29 Mission Operations

29.1 Mission Planning and Operations Development

Developing the Mission Operations Plan

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The Mission Operations Plan (MOP) is the defining document for mission operations development, which describes what mission operations will entail, what are its objectives, how it will be accomplished, and lays out a detailed plan for the development, testing, and application of mission operations. The MOP describes, in operators' and users' terms, the operational attributes of the flight and ground-based elements of the mission. However, the MOP is not just for the mission operators and users. It is used by the mission management and organization as a tool to understand and thus effect changes in mission operations.

Although Fig. 29-2 shows the MOP as being a product of the Development Phase (Phases C & D), it really begins with the development of the Operations Concept Document (OCD), the data and software plans, and the Mission Requirements Document development in the Definition Phase (Phases A & B). The MOP is built upon the foundation formed by these earlier documents (see Table 29-3 for a more detailed description of these documents). Table 29-4 outlines a 17-step process to develop the MOP starting with the top-level requirements and OCD. This is an expanded and modified version of the methodology than was presented in Wertz [1999]. Note that the development of the MOP is an iterative process. The plan will necessarily be modified as the project matures and the nature of the space and ground elements is better understood, and thus how to operate them to best fulfill the mission objectives.

Step 1. Identify Top-Level Requirements and Constraints that Affect Mission Operations, Ops Lessons Learned, and Advanced Technologies & Techniques for Operations

This first step is required to formulate the operations concept (Step 2). A new mission initially starts with a mission statement that defines the purpose of the mission. This statement is then parsed into achievable primary and secondary objectives. The mission objectives define what the mission elements (such as spacecraft, crew, ground segment, and payload users) must do to successfully accomplish the mission. After the objectives have been defined, they are normally assigned success criteria to provide a means to measure the relative success of the mission. (See Sec. 5.4.) These success criteria help in the overall mission design to identify levels for which the system can be designed to achieve steps of partial success on the way to full mission success.

The mission objectives lead to an initial mission concept or description that presents in broad terms an overview of the mission, including some aspects as trajectory profile, launch windows, payload type, mission phases and duration. The mission definition process then determines the top-level requirements and constraints (see Chap. 14) to help define the mission so that its objectives can be achieved within the project constraints. We can usually categorize the requirements and constraints into either technical or programmatic.

Some examples of top-level programmatic constraints that affect operations are:

- Limits on the project cost or schedule profiles
- Restrictions on partnerships (e.g., no foreign partners) or mandated partnerships (e.g., spacecraft bus by one national space agency and payload by another national space agency)
- Establishment of a public website of mission operations for public outreach
- Definition of launch vehicle or launch site to be used

Some examples of top-level technical constraints that affect operations are:

- Maximum spacecraft mass
- Orbit type
- Communication band restrictions (e.g., S-band only) or format (e.g., CCSDS protocols)

The top-level requirements are defined for not just the system-level elements (e.g., spacecraft, ground segment, trajectories/orbits), but also for the various subsystems. These requirements and constraints are usually captured in a document such as the Mission Requirements Document (MRD) or the System Specifications Document (SSD). Included in the top-level requirements are the general requirements for mission operations. These are formed mainly from examining the requirements and constraints defined for the other system elements and subsystems to determine which of them have an effect on operations. Examples would be the type of orbit and trajectory (e.g., a long low-activity cruise period to reach the target versus a LEO mission), the latency and importance of the data delivery (i.e., how quickly does the payload data have to reach the users), the mission length, and the expected complexity of the mission. Note that this step is initially iterative with Step 2, since only the top-level requirements derived directly from the mission objectives will be available. These are not enough to define all the information needed to proceed on to

Table 29-4. Process for Developing a Mission Operations Plan. These steps are summarized in the text.

Step	Notes

1. Identify top-level requirements and constraints that affect mission operations, ops lessons learned, and advanced technologies & techniques for operations	• Determine constraints (e.g., cost, schedule, teaming)
	• Ops requirements come from various mission areas:
	  • Orbit
	  • Communications
	  • Payload (including data latency and tolerance for data losses)
	  • Ground network

2. Develop mission operations concept and supporting architecture	• May have multiple mission ops concepts during Phase A or basic changes in concept during Phase B
3. Develop ops scenarios and techniques that accomplish Mission concept	• For each scenario develop sample timelines to ensure feasibility of scenario
4. Determine ops functions required in Step 3 and develop functional flow block diagram	• To satisfy mission concept identified in Step 2 • Basic functional areas are: Mission Planning and Analysis, Real-time Operations (Contact Execution), Data Management, Trending and Analysis
5. Identify ways to accomplish functions identified in Step 4	• Assesses state-of-the art and legacy solutions that are available with reference to previous similar missions
6. Determine level of automation for both space and ground segments	• Determine how much of the processing and control will be done autonomously on the spacecraft, how much at the ground stations, and how much in the MOC • Determine if the MOC and ground station functions can be automated or require personnel, given the mission cost and schedule constraints
7. Determine whether capabilities identified in Step 5 and 6 currently.	• Are these resources astainable or do they need to be developed
8. Develop staffing plan and identify other resources required	• Determine the operations and support organization including roles (positions) required and level of experience needed • Determine if shifts are needed and work out the shift plan • Determine number of personnel required to support operations (MOC and ground segment) • Determine the staffing profile (rate at which personnel are brought onboard) • Determine what hardware and software resources are required
9. Perform trades to determine best solution from Steps 5-8	• Compares availability, performance, and cost (non-recurring and recurring) of various options identified

10. Determine the operations Work Breakdown Structure (WBS) and ROM mission operations cost	• This is an important element in determining the viability of the current mission concept. Cost is typically based on:
	• WBS
	  • Staffing requirements
	  • Hardware & software procurement
	  • Hardware & software development
	  • Facility/infrastructure development or sustainment for existing facilities

11. Repeat steps 4-10 for development phase (Mission Phases A-D as appropriate)	• If the initial Phase E analysis was just completed, then the developmental phases also need to be analyzed
12. Assess mission utility, complexity, cost drivers	• This is to help select the best mission concept for the baseline by determining which best meets the mission objectives
13. Repeat for alternate mission concepts (starting with Step 2) if required	• This is skipped if the baseline mission concept has been selected
14. Identify derived requirements	• This is done to the selected baseline mission operations concept
15. Develop training plan	• Plan to train and certify flight ops personnel and rehearsal plan
16. Generate MOP that includes technology development plan, personnel staffing and training plan, and documentation plan	• MOP includes the processes governing operations development and validation • Technology development plan identifies the ground segment components that need to be developed, such as databases, or planning software • Personnel staffing and training plan identifies the positions anticipated during operations and the certification plan for those positions • Documentation plan identifies the documents that are needed (e.g., Flight Handbook) and how to develop them
17. Document and iterate/refine as needed	• Publish the MOP and revisions as needed

Step 3—first you have to have a mission concept to determine the top-level requirements within the various system and subsystem areas. There will be various mission concepts considered, and these may have different requirements and constraints on the system. When information is not available, you have to make assumptions until the development matures to a level where the assumptions can be replaced with actual information.

