. The result of this phase is a detailed design description, including all internal and external interfaces, as well as test plans and schedules.

Project phase C ends with a critical design review (CDR), in which the ground segment provider testifies to the ground segment customer the developed design.

The next phase, phase D, comprises three subphases: the development and procurement of the ground segment systems (D1); assembly, integration, and test of these systems (D2); and the verification and operational validation of the ground segment (D3). During subphase D1, the systems, subsystems, and components of the ground segment are procured or manufactured, including functionality and interface tests. The supervision of these activities is the primary task of the SE, supported by QA. During subphase D2, the ground segment is assembled and integrated. The control room is integrated and potentially required infrastructure alterations are implemented. Networks and automated transfer services are configured and computer hardware is integrated in the operational environment. These activities are again supervised by the SE, supported by QA and the FD.

The following activities are content of subphase D2:

- RF-Compatibility Test (6 months until 12 months prior launch, preferably with flight-model RF components)
- Functional and performance tests of internal and external interfaces
- Functional and performance tests of all ground segment subsystems
- Functional test of the whole ground segment
- Composition of the FOT and first trainings (classroom lessons, handbook study, etc.)
- First flight and ground operations procedures
- Validation of the MIB
- Production of test and validation reports
- Compilation of results in report summary

Subphase D2 ends with the Ground Segment Qualification Review (GSQR) and a Critical Operations Review (COR). Both reviews may also be combined into one review.

The operational validation of the ground segment is primary content of subphase D3, with the main roles involved being FD, SE, QA, and SIM. Intense training of the Flight Operations Procedures (FOP), the finalization of flight and ground procedures, as well as their validation must be achieved. Certification of the FOT's readiness for the upcoming launch is thereby achieved through simulations of increasing complexity. The results of these simulations are documented with corresponding reports for the Customer. These reports and eventual report summaries are subject to review during the Operational Readiness Review (ORR), which is the final review before launch.

Table 2.2 Document deliverables per review milestone

	Domain	GSCDR	GSQR	COR	ORR
Space-to-ground ICD	SS	A			
Space segment operability requirements document	SS	A			
CFI and services requirements document	SS	A			
GS engineering plan	GS	F			
ICDs for external an internal entities	GS	F			
GS design definition file	GS	F			
GS design justification file	GS	F			
GS configuration management plan	GS	F			
GS AIT plan	GS	F			
GS verification plan	GS	F			
GS configuration status report	GS		F		
GS integration and test reports	GS		F		
GS verification reports	GS		F		
Ground systems user and maintenance manuals	GSYS		F		
Logistics support plan	LS		F		
Mission analysis report	OPS	F	F		
Operations engineering plan	OPS	F			
Operational validation plan	OPS			F	
Operations training plan	OPS			F	
Mission operation plan	OPS			F	A
Operational validation reports	OPS			F	F

Essential documents resulting from the preparation phase are listed in Table 2.2, together with the review for which they must be available (see also Sect. 2.1.6). According to ECSS (ECSS-E-ST-10-06C), these documents belong to five levels: space system (SS), ground segment (GS), ground system (GSYS), logistics support (LS), and operations (OPS). The letter "A" designates a document issue for approval by the customer and "F" designates a final document issue, which is approved by the respective supplier and for information to the customer. Note that the documents listed above do not actually have to be separate documents. The relevant information may be embedded in other documents. Furthermore, the actual contract may define only a subset of that list as deliverables.

2.1.6 Review Process

A review is a formal project milestone. Passing this milestone successfully shows that all measures have been taken to complete a certain predefined work package, a project phase, or a subphase. That means the project is stopped to examine, evaluate, and assess the project status and to decide on whether to proceed with the next phase or not. The status is thereby presented with respective documentation.

Several reviews are possible during mission preparation, with not all being necessary or required for every mission. The required project-specific tailoring thereby depends on the particular type of the mission and should be fixed in the contract that covers the phases C and D. This subsection lists the possible reviews during these mission phases, describes their content, common and essential preconditions, and when they take place.

ECSS foresees several major reviews, which are described in the following. These reviews are Ground Segment Critical Design Review (GSCDR), GSQR, COR, and ORR. Additional internal reviews are possible, e.g., test readiness reviews or simulation readiness reviews, and need to be included according to the complexity of the particular project.

Although each of these reviews covers very different topics or elements of the ground segment, they generally follow common principles in terms of schedule and organization. Customization to the needs of a project and also for a particular review is, however, possible. A complete description of the review in terms of "Who, How, and When" should therefore be written. This so-called review procedure is communicated on time to the "review team," which should comprise the project team, i.e., the engineers of the space segment and the ground segment, and the review board. The board should preferably consist of external experts in relevant project fields. These experts can be from other companies, research labs, test facilities, or agencies. The more diverse the knowledge gathered in review board the better.

A review starts with a presentation of the current project status. Venue of that presentation is often at the customer. Each project party gives a brief overview of the current status. This presentation allows the project to describe and explain the specific boundary conditions or constraints under which the current status has been achieved. After the presentation, the so-called review data package is given to the review team for study and assessment. Duration of that phase should be chosen in dependence of the size of the data package. In practice, however, this phase lasts between 2 and 6 weeks.

During the study of the documents of the review data package, all review team members should document any occurred concern via a so-called Review Item Discrepancy (RID). The structure and organization of RIDs are under responsibility of the review board lead and must be described in the review procedure, but for each item at least the following information should be provided:

(1) "Item": Identifies the data package item, for which the remark is valid. It can follow a predefined nomenclature or scheme, but the number of the document, page, section, and/or line number suffice as well.
(2) "Observation": This comment describes what caught the attention of the reviewer. Examples are unclear statements, wrong conclusions, insufficient descriptions, inconsistent analysis, but also typographic errors.
(3) "Concern": The reviewer must express the concern resulting from his observation, e.g., a higher risk for failure of a component due to insufficient testing.
(4) "Recommendation": This is a description of the corrective measures or activities that are necessary for solving the observed problem, e.g., extending a test campaign.

It is the responsibility of the project management and the review responsible to determine a set of RID data items adequate for the particular project. To ease the review process organization, for example, a criterion "criticality," with possible values "low," "medium," and "high" (or "major" and "minor"), helps to group the RIDs and to focus on important ones first.

The review period, i.e., the time during which the review team is allowed to provide RIDs, is limited to approximately 75 % of the entire review period. The RIDs are then provided to the project team for answer. The team then assign a responsible person. This person first decides whether the RID observation is justified or not, i.e., whether the RID is accepted or rejected. The accepted RIDs are then analyzed and answered. The answer is normally an action, the provision of more information, or a correction of existing information. This shall always be reflected with document updates, e.g., update or new issues of project documentation.

The last review stage contains a so-called RID discussion and a closeout, which results in a review report. During the RID discussion, which takes between 2 and 3 days, the project team presents and defends its RID answers to the RID owners. Depending on the answers, the review board then decides on passing or failing of the review and documents its decision with the review board report. A passed review often equals the formal "Go" for the next project phase.

In the following, the specific reviews of the mission preparation phase are explained. Each of these should be organized and carried out according to the given generic description. Project-specific alterations are, however, always allowed but should be agreed between involved project partners. Changes should preferably be not of such extent that the character of a review is changed significantly. In general, and if applicable, the reviews of the ground segment may be conducted together with the reviews of the space segment, e.g., combining the critical design reviews of both segments to a system CDR.

According to ECSS (ECSS-E-ST-10-06C), the reviews during preparation phase are:

Ground Segment Critical Design Review (GSCDR)

Date:	End of project phase C "Critical Design"
Objective:	Customer acceptance of the detailed ground segment design
Precondition:	Design complete, justified, and documented
Content:	Documentation providing description and justification of the ground segment design but also test and training specification as well as interface definitions
Chaired by:	Ground segment customer

Ground Segment Qualification Review (GSQR)

Date:	During phase D, at the end of ground segment AIT and verification (D2)
Objective:	To ensure that the ground segment conforms to the technical requirements and that all conditions are met for proceeding with the operational validation phase (D3)
Precondition:	Ground segment AIT and verification has been finished, i.e., the ground segment is technically ready for usage
Content:	Test documentation, e.g., reports and report summaries of AITV activities on various levels
Chaired by:	Ground segment supplier

Critical Operations Review (COR)

Date:	During phase D, after completion of operational validation
Objective:	To ensure that all mission operations data has been validated and that all documentation is available to start the training of an operational validation phase
Precondition:	Passed GSQR and finished validation of operational data
Content:	Test reports
Chaired by:	Operations customer

Operational Readiness Review (ORR)

Date:	End of phase D, after completion of operational validation, often 3–6 weeks before launch
Objective:	To ensure full readiness of the ground segment for in-orbit operations, and to authorize its utilization for space segment in-orbit operations; to ensure validation of all procedures and readiness of the FOT
Precondition:	FOT training finished; operations procedures validated
Content:	Documentation describing content, course, and results of operations team trainings, simulations, and rehearsals
Chaired by:	Operations customer

The ORR is the final and last review of mission operations preparation before launch. It provides the clearance for the following Launch and Early Orbit Phase (LEOP), during which the ground segment must stand the test with real in-orbit operations. Until launch, however, a few final actions must be done, including regular technical checks of the ground segment elements. Depending on the mission and the control center that conducts the operations, it is also worth considering a so-called system freeze. That means, from a defined point in time, changes to technical systems that affect the mission's ground segment are allowed only under strict configuration control. This is especially recommended in multi-mission environments. The organization of the system freeze needs then to be coordinated with the control center management and eventual other projects. A system freeze can end after LEOP.

If the preparation for operations has been completed successfully, real mission operations presumably will run smoothly and with none or hopefully only a few unexpected or unprepared-for contingencies. However, a ground segment and the FOT can hardly be perfectly prepared and trained for any kind of malfunction or non-nominal behavior of the spacecraft. A high degree of flexibility and the ability of improvisation are therefore essential to maximize chances for mission success.

2.2 Mission Operations Execution

Sabrina Eberle, Thomas Uhlig, Ralf Faller, and Michael Schmidhuber

Although the preparation phase of a space mission can exceed the duration of the actual mission execution phase significantly, the execution can be considered as the most important phase, in which the spacecraft is fulfilling subsequently all of its mission objectives. A dedicated Flight Control Team is in this phase overseeing the operations of the satellite. This chapter will briefly discuss this phase of the satellites lifetime and highlight specific processes and setups.

The chapter is mainly focused on satellite operations; however, some aspects of human spaceflight are also highlighted. For more details of the latter, Sect. 8.1 can also be consulted.

2.2.1 Various Phases During Execution

The execution phase can be broken down into different periods, which can be distinguished by their special operational requirements.

The first part of a mission is called the LEOP. It is followed by the Commissioning Phase, in which the spacecraft as well as the payload on board are prepared for nominal operations. The actual mission goals are then accomplished in the Routine Phase, which is in most cases the longest phase. The lifetime of a satellite ends with the Disposal Phase or End-of-Mission (EOM), which ensures that the satellite is either parked in a dedicated graveyard orbit or is destroyed by a controlled reentry into the earth atmosphere. This phase is also called the De-orbit Phase (Figs. 2.4 and 2.5).

Of course the execution phase is strongly dependent on the mission goal. A scientific LEO mission with experiments on board for only a few months or 1 year has to be prepared in the same way as a LEO mission with an expected lifetime of 5–10 years. Geostationary satellites (especially the commercial communication satellites) often have lifetimes of around 20 years. Interplanetary missions have by comparison very long execution phases because normally it takes the spacecraft a long time to get to its destination in the first place.

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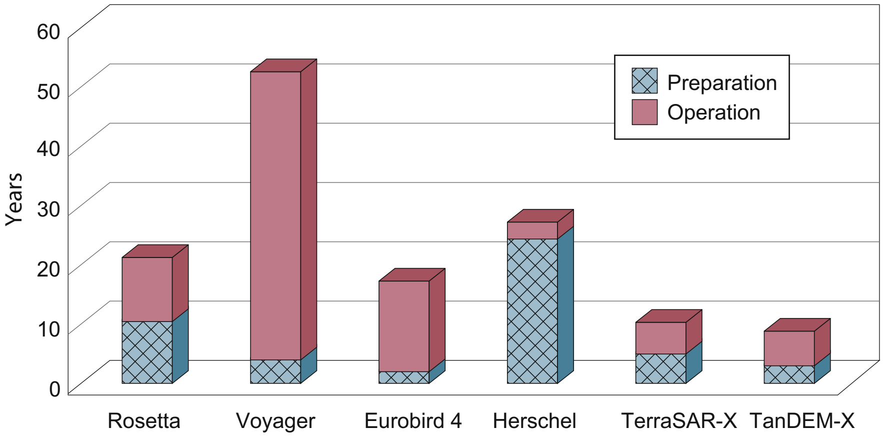

Fig. 2.4 The variable durations of the mission phases using the example of different missions

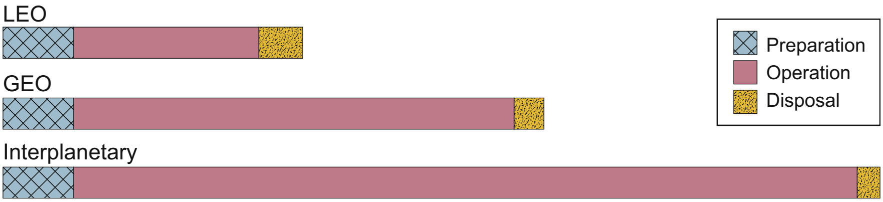

Fig. 2.5 Overview of the differing lengths of mission execution phases on the basis of different mission types. The preparation phase assumed here to be roughly of equal length

2.2.1.1 General Description of the Execution Phase

The abovementioned phases include some common tasks which shall be highlighted in the following section. All spacecrafts have a command and telemetry interface implemented; therefore they can be controlled by telecommands from ground and allow insight into their internal status via the data they send back to the ground stations. This telemetry not only comprises the data from the corresponding payload but also information about important parameters of the satellite's subsystems, like temperatures, currents, status reports from the software or event messages triggered by off-nominal conditions on board. This data – sometimes also referred to as Health and Status or Housekeeping (HK) data—needs to be monitored on ground. Also commanding of the spacecraft is a standard task in the execution phase. Commanding encompasses the operation of the payload as well as the control of the subsystems of the satellite.

Not only the internal performance of the satellite requires surveillance, but also the orbit and the attitude situation of it need to be monitored closely. The active adjustment of orbit and attitude is also required; these maneuvers are described in more detail in Sect. 6.5.

During all execution phases, onboard-maintenance activities like software updates or recalibrations of instruments can take place. Their need is identified during the design phase of the spacecraft and they are usually defined in a maintenance plan, which lists all those activities together with the corresponding time frames, when they need to be conducted.

Satellites are usually designed to be very autonomous. One of the major drivers to involve human Flight Control Teams in the operations is the handling of unexpected situations in the ground or in the space segment. Those events are usually called anomalies or contingencies. Here, humans need to be involved to analyze the sometimes very complex situation—and to put together either troubleshooting plans to identify the root cause of the problem, or to resolve the issue via corrective actions.

Failures can sometimes be prevented, either by preventive actions, which could be part of the regular maintenance activities, or by a detailed short-and long-term analysis of the spacecraft parameters. Tendencies and trends can be observed here, which could result in the decision to take countermeasures to prevent, i.e., further degradation of components or subsystems.

2.2.1.2 Launch and Early Orbit Phase

The LEOP starts after the satellite is launched and released from the carrier. The satellite then has its first time in orbit in which very specific operational requirements take place, which will be discussed in more detail here.

The launch of a vehicle is usually done by a dedicated launch team, which hands over the satellite to the satellite control center after the satellite is released and free-floating. The first major milestone for the controllers is then to establish the first contact with the satellite. Since the ascent phase of the carrier rocket and the release process itself is connected with some uncertainties, the position and orbit of the new satellite is not exactly known; therefore, the first acquisition could be connected with some search activities of the ground antennas. As soon as a radio link is established, the position and orbit can be determined more accurately plus a first checkout of the essential components of the spacecraft follows. In many cases there are also a few very important configuration steps, which need to be performed as soon as possible: The radio link with the satellite is dependent of the satellite's attitude, which determines the orientation of the antennas; therefore, the spacecraft needs to gain attitude control. It is also crucial to ensure power generation capability on board, since the launch phase is usually only supported by the batteries, with limited capacity. This could encompass the deployment of the solar arrays and some reconfigurations of the power distribution system, the proper setup of the battery charge regime, and the switch-on of some vital subsystem components.

With such measures the further survival of the satellite in the harsh space environment is described in more detail in Sect. 1.1. The Space Environment can be ensured. One of the next steps is to bring the satellite to its final destination, be it a dedicated orbit or a dedicated position in the GEO. This might require either several extensive maneuvers with the satellite's propulsion system—or just minor corrections of the orbital parameters. In many cases the maneuvers in this phase of the mission are the main changes of the satellite's orbit over its entire lifetime.

The LEOP phase is probably the most critical phase of the entire mission: After a very demanding ascent in terms of vibrations, acceleration, mechanical stresses, or sound levels, the spacecraft is for the first time exposed to the "real" space environment. The satellite is "unknown" to the operations team and will unveil its characteristics and "features" in this phase—which in most cases leads to several surprises which could lead to a requirement for a redesign of the already prepared operations concept and its corresponding procedures and processes.

Unlike the Routine Phase, which contains usually a series of repeating and well-understood mission activities, a lot of the LEOP activities are singular or even irreversible events. The latter might be due to the fact that the developer decided in the design phase, that only the transition of a given piece of equipment to its nominal ops configuration shall be implemented, but not the transition back into its launch configuration (i.e., only deployment of solar arrays, payload antennas or instrument booms, not the retraction).

The events in the LEOP phase might be time critical, either in the sense that they need to be performed at a very specific time frame (like orbital maneuvers) or that a strict temporal relationship to other activities exist (i.e., a "thermal clock" for equipment, which requires heating after a certain time to prevent degradation or even damage).

Since the LEOP phase contains a lot of transitional states of the onboard configuration, the level of onboard automatisms is usually considerably lower than for the Routine Phase, for which a well-defined configuration of the satellite can be assumed. This also limits the "self-healing" Fault Detection, Isolation, and Recovery (FDIR) possibilities and thus makes the satellite more vulnerable.

All of these abovementioned reasons lead to the requirement to have a good, almost permanent "visibility" of the satellite during LEOP, to have the chance to detect and intervene quickly in case of problems. Therefore multiple ground stations are usually involved to ensure a good coverage, which differs from the Routine Phase, where only one or a low number of ground stations are used for a very limited contact with the spacecraft due to cost reasons.

This setup of multiple ground stations including the coordination of them introduces an additional level of complexity which makes the system more prone to failures. It also requires a high level of redundancy in the ground system to cope with problems in this essential chain link of spacecraft operations.

2.2.1.3 Commissioning Phase

The LEOP phase is followed by the commissioning phase; the transition between them can be blurred. In that phase the satellite is ready to be used; it flies on its designated orbit and its survival is ensured. Now the extensive testing of its payload can be started. This involves checkouts on subsystem level as well as on an integrated level.

In spaceflight it is common to follow a concept of high redundancies. Many subsystems have redundant components—critical ones have even more than one level of redundancy. Elements are called “hot redundant,” if the redundant part is already active and could thus take over the function in a very short time period without interrupting operations. “Cold redundancy” means that the redundant element needs to be activated in a failure case first, which leads to some latency time.

In the commissioning phase also the redundant elements are checked out, to ensure that their performance is sufficient to consider the function as fully redundant and to be able to tune the ops concept accordingly in case of a degraded performance of the redundant component. The test of a hot redundant component is less critical than the test of a cold redundant one, since for the “hot case” the device is already active and some information about its performance is at hand already.

Redundancy testing is important for a future lowering of the operational risks; however, it also constitutes a certain risk in itself: The spacecraft is brought from a good and reliable configuration into a configuration which involves a not-yet-tested component; also the transition process between the nominal and the redundant element can be considered as a more vulnerable phase of the satellite, since it is originally only foreseen to be executed in a contingency case, where the increased risk of switching to another box is justified. For these reasons it is attempted to avoid unnecessary switching processes and to bring them down to an absolute minimum by working on sophisticated checkout sequences.

As already mentioned, checkouts during the commissioning phase are not only done on the subsystems of the satellite platform but also on the payload complement. This subphase is called In-Orbit Testing (IOT). Depending on the payload and its purpose, it might be required to run dedicated configuration procedures or to perform calibration runs with them. The latter might involve additional support or equipment on ground, which is not required during the routine phase. At geostationary communication satellites normally the antenna needs to be positioned to align the antenna beam on the chosen area, the solar panels need to be activated to rotate with the sun, and the payload itself must be started.

In many cases it is also required to prove that the flight hardware meets its specifications or requirements from the design phase. This can have technical or even contractual implications. Therefore there might be test objectives which need to be accomplished during the commissioning phase as well.

All the above tasks which are typically for this phase of the missions require the presence and participation of the corresponding experts, be it from the companies involved in the construction of the components, from the expert teams within the Flight Control Team, or from the side of the payload users, the experimenters, or scientists.

Sometimes a mission control center only conducts the LEOP and Commissioning Phase and transfers the operations to another routine operations center for the comparatively easy routine phase. This transition is called the “handover.” The LEOP control center is still in standby for the first few contacts after the handover and after checking that the routine operations center can operate the spacecraft trouble free, the LEOP control center stops its operations. This scenario is used rather frequently when the satellite manufacturer offers a turn-key delivery to the customer in orbit or when the routine control center does not have the experience or the resources (large control room and access to global ground station network) available to conduct a LEOP.

2.2.1.4 Routine Phase

When the commissioning phase could be successfully completed, the routine phase can be initiated. The operations of the satellite are now usually linked to routine processes, the telemetry is observed and analyzed as already described, and planning as described in Sect. 5.1 governs the day-to-day tasks of the satellite. The payloads are operated to reach the mission objectives, whereas the subsystems are operated to support payload operations and to ensure the well-being of the entire spacecraft.

Planning also encompasses the management of the limited resources the spacecraft has available, like electrical power or also fuel for orbital maneuvers.

The character of the routine phase also allows reducing the manpower utilized during steady-state operations to a minimum; the experts could be assigned to other projects and are only required to be available "on need." Nevertheless they still monitor their subsystem on a daily or at least weekly basis, dependent on the complexity and flexibility of the subsystem. Especially at the thermal system trend analysis is a very important instrument because the system is rather indolent and it takes the temperatures a while to change, so it is important to keep an eye on the long-term monitoring. At other subsystems like Attitude and Orbit Control (AOCS), the specialists monitor their parameters more often. All SSEs analyze trends, in order to prevent foreseeable contingencies or errors during the whole routine phase.

In addition to the monitoring of the telemetry, there are normally weekly team meetings to discuss special mission topics, occurred events, and upcoming actions. Special but expected events are, e.g., orbit correction maneuvers which are calculated by the flight dynamics team (FDS) or antenna tests at the ground stations. In geostationary satellite missions the orbit correction maneuvers are normally very predictable and follow a certain repeating pattern. For LEO missions mostly not many maneuvers are required and depending on the mission will only be done every few month. Further routine tasks beside the weekly team meetings are the monthly reporting to the customer, the maintenance of the change control, and the constant training of the team members to keep them up to date and always trained even during a long routine operations phase.