Step 2. Develop Mission Operations Concept and Supporting Architecture

One of the most important documents developed during the Definition Phases is the Operations Concept Document (OCD). The OCD is the documentation product that captures the operations concept. This ops concept describes how the mission will be executed to accomplish its objectives, and attempts to define the required software, interfaces, timelines, procedures, and various spacecraft modes. The ops concept usually covers the operations of both the space and ground segments, and looks at operational scenarios. The resultant OCD is important in helping to define the mission system architecture and also the requirements for the various system elements and subsystems.

As shown in Fig. 29-2, there are several external inputs that contribute to the development of the ops concept. These include the mission objectives, and top-level requirements and constraints that were determined in Step 1. Another important factor in the development of the ops concept is the mission architecture. The development of the system architecture is usually iterative with the ops concept—an ops concept is needed to develop an architecture, and the architecture defines many of the elements described in the ops concept. The Department of Defense has developed a methodology that you can use to help develop your architecture [DODAF, 2011].

To help develop a comprehensive ops concept it is also useful to consult, and apply where appropriate, operations lessons learned from previous missions of a similar type or from your organization. Although some lessons learned are considered to be priority or unavailable due to security classification, there are some good sources for such information in the public domain. Explore the proceedings from professional conferences that feature papers on mission operations, such as:

- Biennial International SpaceOps Conference conducted by the International Committee on Technical Interchange for Space Mission Operations and Ground Data Systems (also known as SpaceOps Organization) [SpaceOps, 2011]; also see Bruca, Douglas, and Sorensen [2007]
- Annual AIAA Space 20XX Conference (where "20XX" is the year of the conference) [AIAA, 2011]
- Annual Improving Space Operations Workshop conducted by the AIAA Space Operations and Support Technical Committee [SOSTC, 2011]
- Annual AIAA/Utah State University Small Satellite Conference [SmallSat, 2011]
- Annual IEEE Aerospace Conference [IEEE, 2011]
- Annual Reinventing (formerly Responsive) Space Conference [RSpace, 2011]

One problem with current practices in mission operations is the lack of common standards. Various organizations, such as AIAA, IEEE, SAE, CCSDS, and ECSS, have and are attempting to set standards for space missions, but it is difficult to come to an agreement and to implement changes in legacy systems. When the ops concept is defined, some decisions in standards, especially with interface formats, will have to be made. However, most of the decisions on standards can wait until the development of the Mission Operations Plan.

Step 3. Develop Operations Scenarios and Techniques that Accomplish the Mission Concept

Once you have developed the general concept for the mission operations, you need to flesh it out and test it, both to check its feasibility, and to help determine the elements and tasks that are needed to support it. The best way to do this is to put together some operational scenarios that represent various events or phases in the mission, such as deployment, nominal payload data takes or events, communication contacts, or eclipse periods. Early in the development cycle you may not be able to determine a precise power profile to support the scenario, but you should be able to determine the sequence of major events to support the scenario. With the help of the power engineers, you should be able to calculate the associated power profiles, at least to a rough order of magnitude.

Other important resources to track during the scenarios are the data collection, throughput, and delivery. Based on the orbit/trajectory and location of the ground stations, the amount of data to be handled by operations can be determined and potential problems, such as gaps in ground station coverage, can be identified.

The scenarios developed in this step will also help identify techniques that may be needed to efficiently accomplish the various tasks of the scenarios. From sources such as those listed in Step 2, you can also determine the current state-of-the-art in mission operations and identify advanced tools, technologies, and techniques that might be useful in executing the scenarios and formulating your ops concept. However, beware of attempting too much that is new because it usually comes with an increase in risk, cost, and schedule. It is better to apply new technology later in the process when the overall system has matured and the available trade space for operations can be better defined.

Once the scenarios are determined and analyzed, the ops concept can be modified as needed, which may in turn require a change in the mission architecture (Step 2). As the development process matures (i.e., in a later iteration of this process), the scenarios will become more detailed as simulations from the various system ele-

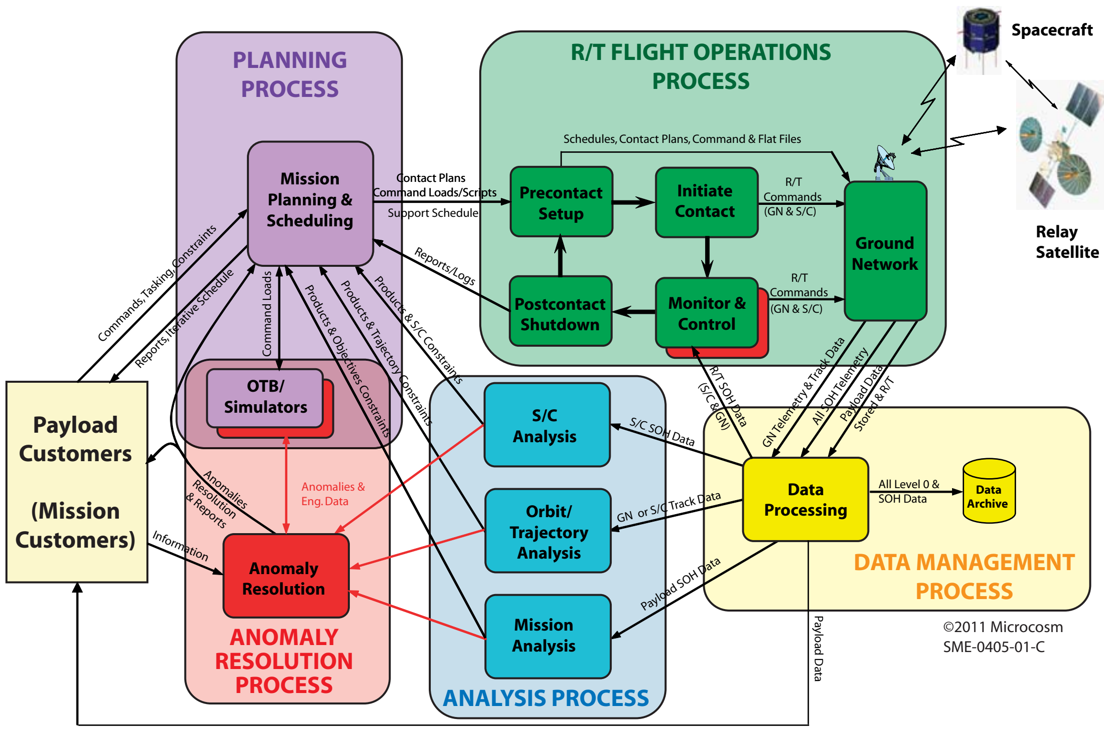

Fig. 29-3. Mission Operations Functional Flow Block Diagram. Operations performed during a space mission usually consist of the following basic processes performed on a cyclic basis: Planning, Real-Time Flight Operations, Data (Processing &) Management, Analysis, and Anomaly Resolution. The actual processes used by a particular mission may vary from this model, but usually the same functions are performed. Some specialized missions (e.g., manned or surface ops) may add additional processes.

ments, such as spacecraft subsystems, can provide detailed information. These include power and temperature profiles, data collection, storage and delivery, orbit parameters, spacecraft attitude, and propellant usage. One technique that is often used for the development of detailed scenarios is called "A Day in the Life of [s/c]" or "A Week in the Life of [s/c]". These provide a detailed minute by minute timeline of the spacecraft's state as it executes its mission. This can be a high fidelity verification of the mission operations concept and useful for helping to size various components and subsystems in the spacecraft or ground system.

Step 4. Determine Ops Functions Required in Step 3 and Develop the Functional Flow Block Diagram

When you have finished Step 3 you should have a good understanding of what mission operations will entail and which tasks or functions are required to fulfill the mission. You can now list the specific tasks or functions that need to be performed during the execution of the mission. Each function identified should have data input and data output and perform a specific function in a process flow. Once you have listed the functions, you can now produce one of the most important products in the design process to understand what needs to happen to accomplish the operations—the Mission Operations Functional Flow Block Diagram (FFBD) or the Functional Block Diagram (FBD). The FFBD shows the functions in the operations process and the flow of process or data between them. The FBD is often the same as the FFBD, although it sometimes just shows connections between the functions without identifying the data flows between them. An example of a typical FFBD showing the execution of the operations cycle for a space mission is in Fig. 29-3.

This FFBD shows the major functional areas in the operations process (Planning Process, Real-time Flight Ops Process, Data Management Process, Analysis Process, and Anomaly Resolution Process) and the major functions within each of these processes. The arrows show the flow between the functions and are labeled to show the nature of the data. The FFBD provides a visual way to understand what happens during operation of a spacecraft and thus, what you need to include in your design. Note that the example given in the figure is typical of operations for small robotic satellites in Earth orbit and are basic functions required by almost any space mission. However, when you have a more complicated mission or a mission of a different type, such as manned missions, or deep space missions, the operations process may differ. Communications satellites in geosynchronous orbits also have a more steady state operational process rather than the cyclic process shown. We will be looking at the operations functions in this process in more detail in the next section.

Step 5. Identify Ways to Accomplish Functions Identified in Step 4

If you have worked in mission operations previously, then you have a head start in accomplishing this step. In that case you will probably start with your previous operations system and then determine where changes need to be made due to the nature of the mission, or where improvements can be made based on lessons learned or advances in technology (identified in Steps 1 and 3).

However, we will assume that this is your first time developing mission operations. Each of the operations functions identified in Step 4 is different and requires different methods and tools to accomplish. It is helpful to set up a spreadsheet table that lists the major processes with their associated functions listed in the leftmost column, and then place existing tools (generally software) listed across the top. These tools are mostly COTS applications (products) that are sold by many vendors or available from various government agencies. You can identify the candidates to occupy this trade space by using web searches, looking at advertisements in trade periodicals, review recent technical papers from conferences (where many of these applications or tools are presented), visiting exhibiter booths at the major conferences (see the list in Step 2), and contacting NASA or other government agencies that operate spacecraft (they are generally happy to share technical information and sometimes can even provide legacy systems or modules).*

Once you have identified the available tools that are available, you should review and characterize them by identifying which of the required functions they would be able to accomplish (usually obtained from their sales literature or technical specifications). Most of the packages (tools) specialize in accomplishing some functions well, but do not attempt to do everything. You might thus have two or three tools to do mission planning and scheduling, one or two for real-time operations, and one or more for trending and analysis. However, you should not limit your trade space to space software. Other industries use monitor and control software that is far more tested and at a much lower cost than their space counterparts.

Evaluating your mission's trade space table should enable you to narrow down the choices of tools you should consider to accomplish your ops functions. Before making your selections, other comparisons need to be made, including: cost (up front, modifications, and maintenance), availability, vendor technical support, performance, ease of use, ability to interface with other applications within your system, upgrade and debug policies, ease of modifying, likelihood that the vendor will still be around to support it in a few years, level of technology, who else is using it and what is their experience with it. In the early phases of the ops development cycle, not all of these comparisons need to be done to select a baseline solution, which is a non-optimized way of accomplishing the required functions (i.e., "good enough" to do the job). However, later in the develop cycle, before making the final selection of the tools to acquire for the mission, the detailed analysis and comparison mentioned (along with other appropriate parameters) should be done. You can use a table like that shown in Table 29web-1 to help you with a more detailed trade study, where you can replace the functions with the other parameters you wish to compare, and you can replace a simple "X" with a number (e.g., 0-9) that reflects how well the tool accomplishes the function (performance) or one of the other considerations (cost, or support).