Unexpected events are, e.g., a collision avoidance maneuver, a switch to a redundant component on board or a software upload, normally provided by the satellite manufacturer. The daily routine operations, e.g., dumping the telemetry and sending the timetable for the next payload operations, can be taken over by command operators (SPACONS), which are not required to have an in-depth knowledge of the satellite's subsystems. In case anything unforeseen happens the operator immediately contacts the Flight Director or the relevant SSE.

At the routine operations the ground network, which is required to maintain the contact to the satellite, is reduced significantly. In many cases only one ground antenna can serve this purpose, depending on the orbit parameters, as described below. In that case the visibility of the satellite is reduced to some passes per day only, which are then used to downlink the payload data, to get an insight into the health and status parameters of the satellite and to uplink commands, which might be "time-tagged," meaning that they are not immediately executed, but only at a well-defined time during the following orbit(s). Often, highly automated planning engines on board of the satellite can take over control on board and execute the payload tasks autonomously.

2.2.1.5 End of Mission or Disposal Phase

There are some actions to be completed before the satellite mission can be declared as ended. This is required by national policies or agreements with the customer. All these tasks are summarized in the disposal or decommissioning phase.

It has to be ensured that the satellite is not posing a risk for future spaceflight missions or for anybody living on Earth and—especially for the case of the very crowded GEO—its position in the sky needs to be freed for its possible successors.

The latter can be achieved by two means: In case of LEO satellites the orbital maneuvering system is used to change the spacecraft's trajectory in a way that it enters the earth atmosphere in a controlled manner and is then destroyed by the thermal energy in which the immense kinetic energy of the object is converted to during reentry. In case the satellite is on a GEO, it is brought into a so-called graveyard orbit, a trajectory in which the satellite does not interfere with other satellites for many decades. This orbit is a few hundred kilometers above the GEO. Each mission is committed to leave enough fuel in the tank so the spacecraft can be maneuvered either into the earth atmosphere or the graveyard orbit. This amount of fuel has to be calculated very thoroughly for each maneuver during the routine phase to ensure that not too much fuel is left, which would cost the mission valuable lifetime, and not too little so the final maneuver can be executed completely.

For the de-orbiting itself normally the payload will be switched off and the satellite will be brought in a safe configuration (Skalden 2013). The systems are passivated by shortening the batteries and emptying the tanks to reduce the danger of explosions.

2.2.2 Staffing of the Flight Control Team

Each mission has other requirements for the composition of the Flight Control Team—and different control centers follow slightly different philosophies. However, some elements and some considerations have general validity and those will be presented below.

The different functions which are represented in a Flight Control Team are often referred to as "consoles" or "positions"; they are interconnected by modern voice communication systems and use dedicated tool suites to spread information to everybody, to document decisions which have been made, to record the shift events in a dedicated shift diary, to command the spacecraft, and to see its telemetry.

2.2.2.1 Mission Operations Team Lead

A complex, multi-person team requires a clear hierarchy, a coordination function, and a decision-making process, which allows quick reactions to unknown situations. Therefore a team lead function is available in all setups of Flight Control Teams. The nomenclature can differ, typically the terms like "Mission Ops Team Lead," "Spacecraft Operations Manager," or "Flight Director" are used. Flight Director (FD) is used in this book.

The person on that position has the full responsibility of all operations conducted by his team, which involves especially all commanding of the spacecraft. Therefore the Flight Director is also the final instance for all decisions and has to approve all commands which are sent to the vehicle.

His authority in real time is usually only limited by the ops documents, which define the operational envelope for the satellite—and under certain emergency circumstances he can also decide to violate those. It is important for the flexibility and adaptability of operations to equip him with extensive power.

Depending on the project setup, the authority of the Flight Director might be limited to real-time processes only. In these cases there needs to be another authority which is not part of the Flight Control Team, but provides the team and the Flight Director in particular with management directives in case need be.

The FOT has the full responsibility for the satellite during operations. During critical operations phases like the LEOP or special tests during commissioning phase, an industry team will assist the FOT. If there are any non-nominal situations which were not described in the handbooks and are not covered with procedures, the industry team may help finding a solution to bring the spacecraft back to the nominal configuration. However, the Flight Director has the overall responsibility of the operations. The SSEs of the industry team only advise their corresponding partners of the FOT. The team lead of the industry team is often called the "Satellite Team Lead" or "STL." This person will directly communicate with the Flight Director.

Representatives of the customer will have a number of console positions in the control room so they can monitor the operations. They communicate within their own team on a dedicated Voice Communications System loop and of course they cannot send commands. If and how the customer is involved in operations and decisions is dependent on the mission.

2.2.2.2 Subsystem Specialists

All subsystems of a spacecraft are usually reflected as positions in the Flight Control Team. That way it can be ensured that the team has sufficient expertise and the manpower to concentrate on their subsystems, to decide in critical situations, where a deviation from the standard processes is required. The subsystem specialists monitor the data of their corresponding subsystem, analyze it, and ensure that possible anomalies are detected and resolved. The level of resolution is again dependent on the overall concept: The Flight Control Team might be empowered and able to bring the spacecraft back into a fully nominal configuration—or they just conduct a first contingency response, which brings the satellite into a safe mode, and have now enough time for the further analysis of the problem. This will then be discussed and forwarded to engineering support teams, which finally provide the team with advices how to recover the anomaly and resume nominal operations. The industry team normally will assist the Flight Control Team.

The Flight Director as the final decision instance in real time is supported by his specialists in his decisions.

For human spaceflight missions, the crew can be considered in a first approximation as (an) additional subsystem(s); therefore additional positions in the Flight Control Team like "spacecraft communications" or "medical operations" are available here.

2.2.2.3 Command Operator

In many teams the actual commanding activity is performed by a dedicated command position. This ensures a good coordination of all commanding, since it is done centralized. The command operator or SPACON (spacecraft controller) takes instructions from the Flight Director. In that way the flight team is relieved from the technical aspect of the MCS and the communication with the network operator (NOPE) and the ground stations (cf. Sect. 3.2).

In routine phases the presence of the Flight Control Team in the control room can be reduced to only the command operator, who receives pre-generated and pre-approved command tasks from the subsystem specialists and the Flight Director. The operator then prepares the command sequence, uploads it, and checks its successful execution. Should he detect any anomaly, he could then alert the Flight Director or the subsystem specialists which are usually on call for that purpose. His autonomy is usually constrained to well-understood and strictly defined situations.

2.2.2.4 Planner

The scheduling of the often very complex activities and a quick and profound reaction in case of malfunctions to ensure that the mission can continue under the new boundary conditions requires the presence of a planning function in the Flight Control Team. The planning concepts for satellites and human spaceflight operations are described in more detail in Chap. 5. The inputs of the mission planning team, the timeline, will be provided as ready-to-send telecommands and will be part of the daily command stack. Conventional geostationary communication missions usually need no dedicated mission planning. The planning tasks are distributed within the FOT.

2.2.2.5 Flight Dynamics

The maneuvers which have to be performed will be calculated and initiated by the flight dynamics group. These can be normal orbit maintenance maneuvers to keep the satellite in its nominal orbit, or an unscheduled maneuver like a collision avoidance maneuver. These maneuvers have a high priority and all the other planned tasks will be canceled and rescheduled in order to prevent the satellite from a possible crash with another spacecraft or an impact with an uncontrollable component. The planning and development of an orbit maneuver is described in more detail in Sect. 4.1.

Also other orbit related information is provided by the Flight Dynamics Team: Contact Times, S/C sensor usability prediction, maneuver calibration, and the collision risk estimation.

2.2.2.6 Ground Data Systems

To communicate with the spacecraft, the data links from the control center to the ground station and on to the satellite and back have to be established and maintained. This is done by the Ground Data Systems Group. The communications with the ground stations from the control room is executed by a special network communications operator. He will also inform the Flight Director about difficulties or changes concerning the antennas. The communications concept is described in more detail in Sect. 3.2.

2.2.2.7 Assistance Team

Essential support to the Flight Control Team comes from the Engineering Support Team, which is in most cases staffed by experienced engineers of the satellite supplier companies. They have the expert knowledge to analyze problems which lie beyond the knowledge and the expertise of the Flight Control Teams. In critical phases (e.g., LEOP) representatives of this team need to be present in the control room; in routine phases they can be contacted remotely if need be. They can be considered the second—and in many cases also the last “line of defense.” Special attention has to be given to the fact that naturally the industry experts are moving on in their careers and the original knowledge is dissipating over time. In long-term missions the Project Manager and the Flight Director need to secure the necessary knowledge and eventually bring this to the attention of the customer.

2.2.3 Interactions within the Flight Control Team and Flight Procedures

2.2.3.1 Interactions within the Flight Control Team

A typical scenario in a full-fledged Flight Control Team is described here for better illustration of the baseline concept.

During the Acquisition of Signal (AOS) one of the subsystem components on board shows a high spike in the current of one of the power devices. The values are sent down to the control center, where the reading appears on the telemetry displays of the Flight Control Team. The out-of-limit condition might be automatically detected by the ground software and the team could have been alerted via a visual—and under certain circumstances maybe also an audible alarm.

Either the Flight Director now prompts his team—or the responsible subsystem specialist proactively approaches the Flight Director and provides some information about the failure signature he has seen, an ad-hoc analysis about the root cause, and—with a reference to the ops documentation—a recommendation on how to react in that specific case. The Flight Director might involve other affected disciplines or might consult an assistance team, in case it is available and then base his decision for the problem response on the information he gathered. He would then advice the command controller to prepare the corresponding telecommands and send them to the vehicle, in close coordination with the corresponding ground station. The success of the commanding and of the problem resolution approach is then checked by the command operator and the subsystem specialist, respectively. Based on the results, further steps of recovery, some troubleshooting measures, analysis by further experts, or the documentation of the anomaly will follow.

All the interactions between the various positions are usually described by ops documents, which are also the foundation of the work and responsibility sharing within the team.

2.2.3.2 Flight Operations Procedures

Safe and reliable operations of a spacecraft in orbit require sufficient knowledge about how to fly the spacecraft. Detailed information about the spacecraft itself and the ground system used for the operations is provided by handbooks, telemetry and telecommand databases, and other reference lists, but the basis for the operations is built on the so-called FOP.

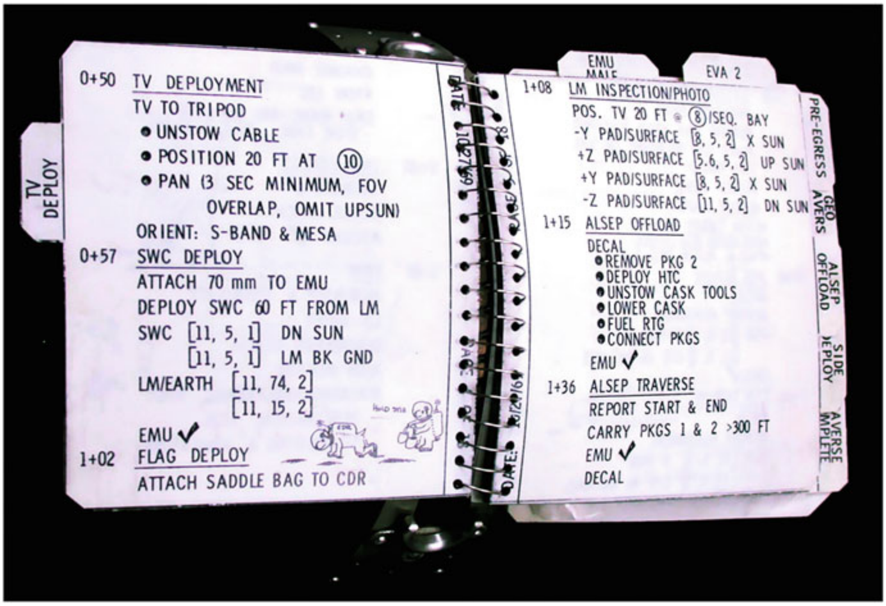

Fig. 2.6 Apollo 12 astronaut cuff checklist, NASA

Definition and Applications

FOP are a prepared, tested, and validated set of work instructions that list in the very detail all activities and checks to be performed for a specific purpose. This includes the exact sequence and timing of the different steps, complemented with comments about the activities and go/no-go criteria for critical events.

Depending on the mission characteristics, e.g., operating a manned or unmanned spacecraft, long (in GEO) or short (LEO) ground station contact times, the kind of monitoring and control system (MCS), level of spacecraft autonomy, or mission budget, different types of FOPs can be used. For manned missions with astronauts in the loop, it may be sufficient to have FOPs in a free text form on paper or screens (see an example of an astronaut checklist on Fig. 2.6). In unmanned missions, most actions are done through telecommands and telemetry. Therefore flight procedures concepts are mostly table-based (see Fig. 2.7). This allows an automated processing of the instructions and thus, safer and easier preparation, and shorter execution times. More sophisticated systems are using script languages, which allow partly- or fully-automated execution of procedures by the ground system with only a minimum of supervisory activities by the operations personnel.

FOPs are typically grouped into procedures for nominal and non-nominal activities and tasks. Nominal procedures might be used for standard and planned situations (e.g., boost maneuver during LEOP), while non-nominal, often called contingency procedures, are prepared for anomalies, error detection, and trouble-shooting (e.g., no telemetry at signal acquisition).

PX1	NP120		Solar Generator Partial Deployment					TPX-Flight Operations Plan Vol 3		Issue 1.3	
STEP	TIME		ACTIVITY				DISPLAY	TM			
n°	ABSOLUTE	RELATIVE	EVENT DESCRIPTION		CODE	DATA	FMT	CODE	DESCRIPTION	RESULT	
1		T0-8min	**Verify Entry Conditions**								
			Check S/C Status								
			VERIFY:								
			AOCS mode				5200	AS100	AOCS mode	**SAM**	O
			Sun vector S/C x				5200	AD451	Sun S/C x	**0 +/- 0.02**	O
			Sun vector S/C y				5200	AD452	Sun S/C y	**0 +/- 0.02**	O
			Sun vector S/C z				5200	AD453	Sun S/C z	**-1 + 0.02**	O
			Main battery power level				6122	PD300	Bat A PWR	**> 50Ah**	O
			Deployment hinge temperature				2200	TP280	Depl H tmp	**> 10 deg**	O
			IF entry Conditions are not correct								
			THEN postpone deployment								
			ELSE proceed with step 2								
2			**Partial Deployment**						**UPS: make hardcopy of #4210**		O
2,1		T0-5min	**Prepare Pyro System for Deployment**								
			SEND:								
			Activate_Pyro_System		11PAD						[]
			Set_Pyro_System		10PAD						[]
			Arm_stage			12					
			VERIFY:								
			Pyro system arming				6122	AS230	Pyro Arming	**ACTIVE**	O
			Arming stage selection				6122	AS235	Arm Stage	**12**	O
2,2			Request Go/NoGo for deployment from all subsystems								O
2,3			Request Go/NoGo for deployment from STL								O
2,4			**Deploy Generator**								
		T0-1min	Set TC system in BD mode						**TC operator: verify TC system in BD-mode**		O
			SEND next 2 commands in sequence:								
		T0			20PAD						[]
			Fire Pyro		21PAX						[]
									TC operator: verify TC system in AD-mode		O

Fig. 2.7 Table-based flight procedure example

Flight Procedures can be "atomic" or "elementary" and contain only a few instructions around one activity (e.g., switch on of S-band transmitter) or they can be encompassing to cover a long complex activity (e.g., in-orbit test of a repeater payload).

FOP Life Cycle

The initial input for the FOP generation is provided by the spacecraft manufacturer, because he has designed the spacecraft and the basic algorithms to operate it. The initial procedures consist of the basic activity flow, the commands to be sent, telemetry checks to be performed, constraints, and basic timing specifications. In the next step, the flight operations specialists complement the procedures by adapting them to the provided Monitoring & Control System and insertion of additional information, like display page references for telemetry checks or ground-based activities. Finally the procedures are validated by running them in simulator sessions or comparable test environments, so the correctness of foreseen commands, TM checks, and timing is confirmed. With the release of the validated FOPs, the utilization phase starts. Caused by updates of the spacecraft database, flight experiences, or changed S/C hardware characteristics, maintenance of the FOP might be required. The procedures need to be updated including additional validation sessions and an official release. A crucial factor is to keep the FOPs under strict configuration control to ensure that only validated and released procedures are used for flight.

Satellites that are built as a series and have a commercial background have the advantage that the flight procedures will be prepared by the manufacturer in a good maturity state. One-of-a-kind missions like scientific satellites or new models will require substantially more work to be done on flight procedure development and the control center may be asked to contribute in that work.

2.2.3.3 Anomalies and Recommendations

In the previous chapter, flight procedures were introduced as the central element for flight operations. It is obvious, however, that in spite of optimal mission preparation, a comprehensive set of FOPs and intensive testing of all space and ground components beforehand, anomalies during the mission cannot be avoided. All kinds of glitches and malfunctions, in the space segment or on ground, might cause a disruption of the running activities and require proper reactions to resume nominal flight operations again.

Anomalies

Anomaly handling is the process of a controlled reaction on problems and anomalies, which is required by common quality management standards. A usual approach is to process ground related problems, e.g., control room or ground network hardware or software problems, by the established issue tracking system of the ground facility by generating nonconformance or discrepancy reports for logging and troubleshooting. Space segment related problems are covered by the FOT. A work flow has to be established to issue a corresponding anomaly, to inform the involved persons for problem solving and to decide the corrective measure (see next paragraph). All steps of the process will be logged. The size of the work flow and the number of roles involved in the process depends on the project size and its complexity, but at least the Flight Director and a responsible subsystem specialist need to be involved.

Recommendations

Recommendations are the controlled way to introduce and process additional actions or changes to the planned flight operations. A recommendation typically consists of a short description of the context and purpose of the desired action and step-by-step orders to be performed. All kinds of actions can be addressed, e.g., sending of an additional command and altering a pending or execution of a so far unplanned flight procedure. Within the process of anomaly handling, recommendations represent the corrective measure.

Key element for the recommendation is the at least a four eye principle, i.e., the recommended action needs to be checked and approved by involved engineers and the person in charge of the flight operations (Flight Director). An example of a recommendation work flow is described as follows: A member of the flight ops team prepares the recommendation, which is checked and complemented if necessary by the affected subsystem specialists or an assistance team responsible (e.g., during LEOP), and finally approved for execution by the Flight Director. The recommendation is completed after its execution and the confirmation of the expected results by the SSE and the Flight Director.

All recommendations have to be noted in a written form, either on paper, or using a dedicated tool. The steps have to be signed by the corresponding persons/roles. In critical situations, where a quick response is needed, a recommendation can be processed verbally first, but shall be noted and fully logged later.

2.2.4 The Mission Type Defines the Operational Concept

Basically there are four different types of operational concepts which are operated at GSOC: the LEO satellites, the GEO satellites, the deep space missions, and the Human Spaceflight. A typical example of LEO satellites are the Grace twin satellites (Tapley et al. 2004a, b). They were designed to measure the gravitational field of the earth. They were launched in 2002 and use changes in their relative distance and speed to derive information about the local gravity forces.

SATCOMBw is a communication satellite family consisting of two satellites identically constructed. The first one was launched in 2009, the second in 2010. Their representatives are examples for geostationary satellites.

Galileo was a deep space probe whose science objective was to explore Jupiter and the Jovian system (Belton et al. 1996). It was launched in 1989 by the Space Shuttle and its lifetime ended by the deliberate entry into Jupiter's atmosphere in 2003. Its mission significantly contributed to our understanding of the Solar system. A GSOC team was located at the JPL to support operations during the mission duration.

For more information on Human Spaceflight, please see Sect. 7.1.

2.2.4.1 Low Earth Orbit: GRACE

The GRACE satellites are orbiting the earth at an altitude of approximately 430 km in a polar orbit with an inclination of 89°. The orbital period is approximately 93 min (Fig. 2.8).

For LEO missions one of the typical operations tasks during the routine phase is the "housekeeping" of the spacecraft. Nearly all the telemetry parameters are monitored. Each SSE monitors his subsystem and reports to the Flight Director in case any of the parameters do not behave as expected. The team will not only react when yellow or red alarm situations are indicated in telemetry, the SSEs will also perform long-term monitoring where the data will be recorded and plotted over an

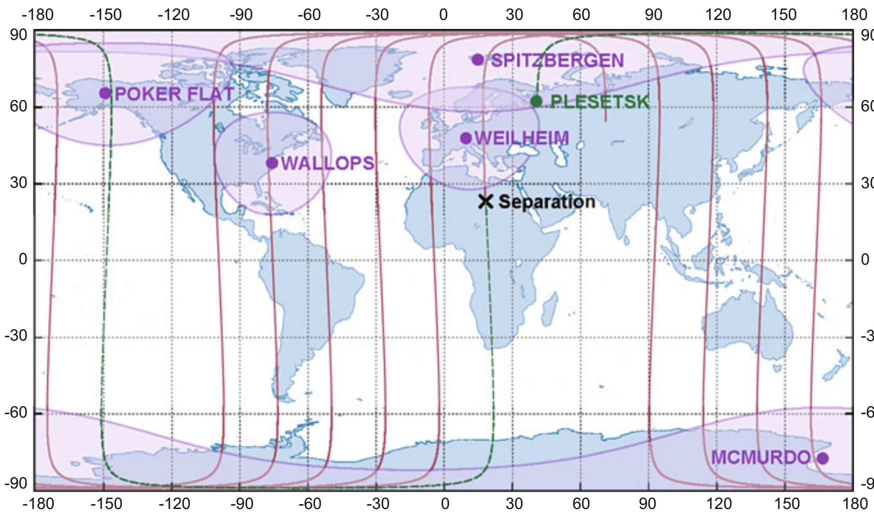

Fig. 2.8 The ground track after launch (the *green line* is the track before first acquisition which was over Weilheim) of GRACE shows that only a few contacts are possible

extended time frame, sometimes even years, and evaluated by the experts to perform predictions and react in advance to trends and tendencies. During the nights and weekends Command Operators will watch the telemetry during the station passes and inform the Flight Director and the responsible SSE immediately in case any anomalies occur.

Another major task during LEO routine operations is the attitude and orbit determination. The flight dynamics team collects the orbit measurement data (typically GPS measurements) and calculates the exact orbit and generates the information for the next maneuver. The FOT will command the satellite with the orbit maneuver data and execute the maneuver. Afterwards the specialists of FDS will check the satellite orbit again und evaluate the accuracy of the orbit maneuver. For the detailed description of the execution of the maneuver please see Sect. 4.1.

The payload operations are depending on the corresponding payload the satellite is carrying. In case of the GRACE satellites there are scientific experiments which have to be commanded and monitored. The recorded data of the satellite payload are dumped over the ground stations and will be distributed to the scientists afterwards. A dump is the download of a data storage that contains previously recorded telemetry. All these tasks have to be organized and scheduled and this will normally be done by the mission planning tools. For further details see Sect. 5.2.