* For example, all operators in ESA member countries can use MICONYS (SCOS2000 spacecraft monitoring and control tools) and SIMULUS (Simsat software-based spacecraft simulation tools) free of charge for a license with ESA, and in the USA, tools such as ITOS and AMMOS are free from NASA.

Step 6. Determine Level of Automation for Both Space and Ground Segments

Before you can size mission operations for the number of personnel needed, and cost, you will need to determine how much of the operation will be automated and how much requires human operators. This includes not only the spacecraft, but also the ground segment [Calzolari, 2007]. As mentioned in Chap. 20, the advances in miniaturization and computing power have enabled the placing of more tasking responsibilities and automation on the spacecraft rather than on the ground [Sherwood, 2007]. Mission operations recognize the importance of automation as a productivity enhancer, useful for performing repetitive tasks and responding to well documented contingencies. However, there can be a performance downside to extensive automation. Validating complex automation can itself be extremely complex and costly. Over-dependence on automation results in lower operator technical proficiency and only experienced, technically current and knowledgeable personnel can effectively respond to non-standard situations.

Looking at the space segment, there are two basic levels of automation for space segment health management and four basic levels of mission execution automation as shown in Table 29-6. These levels are based on the ECSS standards regarding space segment autonomy [ECSS, 2008]. The reference also lists two levels of autonomy for mission data management.

The lowest level of space segment health maintenance automation is the closed-loop processes that respond to conditions sensed on-board the spacecraft. Routine examples are momentum management, closed-loop thermal or environmental control, attitude control, and orbit maintenance. In each of these cases, the spacecraft operators have set some on-board rules or algorithms and limits which govern the spacecraft's response to changing nominal conditions without human intervention. The second level is the detection of on-board failures. Once the space segment has identified the serious anomaly it will inform the ground, take immediate action to minimize the effect of the failure (if the action is predetermined), and put the space segment into a safe mode awaiting intervention by the ground. The top level of health maintenance automation removes the requirement for ground action from the loop and will take steps to restore the space segment to nominal operation.

Table 29web-1. Example Trade Space Table for Identifying Tools that Accomplish Ops Functions. This table lists the functions required in the left column, and the various tools (products) and their vendors across the top. If the product performs the function, an "X" is placed at their intersection. This example is from a trade study done in the late 1990s and some vendors or products shown may no longer exist or are different in their capabilities. You should not use it for your own trade study.

	Vendor/Source	Science Systems	Altair Aerospace	JPL	SprectrumAstro	Cisco	DataViews Corp.	Predict/DLI	Integral Systems Inc.	Microsoft Corp.	AI Solutions	Gensym	Pacific-Sierra Research	Research Systems	ILOG	ILOG	Storm Control Systems	National Instruments Inc.	L3	ADC Metrics	Monico, Inc.	GSFC	UDP Consulting	Optimal Networks	Integral Systems	HP	Gensym	Matra Marconi	Matra Marconi	Science Systems	STI	GSFC	Visual Numerics	Talarian	Interface Control Systems	Lockheed-Martin	Analytical Graphics	Sun Corporation	Tivoli
Function	Product	Advanced SLICK	Altair AMCS	ASPEN	AstroDACS	CiscoWorks	DataViews	EAV	Epoch 2000	Excel	FreeFlyer	G2	GREAS	IDL	ILOG Solver/Scheduler	ILOG Views	IMT	LabViews	L3 System 500 Model 550	Metrics	Monitor	MOPSS	NetLayer7	OAE & OAI	OASYS	OpenView	Operations Expert	OpsCenter	OPSWARE	ORATOS	OS Comet	PARR	PV-Wave	RT Works	SCL	SCS 21	STK	Sun Solstice	TME 10
Real-Time String																																							
Anomaly Detection and Response		X	X		X				X			X					X														X				X	X			
Command Verification		X	X						X			X					X											X			X				X	X			
Constraint Checking		X	X		X				X			X					X											X			X				X	X			
Control Input		X	X		X		X		X			X				X	X	X	X									X			X			X		X			
Decommutation			X		X				X										X												X			X	X	X			
Engineering Data Storage and Retrieval		X	X		X				X								X		X												X			X					
EU Conversion		X	X		X				X										X									X			X			X	X	X			
Frame Synchronization			X		X				X										X												X			X	X	X			
Mnemonic to Binary Conversion		X	X						X			X					X											X			X				X	X			
Script Processing		X	X						X			X					X											X			X				X	X			
Remote Data Display																X																							
S/C Telemetry Display		X	X		X		X		X			X				X	X	X	X									X			X			X		X			
Mission Planning																																							
Activity Planning		X		X									X		X							X							X			X							
Activity Scheduling		X		X	X		X						X		X							X							X			X							
Flight Dynamics																																							
Attitude Ephemeris Generation																																					X		
Tracking Data Preprocessing																									X												X		
Ephemeris Generation											X														X												X		
Orbit determination																									X												X		
Orbit Event Product Generation																									X					X							X		
Orbit Maneuver Calculations											X														X														
Pointing Angle Determination																																					X		
Health and Safety Trending																																							
Data Analysis								X	X	X				X						X	X										X		X						
Data Trending								X	X	X				X						X	X										X		X						
System Management																																							
Network Monitoring						X																	X	X		X	X									X		X	X

Table 29-5. Definitions of Autonomy Levels. Table (a) shows the basic levels of autonomy for space segment health management, while (b) shows the basic levels of autonomy for mission execution. These are based on the ECSS standards regarding space segment autonomy, but are fairly standard globally.