Because of the low altitude of the LEO satellites, the contacts with the ground stations are quite short. Normally at an altitude of ca. 500 km the time that the ground station has contact to the satellite is only around 10 min. With scientific missions like GRACE, the number of ground stations is limited due to the costs of each ground station contact. As a consequence the number of ground station contacts with one or two ground stations leads to about five contacts per satellite

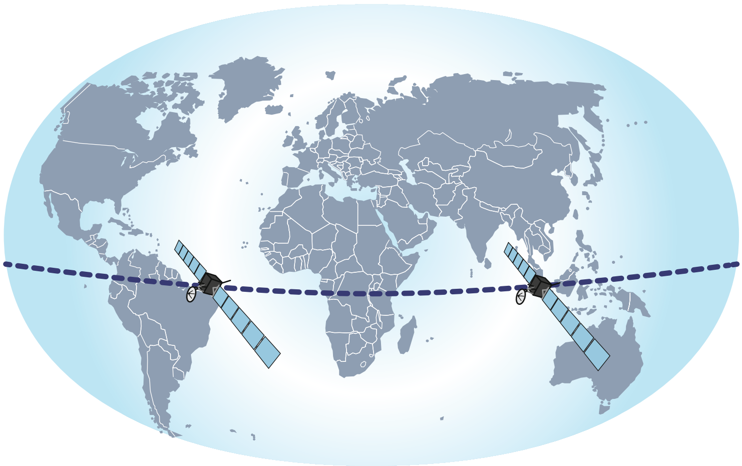

Fig. 2.9 In a geostationary earth orbit the satellite seems to "stand still" over one location; that means the ground track is only a spot. The *shaded area* indicates the regions on the earth from which the satellite can be seen

per day. This is the reason why most of the routine operations are conducted with time-tagged commands. These commands are sent to the spacecraft during the contacts. They have a certain time stamp which means they will not be executed right away but be stored on board until their intended execution time. This allows the execution of orbit maneuvers, payload-specific actions, or software uploads, which normally take a long time, any time and not only during ground contacts. Without the option of time-tagged commands, the operations would be much more complicated and insufficient.

The command verification can either be done via mechanisms provided by the data handling system (see Sect. 6.2) or by checking if it was executed in the telemetry during the next pass, which would be the indirect verification.

During the LEOP the ground station network is of course more extended than during the routine phase, although there normally still is no full coverage. Depending on the mission there are four or more ground stations involved. In case of emergency operations there will be booked additional ground stations to support the mission and bring it back to normal operations as soon as possible.

2.2.4.2 Geostationary Earth Orbit: SATCOMBw

At the altitude of approximately 36,000 km above the earth and at an inclination of 0° against the equator, the geostationary satellite seems to stand still over one location. With this fact the control center has a 24 h per day visibility of the satellite with a single antenna located in a suitable region of the earth (Fig. 2.9). The two geostationary satellites of the German Bundeswehr (Armed Forces) called

COMSATBw1 and COMSATBw2 are located at two positions of the GEO so that they both can be operated through ground stations located in Germany. Due to the permanent visibility, the GEO satellites can be monitored all the time. The spacecraft surveillance including the monitoring of the spacecraft housekeeping is performed with a 24-h 7-days-a-week Operator shift concept. The telemetry surveillance and the long-term monitoring of the data are conducted by the SSEs as described in the chapter above. The orbit maneuvers, the payload operations, and the software upload can be monitored in real time. The use of time-tagged commands is reduced.

The first days of the GEO-LEOP are not fundamentally different from a LEO-LEOP. The control center takes over the satellite after separation from the launcher and checks out the bus systems. Notable differences from a LEO are the facts that a propulsion system has to be prepared and that solar panels have to be unfolded. Usually the satellite is released by the launcher into a highly elliptic trajectory, the geostationary transfer orbit (GTO). As shown in Fig. 2.10, this orbit has a height above the earth ranging from 300 km in perigee (point closest to the earth) up to 36,000 km in apogee (highest point of the orbit). Variations are possible. Some launchers allow to release the satellite directly in the GEO; others are using a super-synchronous orbit (apogee higher than 36,000 km height above the earth) to be able to change the orbit inclination more efficiently. The orbit duration in this phase is about 11 h. Station visibilities are several hours long. Interestingly, seen from the ground station the satellite can change the apparent direction of movement in the sky, as depicted in Fig. 2.10. The general approach is to be able to monitor and control the satellite as continuously as possible and therefore to include many ground stations in the LEOP network. For critical operations (e.g., for maneuvers) it is advisable to even have redundant stations available. The maneuver sequence also dictates that critical events are often happening at night hours and are possibly not compatible with convenient work shift arrangements.

When the satellite is stable and the main bus components have been checked, orbit maneuvers with the satellite motor are performed around apogee position. This maneuver sequence will increase the perigee height in several steps to an altitude of 36,000 km and to the desired longitude. Once the spacecraft reaches its final position in the GEO, only one ground station is needed for continuous visibility (Fig. 2.11). In case of SATCOMBw there are additional ground stations available from which the satellites could be operated in the event of contingency situations. These ground stations have to be tested on a regular basis to make sure that the handover works flawless if needed.

The limited possibilities of the spacecraft of the 1990s to determine their orbit and attitude influence the classical GTO operations scenario. In the time when the classical GEO communication satellite was designed, no GPS was available and its use is limited, as during large parts of the orbit (above approximately 3,000 km height above the earth) the GPS signals are not continuously receivable. Ranging and angle tracking from ground has to be performed. Also the attitude was usually determined with sun and earth sensors only. This influences operations during

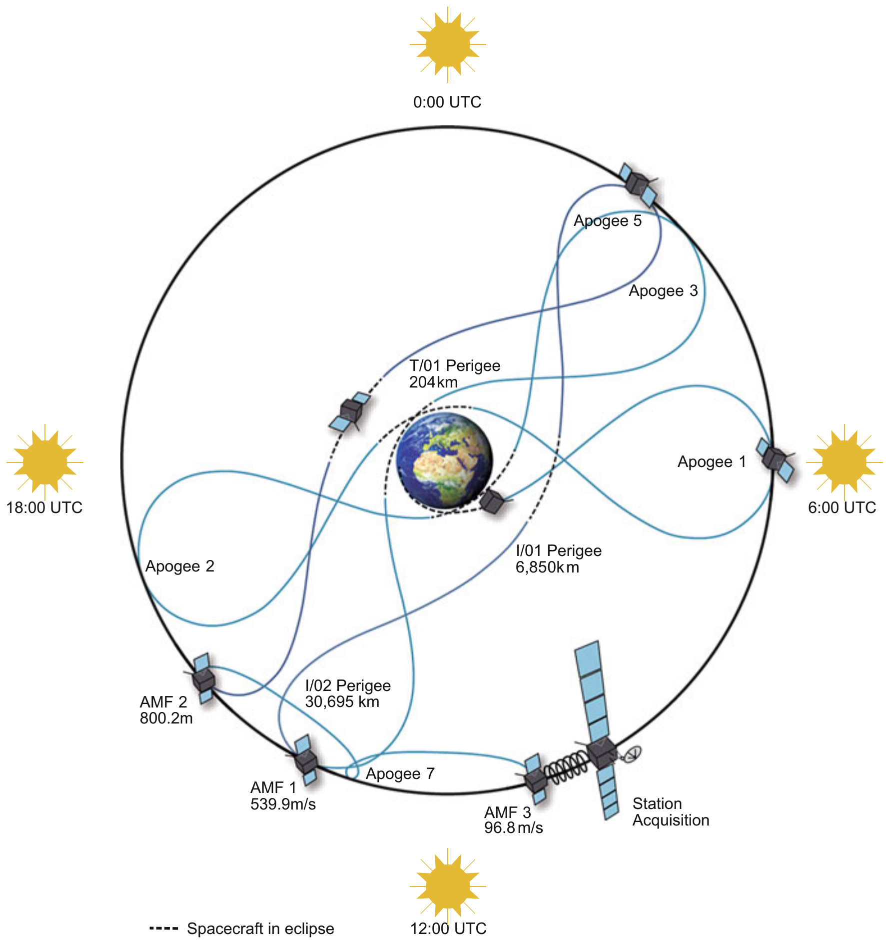

Fig. 2.10 The LEOP trajectory of Eutelsat II-F2 in the earth-fixed coordinates as seen from the north. This illustration allows to see the movement of the spacecraft across the sky as seen, e.g., from the ground stations (Illustration based on P. Brittinger, H. Wobbe, F. Jochim, DLR)

eclipse phases and during maneuvers, resulting in costly ground networks, complex activities, and long waiting periods. Modern spacecraft will be equipped with star sensors and high-sensitivity GPS receivers, which will reduce some of the limitations as described in Zentgraf et al. (2010).

The routine phase of a geostationary satellite is mostly focussed on payload operations. In regular intervals of a few weeks, the satellite's position has to be corrected, as perturbation forces influence the orbit. Short boost maneuvers will be executed that normally do not disturb payload transmission. Repeater payload activities have to be performed in long intervals. They are described in Sect. 6.6. Apart from long-term trend analyses of the equipment, the remaining fuel mass has to be calculated. Comparatively small teams can easily supervise entire fleets of satellites at the same time.

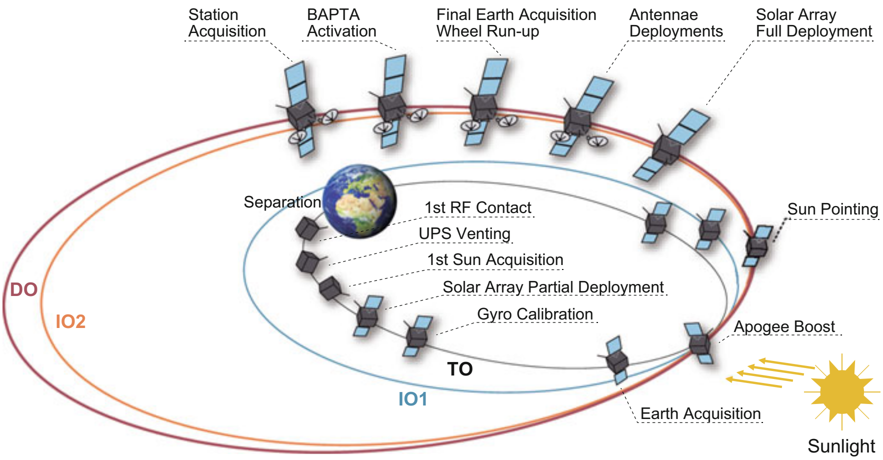

Fig. 2.11 The LEOP orbit of SATCOMBw in inertial coordinates. This view shows the successively larger orbits after the motor firings

Finally an aspect that should not be neglected is the fact that GEO missions are different from all other space missions in that they are often highly commercial in nature. Serious business plans and large sums of money rely on a timely service entry. The spacecraft involved are mostly from an established series with proven equipment. The spacecraft are extremely expensive and expectations are high. On the positive side, manufacturers will provide a complete set of documentation including flight procedures along with a convenient full scale software satellite simulator.

2.2.4.3 Deep Space Missions: GALILEO

The typical deep space mission spacecraft is operated outside of the earth's gravitation field at a long distance from earth. It normally takes a very long time, compared to LEO or GEO missions, for the spacecraft to reach its destination. It took the deep space mission GALILEO nearly 6 years to reach the Jupiter orbit with the goal to study the planet and its moons. It took the spacecraft five flyby maneuvers at Venus and Earth to gain the necessary speed to reach Jupiter. The satellite needs a very high degree of autonomy to detect failures by itself and to autonomously recover from them because the response from ground can be delayed by several hours due to the radio signal travel time. Because of the geometry of the orbit, the contact durations are often several hours long. Depending on the mission phase only one antenna may be used, which results in daily repeating periods without contact (Fig. 2.12).

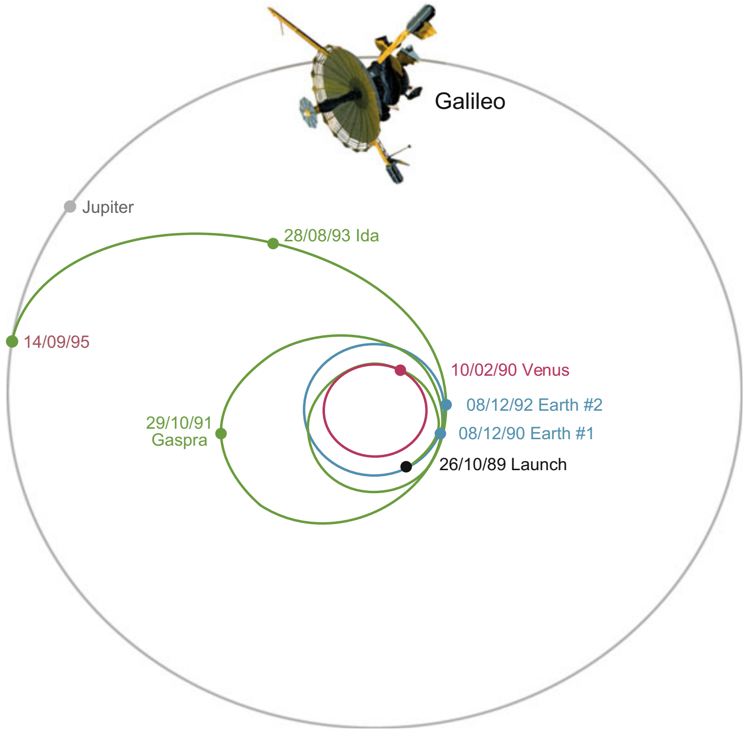

Fig. 2.12 GALILEO's long journey to the Jupiter System

A challenge coming from the long transfer times is to keep up the expertise in the operations team, from the manufacturer side and in the scientific community. Projects like Rosetta can span entire careers. It is wise to build up the necessary spacecraft knowledge inside the control center and to preserve access to the engineering model. For more details on deep space missions, please see Sect. 7.3.

2.2.5 *Summary*

The operational concept is very much dependent on the mission type and may vary for the different missions. The composition of the Flight Control Team is in turn driven by the requirements derived from the operational concept; however, some basic commonalities can be deduced.

2.3 Flight Experience

Ralph Ballweg

This section will cover examples of lessons learnt at DLR/GSOC, particularly in the course of multiple LEOP phases of communication satellites. It will then handle the process of dealing with system contingencies, mostly on spacecraft side and wrap up with several spacecraft anomalies and the attempts to deal with them.

2.3.1 Statistics

From 1987 to the year 2002 GSOC supported on an average of one launch per year LEOPs of geostationary communication satellites. Among these were two series of six almost identical satellites for the provider EUTELSAT from 1990 to 1995 and 1998 to 2002. We will use the first series of EUTELSAT II satellites to demonstrate how leaning curves can develop. The satellite TV-SAT 1 will be used to illustrate problems that occurred in the course of a mission.

At first we will take a look at the LEOP duration (Fig. 2.13). The LEOP operations for a geostationary communication satellite can typically be performed within 2–3 weeks. These operations include the positioning, configuration, and in-orbit testing of the satellite bus. Short LEOPs are desired by the customer in order to bring the satellite into service as early as possible.

Proficiency and reliability of the ground system, its components, and the team have a direct impact on LEOP duration as experience grows which can be seen in the next paragraphs. Over the course of the six Eutelsat II missions, the LEOP durations were cut from 18 days with EUTELSAT II F1 in 1990 to 11 days for EUTELSAT II F6 in 1995. Flight F5 was lost due to a launcher failure.

There were several areas where refinements and optimization improved the performance:

(a) Station acquisition strategies
(b) Procedures
(c) The SOE (sequence of events)
(d) And within the control center hardware and software tools which for example allowed a faster analysis of data for further processing like ranging data and expedited maneuver calculation

Another indication of the level of maturity of the operations concept is reflected in the number of Engineering Change Requests (ECR) and Non Conformance

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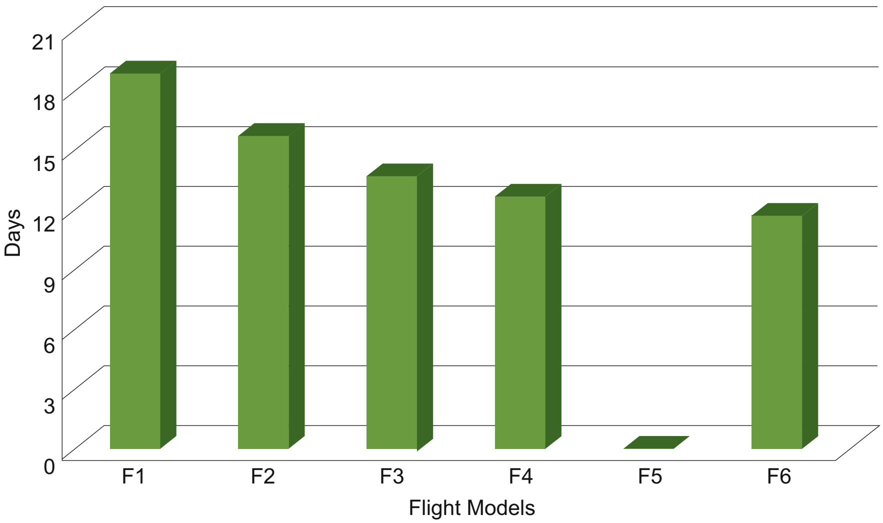

Fig. 2.13 Duration of LEOP for a series of EUTELSAT II satellites

Reports (NCR) that were issued in the course of the mission preparation (Fig. 2.14). Configuration control during mission preparation and mission performance phase is formally managed by ECRs and NCRs. An ECR is raised whenever it is intended to modify a certain topic to the specifications or the existing configuration. An NCR is issued whenever a deviation with respect to the specifications is observed or if a subsystem differs from the expected behavior during the mission preparation phase.

The number of ECRs dropped from Flight 1 with ~170 to ~50 for Flight 6. The high number of change requests at the beginning is easily explained with the fact that the ground segment had to be configured for a completely new mission. For the next launch the change requests already dropped to about 60 CRs as a result of the previous experience. The slight increase for Flight 3 was due to the fact that for this mission the launcher was changed. While for the previous two launches the satellite was mounted on an Ariane; for this mission a Lockheed Atlas was selected. This launcher placed the spacecraft into a super synchronous transfer orbit and the launch took place from the Kennedy Space Center in Florida. The differences that incurred were different interfaces to the launcher and launch site, different ground station selection and schedule, and considerable updates to the flight dynamics software to include a perigee maneuver to lower the apogee.

Again a small increase can be detected between Flight 4 & 5. At that time GSOC made a change in its control facility. It moved to a different building and also implemented new hardware with the corresponding operating systems being adapted.

The decrease in ECRs from 5 to 6 again is not as large as can be expected because there a change in the spacecraft hardware was implemented that resulted in updates to the ground software. Those were in particular in the satellite power subsystem.

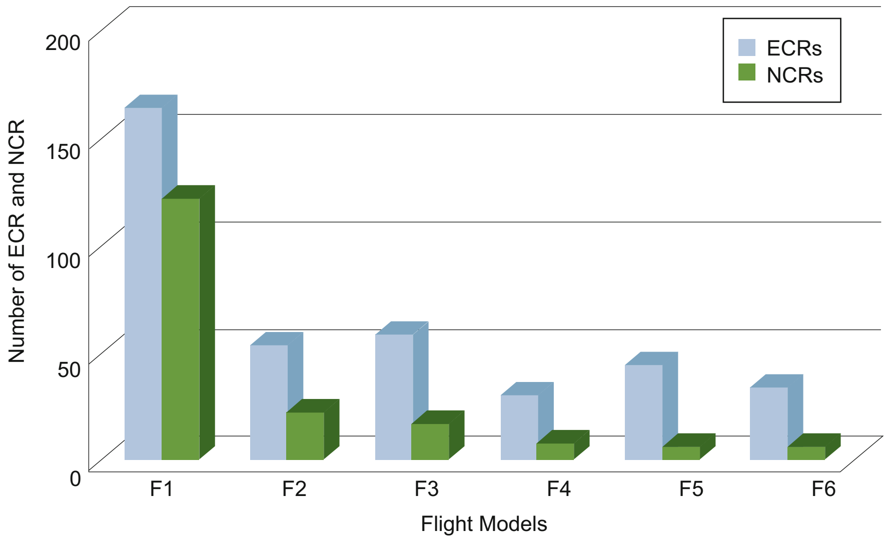

Fig. 2.14 Number of ECR/NCR for EUTELSAT II series

During mission execution all deviations from the nominal procedures and actions caused by unexpected and non-nominal satellite behavior are handled by Satellite Anomalies Reports and Recommendations (SAR). SARs can be issued by any person on the mission control team, control center personnel, as well as representatives of the satellite manufacturer or the end customer. SARs are issued in case of:

- Unexpected and non nominal S/C behavior (not covered by prepared procedures)
- Online procedure changes
- Online mission sequence changes

In the course of the launches from Flight 1 to Flight 4 one can see a significant decrease in the numbers of SARs from roughly 200 down to 60 (Fig. 2.15). Flight 5, even though it was a launch failure, had some SARs because last minute changes to the database and procedures were introduced, which caused changes to the operational system at GSOC.

Flight 6 had an increase in the SARs because there were several modifications to the spacecraft bus, in particular to the power subsystem.

2.3.2 *Interpretation of Telemetry*

This next chapter shall give an example of which kind of information can be gained through detailed analysis of telemetry. As an example we are using a plot of the spacecraft receivers Automatic Gain Control (AGC) (Fig. 2.16).

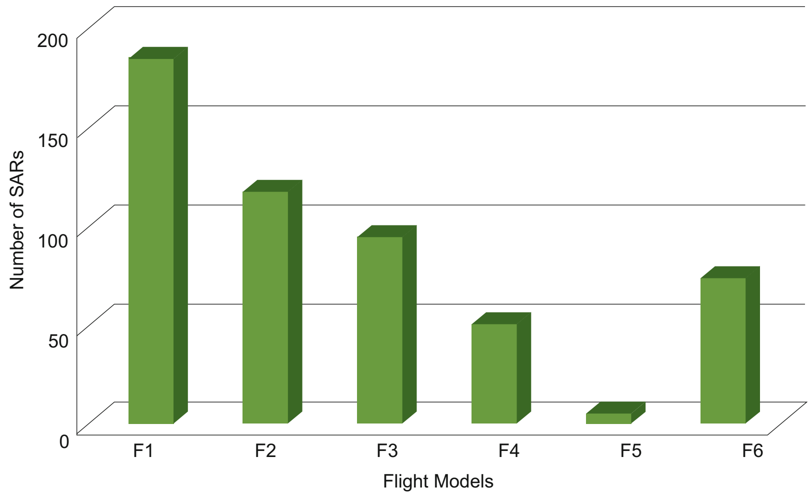

Fig. 2.15 Number of SAR for EUTELSAT II series

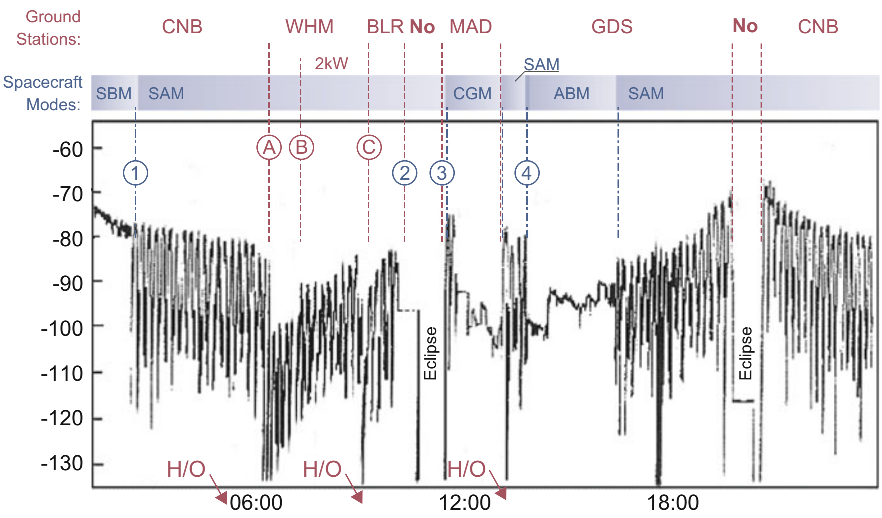

Fig. 2.16 Telemetry data "Automatic Gain Control" (AGC) during the first day of a LEOP

The uplink AGC—a telemetry parameter which is transmitted from the S/C to the ground—indicates the onboard measured signal strength of the telecommand carrier, uplinked from the ground station. The various S/C attitude modes, the evolution of the orbit, as well as the ground station coverage are reflected in this AGC plot of the first 24 h in the transfer orbit.