(a) Space Segment Health Maintenance Autonomy Levels		
Level	**Description**	**Functions**
1	**Closed-loop:** Pre-planned automatic response to detection of a particular state or condition that does not require ground input	For example, thermal control (automatic powering of heaters when temperature drops) Includes actions that can help prevent potential anomalies that would require safing of spacecraft (e.g., power management to prevent critical power condition)
2	**Closed-loop/Open-loop:** Establish safe space segment configuration following an on-board failure and wait for ground response	Identify anomalies and report to ground segment Reconfigure on-board systems to isolate failed equipment or functions Place space segment in a safe state
3	**Closed-loop:** Re-establish nominal mission operations following an on-board failure	As Step 2, plus configure to a nominal operational configuration Resume execution of nominal operations Resume generation of mission products

(b) Mission Execution Autonomy Levels		
Level	**Description**	**Functions**
1	**Open-loop:** Mission control under ground control; limited on-board capability for safety issues	Real-time control from ground for nominal operations Execution of time-tagged commands for safety issues
2	**Open-loop/Closed-loop:** Execution of pre-planned, ground-defined, mission operations on-board	Capability to store time-based commands in an on-board scheduler Limited capability to react to execution of commands (e.g., retry if unsuccessful)
3	**Closed-loop:** Execution of adaptive mission operations on-board	Event-based autonomous operations Execution of on-board operations control procedures
4	**Closed-loop:** Execution of goal-oriented mission operations on-board	Goal-oriented mission re-planning

For mission execution, there are four levels of automation. (1) The first is simple open-loop real-time control of the space segment by the ground and possibly some time-tagged commands required for safety issues. (2) The next level of automation is the ability for the space segment to respond to a sequence of timed commands using an on-board scheduler, without the need of human oversight or intervention. Examples of this would be the command sequences to perform a remote-sensing mapping pass; a flyby of a target, such as an asteroid, with the proper sequence of instruments collecting data; or routine scheduled events, such as sensor calibration, momentum dumping, or thermal conditioning. (3) The third level of automation is where the space segment has been equipped with a set of rules that will enable it to react correctly in various anticipated situations, the exact time of which might not be known in advance, as is required for a stored sequence of timed commands. This level would typically be used for repetitive events during the mission that are well understood, but could occur at unpredictable or uncertain times, or if there is no opportunity or need to upload a command sequence from the ground. (4) The fourth level of automation is a fully autonomous mode, where not only does the spacecraft have rules to govern its actions, but it is able to modify its reactions to stimuli based on the success of previous responses to similar stimuli (i.e., it has the ability to "learn"). This level of automation is what will probably be required for future interplanetary probes or robotic probes to the outer planets where the time lag or even lack of communication with the Earth for extended periods requires the spacecraft to take care of itself in almost any situation.

Most robotic spacecraft since the dawn of the space age in 1957 have had some degree of the levels 1 and 2 (both health maintenance and mission execution) automation out of necessity to conduct a successful mission where there is not continuous and near-instant communication with the controllers on the ground. The third level of mission execution automation was successfully tested for the first time in 1994 by the Clementine lunar mission [Sorensen, Oswald, Shook, Van Gaasbeck, 1995], and the USAF's TAOS mission [Anthony, 1992]. The fourth level of automation is in its infancy, but will become more common in deep space missions in the future.

You may expect that the spacecraft automation would not be under the control of the operations engineering team, which would rather just use the level of automation upon which the spacecraft engineers decide. Although it could happen this way, this goes against the basic principle of operations engineering, which is that operations is a vital consideration in the entire system design and operations engineering needs to be involved in all aspects of spacecraft design from the beginning. The design of the ground segment automation is also important, the level of which is closely tied to the level of automation of the spacecraft. The level of automation for the mission involves several important factors, including:

- Length of project/mission (both development and test time and length of operational mission)
- Automation experience of the project team
- Repeatability and complexity of operational tasks
- Legacy automation software (availability, suitability, cost)
- Latency (e.g., communications lag due to distance, or timeliness requirement for collected data)
- Anticipated threats and required response time
- Tolerance to errors (e.g., human errors in preparing commanding)
- Communication bandwidth requirements and cost

The effect of these factors on the amount of automation typically required by space missions is shown in Table 29-7. These are only general trends and may differ for your mission, but can help determine weighting factors in your decision process. You will notice that they are also subjective—there are no quantities associated with the factors. This is because of the danger of assuming that what is true for one mission is also true for another mission, which may be of a completely different type. However, some of them can be quantified to some degree, although the factors do not act in isolation and may counteract each other. For instance, if a nominal mission lasts six months, then it would tend to have less automation than a mission lasting 10 years, everything else being equal. However, it seldom is and there can often be inverse correlations between the factors. Using the previous example, a six-month mission may have repetitive tasks that are critical to the success of the mission (i.e., no tolerance for error), in which case it would make sense to automate the generation of commands on the ground or apply a higher operations level of automation in the spacecraft despite the shortness of the mission. Thus you will have to weigh the importance of these factors when selecting the amount of automation to use.

Simulations, including Monte Carlo, can be useful in determining the efficiency or even feasibility of a particular operations architecture and its level of automation [Rao, 1998], [Sierhuis, 2002]. The communications and computational time lags are important to analyze for the system. Doing a "day in the life of" or similar simulations can help in understanding your requirements.

Step 7. Determine Whether Capabilities Identified in Steps 5 and 6 Exist, are Obtainable, or Must be Developed

Once you have determined the operations functions required by your project, and the expected level of automation in both the space and ground segments, you need to determine which of these can be addressed by assets already possessed by or available to your team, which ones you will have to obtain from external sources (e.g., vendors or government sources) or have developed (either by the team or contracted out). The answers can have a large effect on the both the schedule and cost of the project. Some of this step may have been done during the accomplishment of steps 5 and 6 just by gathering the information on the various options.

Table 29web-2. How Factors Affect the Amount of Automation for Missions. These are general trends and are subjective. They are not applicable to all missions, but are meant just as a general guide.

Factors Affecting Automation	Comments	Amount of Automation LOW	→	HIGH
Length of Development Project	Length of time (& cost) to develop automation	Short	→	Long
Length of Mission	From launch to designed end of mission	Short	→	Long
Automation Experience of Project Team	Inexperience requires steep learning curve	Little	→	Much
Repeatability of Operational Tasks	Unique tasks make automation more difficult	Unique	→	Repeatable
Complexity of Operational Tasks	Very complex tasks make automation more difficult	Complex	→	Simple
Legacy Automation Software	Reusing existing software reduces time, cost, and risk	None	→	All
Latency (timeliness of data)	(1) Communication time lag	Short	→	Long
	(2) Timeliness requirement	None	→	Immediate
Anticipated Threats Requiring Fast Response Time	Expected threats that require fast response requires automation	None	→	Frequent
Tolerance of Errors	Automation tends to reduce human errors, especially during high stress or repetitive activities	Very	→	Not
Communications Bandwidth Requirements and Cost	If bandwidth requirement is high or costly, then it might be better to do some data processing on the s/c	Low	→	High

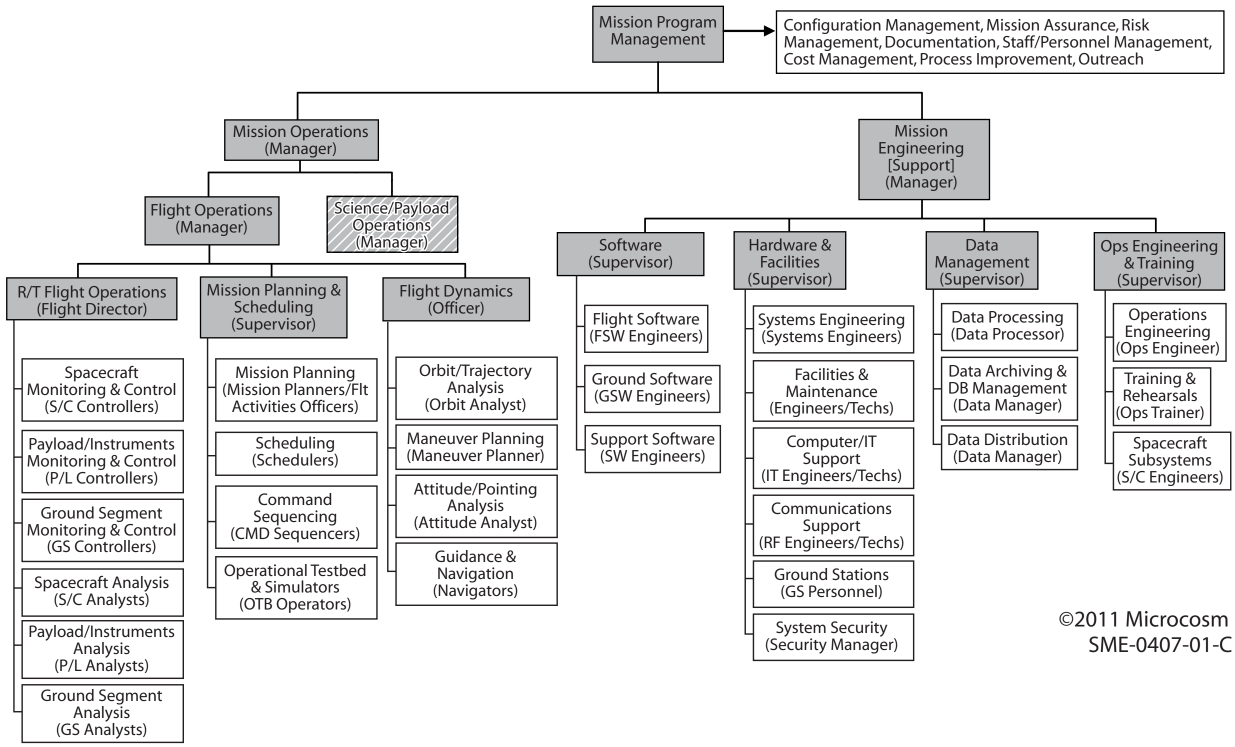

Fig. 29-4. Sample Mission Operations Organization. This organization chart shows typical groupings of operations functions, which may or may not map directly one on one to personnel. Common staff positions that fulfill each function is shown in parentheses below the function name. This is just an example and actual operations organizations can vary significantly from these—smaller, larger, or using different terminology for the functions and/or positions. The Science/Payload function is often a separate organization.

Step 8. Develop Staffing Plan and Identify Other Resources Required

One of the most important factors in determining the cost and performance of mission operations is the staffing—both the level of staffing throughout the project life cycle and the personnel qualifications required. In Steps 4–6 of this operations development process, you determined the functions required to do the operations for your mission, the means to accomplish the functions, and the level of automation that you could use. Now you should look at those functions again to see which require the support of human operators and to what extent. Are the operators just needed for supervision of an automated process, required to make decisions at critical points in the process, conduct the function entirely manually, or just be on standby to intervene when something anomalous occurs? The frequency of the human participation needs to also be considered. In manned space missions, like for the Space Shuttle or ISS, human operators are present continually—24/7. For many robotic spacecraft, such as nanosatellites orbiting the Earth or probes deep in space with long communication lags or infrequent contacts, little time may be needed to support operations, although some non-real-time functions, such as mission planning or data analysis, do not depend on having contact with the spacecraft but will be staffed during office hours.

One of the products to come out of this step is an operations organization chart or tree, an example of which is shown in Fig. 29-4. At this point it is useful to define the typical staff positions used for operations. Note that these are just some of the more common ones, some of which will be found in nearly all operations teams, but they may have different names in a particular organization. There are also some other positions that may be used based on the nature of the mission or the organization's operations philosophy. For smaller missions, some of these functional positions may not be in the functional organization and the responsibilities of those positions will be assumed by other positions. For example, the Mission Operations and Flight Operations functions, or the Flight Operations Director and the Real-time Flight Operations Supervisor functions may be combined.

The mission staffing plan accounts for the criticality of an operator in the loop that is supplemented by, but not supplanted with, automation tools. Basically, the mission operational staffing concept is primarily dependent on several variables including the duty cycle of mission payload events; the complexity of the operations; the cost; and the degree of automation that has evolved. Mission operations staffing can be divided between management, science, flight operations, and engineering support elements. Together they comprise the Mission Operations staff. The organization is first developed to be functional rather than actual. This means that one actual person might perform more than one function shown in the organization or a function may not have a person dedicated to it. Note that the organization shown does not include ancillary positions such as administrative assistants. It should also be noted that some positions may be shared between more than one mission, so the costs would also be shared.