At first view the graph seems to represent a very erratic behavior of the telemetry value plotted. We see periods of constant or moderate changes, long time spans of extreme oscillations, and gaps without any telemetry. But still this represents actual behavior of the telemetry. How can we interpret this?

First let us take a look at the spacecraft, its configuration, and the activities performed during the first 24 h:

From the start of the plot during the Standby Mode (SBM), we see a rather stable but slightly decreasing level of the automatic gain control level. Here the spacecraft was released by the launcher with a predefined attitude at a certain altitude and distance to the ground station. The decrease in signal strength displays the increase in distance between the ground station and the satellite, as it flies within the GTO towards the apogee. Thus the loss in signal strength is related to the increasing distance to the satellite.

At Point 1 we command the satellite into sun-pointing or sun-acquisition-mode (SAM). The satellite is rotating around the X-axis, which is pointing to the sun. The oscillation with an amplitude of roughly 25 dBm is caused by the fact the there is only one receive antenna. Due to the rotation of the spacecraft, this antenna is sometimes pointing towards the earth, sometimes away or shielded by the satellite bus. This oscillation is also a possible mean to determine the rotation rate of the spacecraft. The graph also shows steady decrease in signal strength up until around 6:00, when it starts increasing again. This is the time when the satellite reaches apogee, the point furthest away from the earth on its orbit, after which the relative distance to the earth becomes smaller again. The overall dip in the AGC level around 06:00 will be explained a little later.

Between point 2 and 3 there is a gap in the telemetry, which indicates a loss of signal. At this time the satellite was passing through perigee and due to the low altitude there was no station available to receive a signal.

At point 3 the signal was acquired again with the spacecraft in SAM, shortly afterwards the satellite was commanded to “Gyro-Calibration-Mode” (GCM) which is a 3-axis stabilized mode. There the antenna is pointing in a fix direction. Therefore there is no fluctuation in the receive signal strength. The telemetry shows a rather constant value that is only decreasing due to the rising distance to the ground station. After completion of the GCM, the spacecraft was returned to SAM which can be seen by the fluctuating telemetry values.

Point 4: The spacecraft is configured for the first Apogee Boost Maneuver (ABM). This is again a 3-axis mode with more or less constant receive strength. After completion it returns to SAM, interrupted by another eclipse during a perigee pass with no ground station contact.

But there is another way to interpret this plot and receive other information. We will focus now on ground activities. From the beginning to point A, we acquired the signal of the spacecraft via the ground station Canberra (CNB), with the AGC level decreasing. At point A the signal drops to a minimum, indicating basically no receive signal from the satellite. At that time there was a ground station handover from Canberra to Weilheim (WHM) with a short interruption in the uplink. The quality up the uplink, i.e., the receive strength, was unsatisfactory, with it dropping basically down to minimum depending on the S/C attitude. So, at point B the uplink power at the ground station was increased from 1 to 2 kW which resulted in a satisfying receive signal strength. Point C marks another station handover with a brief interruption of uplink, this time from Weilheim to Bangalore (BLR). Other stations used during this period were Madrid (MAD), Goldstone (GDS), and again Canberra, in that order with the handovers clearly identifiable.

2.3.3 Failure Probability Vs. Operational Experience

The typical evolution of mission failure probability shows peaks at the beginning of mission, i.e., the LEOP and in the region of planned End of Mission (EOM) (Fig. 2.17, dashed line). An experienced operations team, assisted by the satellite manufacturer is required to cope with the LEOP risks. Operational experience is growing throughout the following routine phase; for long-term mission this experience might get (partially) lost on the operations side as well as at the manufacturer (experts leaving the teams by various reasons).

- Thorough operational documentation required
- Never change a winning team…

First let us take a look at the failure probability during a mission. It starts out with a rather high likelihood of problems at the beginning; one could call it "infant mortality."

The most likely reasons at this time are:

- A launcher failure, which does not really effect the S/C mission control team.
- Failures induced by stress during launch, e.g., vibrations.
- Units or instruments experience space environment for the first time and react differently than expected.
- Operations that are time critical and singular. Time critical event for example are the deployment of solar arrays to charge the batteries or the activation of heaters to keep propellant from freezing. One time executions can be deployment of an antenna or the activation of pyros.
- And finally design or manufacturing errors that were not discovered during testing, like faulty sun sensors.

Once the IOT phase is successfully completed, the likelihood of failures drops significantly. The spacecraft is operated in a stable configuration without many changes. Most problems from that time on originate from single event upsets, like a reboot, equipment failures, or in many cases human/operational errors.

Close to the nominal end of the mission (EOM), the failure rate increases again due to aging effects on the equipment and exhausted resources, which makes resource management an important issue during the course of the operations.

The operational experience of the mission control team is shown in Fig. 2.17 with solid and dotted lines. At the beginning of the mission there will be a team with a high level of experience. This is based on the fact that on the one hand the core team members are chosen from staff that has already supported similar tasks and on

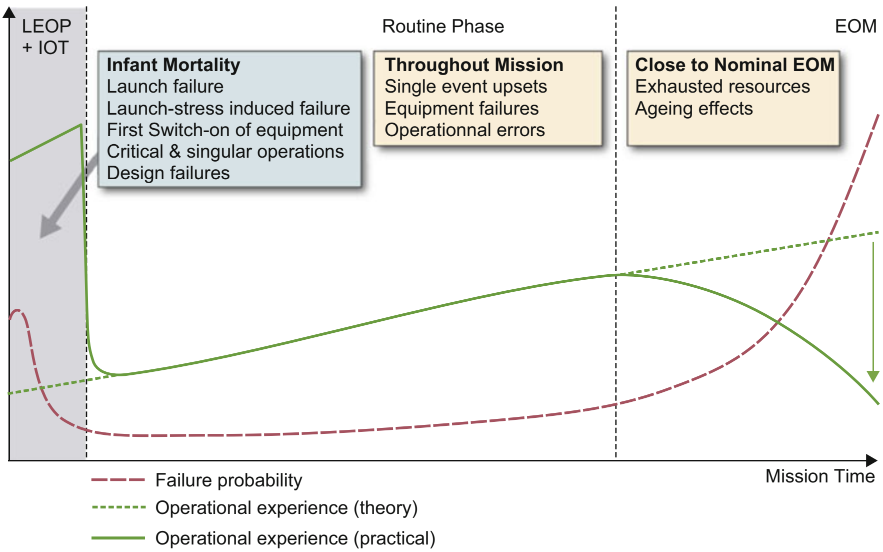

Fig. 2.17 Failure probability vs. operational experience

the other hand that by the time of launch the complete team has participated in the preparation phase, analyzing requirements and databases, defining the mission control system, writing procedures, testing the system, and participating in simulations. The qualification increases during the LEOP, as this is the most demanding phase with all the testing occurring there and typical problems happening in that phase.

Shortly after LEOP is completed the experience level drops significantly (solid line). This is caused by several facts: first of all, during LEOP the team is augmented by staff from the satellite manufacturer, that leave the control center once the spacecraft is checked out, then people are taken off the team to work on new missions and only a core team is left to support the routine operations phase. Once the operational phase is established, the experience increases gradually again in the course of the mission.

Unfortunately, experience shows that once the mission has reached a mature lifetime, the experience level of the team starts to decrease again due to natural attrition, team members leaving for other jobs, or because of budget constraints and finances being cut. More often than not this coincides with the time when failures on the spacecraft start to increase again due to the exhaust of resources and the aging effects.

2.3.4 Contingency Handling

This section covers the aspects of contingency handling during operations. The first level of contingency handling should be covered by the onboard FDIR software. The objective of the onboard FDIR, also known sometimes as Redundancy

Management, is the survival of the spacecraft after a single failure for a specified time span. For detailed information on how FDIR is embedded in the Data Handling subsystem please refer to the corresponding Sect. 6.2 about onboard data handling. Communication spacecraft are typically designed to survive up to 48 h without ground intervention. The individual steps are:

- Failure detection by check of exceeded thresholds: The onboard FDIR has limits stored in its software that are periodically checked. Rules can be defined within the FDIR process that further refine the reaction to limit violations, e.g., a limit has to violate a specific number of times with within a fixed number of checks before a reaction is triggered. This is to avoid a premature reaction based on a faulty reading of a telemetry value. In addition to analog values like temperatures, voltages, or angles also status bits, ON or OFF, or complex error words are monitored.
- The next step is the isolation of the problems. This means either taking a faulty piece of equipment out of the loop by switching to a backup unit, if the issue cannot be tracked to a single instrument or processor then a switch to a backup mode is performed or in extreme cases the complete satellite is commanded to a safety mode by turning off nonessential loads and bringing the attitude to a mode that ensures power and thermal balance for survival.
- The spacecraft should be able to survive in the corresponding configuration for a predefined period of time. Depending on how sophisticated the software is in rare cases, the possibility exists that the satellite can recover to its nominal configuration autonomously, e.g., as reaction to brief attitude deviations.

Once the onboard FDIR software has triggered the detailed failure analysis of the cause of the incident, any recovery actions, like returning to normal mode and restoring the mission, if possible, has to be performed by the mission control team on ground. The FDIR functionality can not only be triggered by the malfunction on a unit on board, a single vent upset, which is not reproducible, can also be the cause for a reaction or reconfiguration. So one possible recovery action can simply be to restore the nominal configuration and the issue is solved. If there is actually a defect on board, then there are more consequences to be considered: Limits within the mission control system have to changed, procedures updated, and the FDIR software need to be rewritten to reflect the operations on the backup system, because different telemetry parameters need to be checked and new switching automatisms and reconfigurations have to be defined and implemented.

On the other hand it is always preferred to detect problems before the onboard software takes action. To support this, the ground system has similar functions implemented to the ones that can be found on board. These are more refined and enable detection of issues before they become a problem. For example there are two stages of out-of-limit conditions defined, a warning and an alarm stage. The warning indicates that the situation has to be monitored, but no immediate action is necessary. The alarm stage calls for action; otherwise an instrument or function could be lost.

Other means of detecting satellite issues by ground monitoring is to recognize secondary effects by analyzing telemetry. These can be the unexpected change of telemetry values like temperatures, currents, or sensor values even though they still stay within the range of nominal values. Other effects can be attitude perturbations that are not recognized by the onboard software as problems or the loss of up-or downlink. And finally the long-term analysis of telemetry and consumables. This can give an indication of the remaining lifetime of a unit, instrument, or the mission.

The isolation of problems by ground activities can be of course much more subtle than just switching to backup units. The first step is the identification of the problem or failure. Starting with a systematic approach one first identifies the area of the issue: Is it an operator error, is the cause within the ground system, or is it a malfunction within the space system?

Based on this analysis the corresponding action, best recovery, can be chosen. These can result among other things for example in improved training for operators, new procedures, update of the ground system, databases, or hardware. In case the space system is affected, the goals return to a normal operational configuration, recover the mission, restore payload, and as much as possible activate the nominal equipment again. A closing action can be the necessary update of the onboard FDIR logic in case equipment is permanently damaged.

The baseline for a controlled reaction to system contingencies must be verified and approved processes and procedures. Often the handling of a contingency might be too complex to be handled by a single procedure. In those cases flowcharts are useful. In the following we show how the analysis of a problem can develop into a complex process and flowchart.