Besides automating the maximum number of repetitive and predictive tasks, another key way to keep operations costs down is to reduce staff size to the minimum necessary to meet all requirements. If the mission staffing approach is based on a minimization concept, such a cost savings objective is attainable. However, reduced staff, while effective at reducing costs, might introduce risk that must be mitigated if quality service is to be provided with a high degree of reliability, maintainability, and availability (RMA). The primary risk of minimized staff is lack of depth at key positions. For ome small missions, many of these functions might be performed by one person or several functions might be shared by a few people thereby providing backups. On some big missions one function might be done by several people. The following describes the functional staff positions in an operations organization.

The *Mission Operations Manager (MOM)* is the supervisor for all operational personnel and delegates authority through the operational supervisors. The MOM also ensures that the mission (science) objectives are met and the smooth working of the science/payload team with the flight operations team. Although not always required, it is very helpful if the MOM understands the basic workings of the various positions within flight operations, mission planning, and flight dynamics. However, the major function of the MOM is to ensure the smooth running and performance of the flight operations teams.

The *Mission Engineering Manager (MEM)* is responsible for the smooth functioning of the mission spacecraft and ground segment facilities, including equipment, operations and software. The MEM oversees the technicians, engineers, and ground station and testbed operators that are required to perform the maintenance and support, and the operations of the mission space and ground systems. The MEM's responsibilities include generating purchase requests for equipment and repairs, scheduling and monitoring installations, supervising the maintenance technicians, ensuring remote site security, and maintaining the overall facility support environment.

The *Science/Payload Operations Manager (SOM)* is responsible for soliciting, reviewing, selecting, and scheduling science experiments or payload activities for the mission, or interfacing with the entity that is responsible for these activities (e.g., external Science Team or the payload customer). The SOM may be part of the operations organization or part of the Science Team/customer organization. The SOM deals directly with the scientists/customers to ensure that they are ready to conduct their scheduled experiments, and with the Flight Operations Team (FOT) to ensure that the planned experiments/activities will be successfully conducted. The SOM or members of the Science/Payload Team may work directly with some members of the FOT, especially the Mission Planners, Instrument Controllers and Analysts.

The *Flight Operations Team (FOT)* members are generally those that have direct operational interactions with the spacecraft and ground systems. The FOT consists of the controllers that routinely operate the mission system during real-time contacts; the analysts that provide direct support to real-time operations, even participating in real-time operations as needed; and the planners and analysts who generate the products that are used to operate the spacecraft and ground system or process the operational data products for final disposition.

The real-time operator positions are the Spacecraft Controllers, the Payload/Instrument Controllers, and the Ground Network Controllers. These positions are usually staffed whenever there are contacts with the spacecraft. However, due to increasing usage of autonomous operation of the mission ground stations and even the spacecraft, routine contacts may not have to be staffed, or at least not with all of these positions. Instead, the Spacecraft Controller could routinely conduct this function. During launch, transition, and until the autonomous operations have been proven or during special events (e.g., propulsive maneuvers, special experiments or observations), one or more of these positions may be manned.

The *Flight Operations Director (FOD)* directly supervises all real-time operations and supporting analysis personnel that are directly concerned with the health and operation of the mission spacecraft and ground network.

The *Mission Engineering [Support] Team (MEST)* supports the FOT, but are usually not directly involved with the flight or ground operations. Although the MEST personnel generally work a standard five-day workweek, they are always on call to respond to system problems that threaten operations. These positions interact primarily with operations personnel, their processes and the mission system components to indirectly support each mission and operation. Their primary function is to ensure that all mission infrastructure and system components support the processes put in place by the mission operations teams to perform readiness and operations. Some of the positions included in this area are the operations engineer (expert on operation of the mission spacecraft and the overall operations architecture), ground systems engineer responsible for overall integrity and performance of the mission ground system), RF engineer (expert on communications equipment at ground stations), network engineer (expert on communication networks, both WAN and LAN), flight and ground software engineers, technicians, testbed/simulator engineers, data management engineers, database administrator, configuration management administrator, system security specialist, spacecraft systems engineer (spacecraft systems expert who ideally was involved with the mission development and I&T phases), spacecraft subsystem engineers, and payload or instrument engineers (expert on science instrument or other payload subsystem).

We will look at the roles and responsibilities of the common positions found in a Mission Operations Team. Some of the functions and corresponding positions in the MOT shown in Fig. 29-4 are actually in some cases a collective category that can be differentiated into further actual positions that help fulfill that function. An example of this would be the Spacecraft Analyst, which may be differentiated into various subsystem analysts, or the spacecraft controller, which may be further differentiated into Propulsion, Communications, Power, or other spacecraft subsystems, although there is usually only one spacecraft controller that normally interacts with (commands) the spacecraft.

The *Flight Director (FD)* has overall responsibility for the FOT and operation of the space and ground segments in support of the mission and is usually involved in the Mission Operations Center with the real-time operations. The FD directly supervises the Spacecraft Controllers, Payload/Instrument Controllers, Ground Segment Controllers, mission analysts, flight dynamics officer, and anyone else involved with the real-time operations. This can include planning for real-time operations, not just during their execution. In NASA and some other organizations, the FD is the ultimate authority during real-time operations in the MOC. Depending on the operations organization, the FD may be a stand-alone position, it may just be the lead Spacecraft Controller, or it may be the R/T Flight Operations Director, the Flight Operations Manager, or even the Mission Operations Manager.

The *Spacecraft Controller (SC)* is a mission generalist shift console position that directly interacts with a spacecraft during real-time supports and is only to support mission operations passes. SC's are responsible for implementing the plans generated by the mission planning and scheduling process. Generally, the SC uploads commands to the spacecraft according to pass plans (if this is not done automatically), verifies spacecraft response to these commands, monitors "tactical" spacecraft performance, detects spacecraft anomalies, notifies Spacecraft Analysts of new anomalies, and logs the details of each pass. At times the SC may implement certain contingency plans and will routinely implement alternative operations as required. However, in large operations teams the SC usually does not investigate or resolve anomalies, they merely detect and report them. The reason for this approach is because of the SC's limited training, experience, and exposure to mission specific information. Therefore, the SC is not considered an expert on any spacecraft and does not implement any operations without the pre-approval or guidance of the relevant Mission Operations Team member. During nights, weekends, and other off hours, the SC may also serve as shift supervisor within the MOC. For missions with limited staffing resources, the SC position may be filled by one or more of the spacecraft subsystem or systems engineers, or by students.