In the following we discuss the FDIR process which is activated whenever no telemetry data is received (Fig. 2.18).

If at the expected AOS time no telemetry is received by the FOT, it is first checked whether the receiving ground station sees a downlink (D/L) signal/carrier from the spacecraft (Fig. 2.18, left side). If that is not the case we try to verify if the orbit used for the prediction is correct. The sources of information are the Flight Dynamic (FD), the launch provider, and possible co-passengers. They might be able to tell if they received signal from their spacecraft. At this point the control center should be able to determine if the predictions were made with wrong orbit data, modify the orbit, predict and correct the antenna pointing angels and adjust the antenna. In case the used orbit data prove to be correct, the ground station configuration should be checked and corrected if necessary.

The next possibility could be that a downlink carrier is received and a subcarrier is modulated to it (Fig. 2.18, right side). This would point to a failure in the data handling subsystem of the spacecraft and a manual reconfiguration on the spacecraft has to be attempted. In this case the activities would involve commanding “in the blind,” mean without telemetry verification. If that was the root cause the telemetry should appear in the control room.

But there are many more possible causes for that problem and it would be out of the scope of this chapter to describe them all. Just to summarize, beside the mentioned possibilities of wrong orbit, ground station problems or DH subsystem (of which there could be several), the anomaly could also be within the TCR subsystem, the spacecraft attitude.

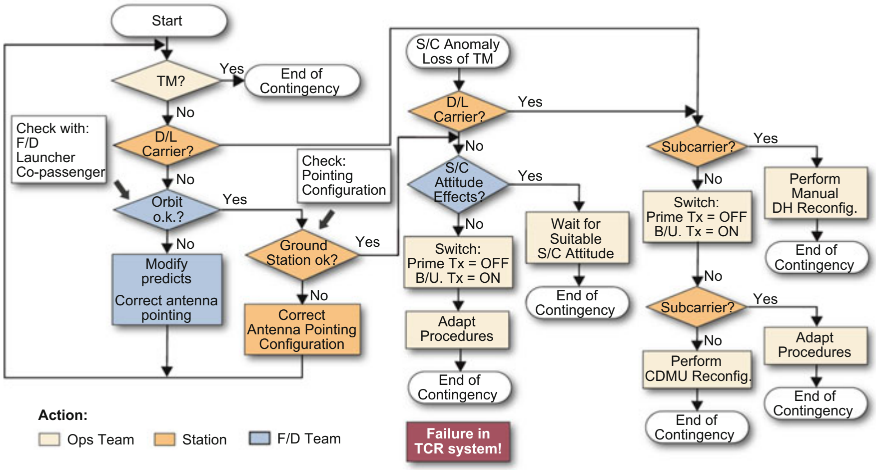

Fig. 2.18 Flowchart for FDIR process in case no telemetry is received

2.3.5 Mission Example TV-SAT 1

TV-SAT 1 was the first commercial German communication satellite, a joint French-German coproduction. It was a small satellite of two metric tons with five transponders on board, designed for direct broadcasting of TV programs (Fig. 2.19).

TV-SAT 1 was a prime example of a mission that went wrong. It provided the mission control teams with unique challenges. The problems GSOC encountered already very early in the mission:

- A partial deployment failure
- Gyro failure
- Thruster temperature problems

In the following we describe the partial deployment failure in more detail including the numerous tests, to determine the exact cause of the failure. We will cover the immediate actions, evaluation of impacts, offline failure analysis, failure investigation, and recovery action attempts. The problem was caused by one of the solar arrays which failed to deploy at the very begin of the mission (Fig. 2.20).

2.3.5.1 Failure Analysis

The partial deployment of the solar arrays was part of the automatic onboard timer function, triggered by S/C separation. The failure was detected by the status of the deployment microswitch at the first contact, when the S/C was still in eclipse. The immediate actions were:

Fig. 2.19 Artist view of TV-SAT1

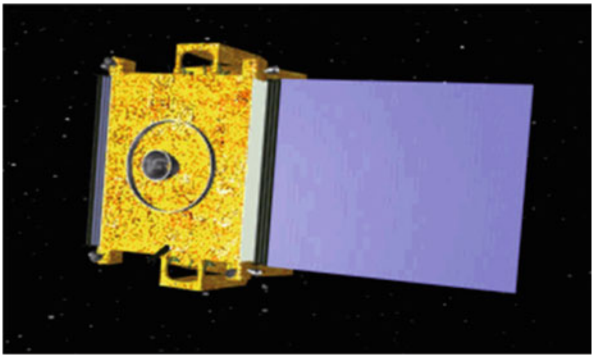

Fig. 2.20 Partial deployment failure of TV-SAT 1

- Checking the ground database, if there was any bit inversion—no failure was detected.
- After eclipse: checking the output power of the affected solar array—the low power levels confirmed the unsuccessful deployment.
- Next the functioning of the onboard timer was checked and there was indication of a failure.
- Following these checks the procedure called for the sending a manual deployment command sequence. Those commands were sent, but there was no change in the status.
- Finally we sent a command sequence to fire the redundant deployment pyros—again with no effect.

Now the operations team knew that the S/C was in deep trouble.

In order to be able to proceed with the operations, the failure impacts on the mission had to be quickly evaluated. It was found that the S/C was generally safe from system side; impacts on the subsystems, mainly power, thermal, and attitude, were reviewed and found to be not mission critical at this mission phase. Apart from some tests it was decided to proceed according to the nominal sequence of events,

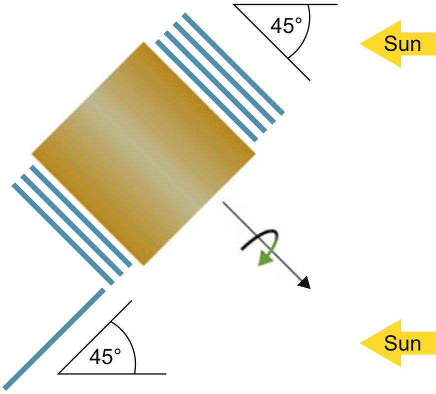

Fig. 2.21 Failure investigation of TV-SAT 1—tilt S/C by 45°

namely to perform all operations including the first apogee boost maneuver. A number of satellite flight procedures as well as elements of the ground system (e.g., alarm flags) had to be modified and adapted.

An offline analysis by the manufacturer identified a number of more than 50 possible causes for the failure, some of them very unlikely. Test strategies and procedures were defined and developed in order to reduce the number of possible causes. In addition recovery strategies and procedures were prepared for the different failure scenarios. A review of the Failure Mode Effects and Analysis (FMECA) revealed the blocking of the receive antenna as a fatal mission impact of the non-deployed solar array.

For the failure investigation new tests had be defined. Once that was completed, the procedures had to be prepared, validated then executed, and the tests evaluated. Here are some of the tests that were performed:

The first test was to tilt the spacecraft by 45° (Fig. 2.21). The solar array currents were measured to give a rough determination of a possible deployment angle. The expected accuracy was ~2°. The result was that if any, the opening angle was less than 2°.

The next test called titled “Shadowing”: Principle of this test was to illuminate the panel at low solar incidence angles. Any stirrups holding the panel would thus cast large shadows, which would be measurable from the reduction in the amount of current generated (Fig. 2.22). No conclusions could be deducted from this test; it was not sensitive enough to distinguish between the possible cases: No stirrup closed/1 stirrup closed/2 stirrups closed/3 stirrups closed.

This was followed by “Current Mapping”: This test consisted in measuring the power output of the north panel for a variety of solar incidence angles (Fig. 2.23). Power output was expected to vary as the cosine of the angle between the normal to the panel and the solar incidence direction. Any offset in this cosine response could correspond to an opening of the panel. The conclusion from this test was a maximum opening of the panel by 0.85°. This test was repeated after all satellite maneuvers and events to find out if they had any effect on the solar array.

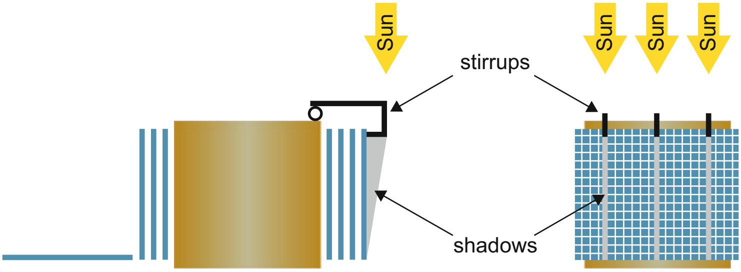

Fig. 2.22 Failure investigation of TV-SAT 1—shadowing test

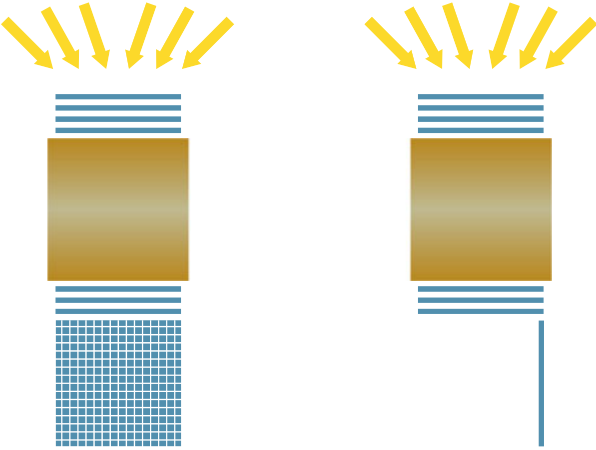

Fig. 2.23 Failure investigation of TV-SAT 1—current mapping

Another test consisted of shaking of the spacecraft angles (Fig. 2.24). Purpose of the shaking tests was to determine the resonant frequencies of the north panel. By shaking the S/C at particular frequencies, oscillations were set up in the panel. After stopping the excitation, the continuing oscillations of the panel were transferred to the S/C body and measured with the gyros. No resonant frequencies in the expected range could be measured, another indication of a fully blocked array.

2.3.5.2 Recovery Attempts

As a result of all the tests the number of possible failure causes could be reduced to 13. A very likely cause for the unsuccessful deployment was a jamming of one or even more stirrups. Different recovery actions were performed, unfortunately all without success:

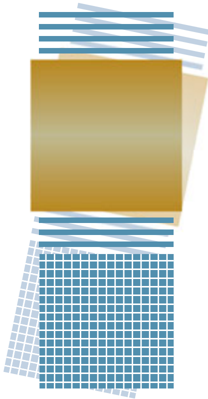

Fig. 2.24 Failure investigation of TV-SAT 1—shaking test

- Fast spin mode around the S/C Y and Z axis in order to exert forces on the stirrups and the panel which could overcome the friction in some failure cases.
- Performing apogee boosts and station keeping boosts in pulsed mode in order to excite proper resonant frequencies with high amplitudes.
- Exposing the panel and stirrups to alternating hot and cold temperatures.
- The solar array full deployment, the BAPTA activation, and the shock of the antenna deployment could also overcome some failure cases.

2.3.5.3 Final Actions

Although it was finally not possible to deploy the solar array, a high amount of operational experience could be gained. For the preparation of the following flight models, preventive actions could be taken for all remaining 13 possible failure modes to make them a success.

In the end it was found out that the actual cause was that it was missed to exchange the transport stirups with the flight stirups. As a consequence payload operations were not possible because the non-deployed solar generator prevented the receive antenna from full deployment. The TV-SAT 1 mission was terminated about 6 months after launch. Therefore the satellite was injected into a 325 km over-synchronous orbit by 2 boost maneuvers. All subsystems were deactivated in order to avoid any risk for other satellites.

The S/C telemetry transmitter was switched on again after 7 years for a short time in order to gain attitude information for the Experimental Servicing Satellite (ESS) study (see Fig. 7.7). The switch on was successful and the satellite signal was acquired at the first attempt.

All following TV-SAT flight models could be operated successfully in orbit.

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