The *Ground Segment Controller (GC)* is a mission generalist shift console position that is responsible for ensuring the network assets (including ground stations) are able to support a spacecraft pass and collect, transfer and store its data stream, and is the realtime keeper of the Ground Network System (GNS) schedule. The primary GC function is to monitor (and as the situation requires and authority allows, modify) the GNS pass schedule and ensure that the network is properly configured in time to support each scheduled pass. As ground segment anomalies occur, the GC is also responsible for realtime troubleshooting and implementing work around procedures to maximize the chances of pass success. Finally, the GC maintains a log of all activities for each pass and notifies the engineering support personnel of system outages and problems that may require maintenance or repair. On shift, the GC position is usually considered subordinate to that of the SC. However, during nominal operations for any type of mission support only the GC is authorized to configure, reconfigure or control the ground network. In these situations, other personnel who are monitoring the network may request configuration alterations. However, all these requests must go through the GC in charge of the pass who is solely responsible for implementing these changes. After the IOC the ground stations and network are often operated autonomously, for which a GC may not be required. In this case, the SC may monitor the GNS and call in a GC or engineer, if required. However, in cases of full "lights out" autonomy, the monitoring will be done by the MOC system since routine passes will not require the presence of even the SC.

The analysis function can be done by a position for small missions, or, as is more usual, can be differentiated into several specialist analyst positions, the most common being the spacecraft analyst, payload/instruments analyst, ground segment analyst, and mission analyst. In some operations schemes, the analysts will be part of the real-time operations team, analyzing their data during the contacts with the spacecraft, while in other schemes their function can be performed off-line at any time and does not require real-time contact. Of course, when an anomaly or special situation arises, they may have to participate in the real-time operations. The description of the responsibilities of these analysts is described in Mission Operations Processes in Sec. 29.2.

The *Mission Planner (MP)* prepares all the products required to operate the mission on a nominal, daily basis. In some organizations (such as NASA manned space operations) the mission planner may be known as the *Flight Activities Officer (FAO)*. The primary mission planning and scheduling functions are to determine the spacecraft's ground visibilities, coordinate with the science team/customer to select and schedule payload operations, schedule passes, create, verify and transfer command loads to execute these operations and passes, and build pass plans to guide the SC (and GC) through each contact support. For large missions, the mission planning and scheduling function may be split up into positions supporting the major tasks within the function, such as *Mission Planner*, *Scheduler*, and *Command*

*Sequence*r. For smaller missions, these are usually combined, and will be treated as such here. In general, the MP is the primary interface between the MOT and the mission scientists or payload customers.

The *Operational Test Bed (OTB) Operator* runs the mission operational test bed and simulators in support of the mission. The major function performed by the OTB operator in support of flight operations is to test command sequences/scripts on the OTB before uplinking to the spacecraft to help ensure the spacecraft will behave as expected. It is important for the OTB Operator to ensure that the same flight software version (with any patches) is running on the OTB as on the spacecraft and the operating configuration (e.g., mode, or subsystem settings) are the same as well. If this is not done, then the OTB may indicate that everything is fine with a certain command load, which could cause the spacecraft to act differently, sometimes with catastrophic results, as happened with the Clementine spacecraft after it had completed its lunar mission and was on the way to an asteroid [COMPLEX/SSB, 1997]. Other functions of the OTB operator in support of flight operations include anomaly resolution, testing new software versions or applications before uplinking to the spacecraft, and training and rehearsals for the flight operations team to either practice upcoming special events or to train new personnel or increase the proficiency of veteran personnel.

The *Flight Dynamics Officer (FDO)* is responsible for monitoring, analysis, and in some cases, controlling the orbit/trajectory of the spacecraft and possibly its attitude. For larger missions, the FDO may have several personnel to perform these functions.

The *Orbit Analyst (OA)* is responsible for determining the current position and orbit/trajectory parameters of the spacecraft using information from several possible sources, such as on-board GPS data, ground station tracking data, optical or laser tracking data. The OA generates an orbit ephemeris or state vector on a regular basis and distributes it to the rest of the operations team.

The *Attitude/Pointing Analyst (AA)* performs a similar function for the attitude of the spacecraft. Most spacecraft now perform this function on board since the processors have become more powerful. However, there are still times when the on-board software needs to be verified, especially when testing upgrades. The AA may also help in the design of planned maneuvers by determining the pointing required.

For spacecraft with either a propulsive system or other means to alter its trajectory (such as aerobraking), then a *Maneuver Planner (MP)* is required to design, develop, test, and implement the required maneuvers. The results of the maneuvers are evaluated by the OA and MP to determine if they were successful and whether or not any correction maneuvers are required. During the execution of a planned maneuver (including the preparation leading up to the maneuver), the lead MP is often present in the MOC to monitor events in real-time (if possible).

The *Navigator or Guidance Officer (Nav or Guido)* looks at the long-term orbit or trajectory and plans the maneuvers required to accomplish the mission. They work closely with the rest of the flight dynamics team to fulfill this function.

Once the staffing positions have been defined, the next step is to determine what functions the operations personnel need to perform (maybe not all the identified staff positions are required) and when they are needed. The tool that is used for this purpose and to later determine the staffing costs, is the Work Breakdown Structure (WBS). This basically defines the tasks that have to be performed to successfully develop or conduct operations, and when applied to workload (FTE personnel) estimates and a schedule, becomes the basis for the staffing plan. The WBS and how to develop one are described in Sec. 29.1. An example WBS for mission operations is shown in Table 29web-5.

Once the WBS has been developed and it has been fitted to a schedule to identify when in the project life-cycle they need to be performed (and thus staffed), the workload for each task can be estimated along with identifying the staff position to accomplish it. There are several good COTS software packages available to perform this project management function such as Microsoft Project® and dotProject, which is an open source project management tool.

Once the positions required for mission operations have been identified and their expected workload and utility have been determined, as well as when they are required in the project life cycle, a staffing profile can be built. The first step is to list all positions on a spreadsheet that shows the schedule of the project at an appropriate time resolution (e.g., monthly). Note on the spreadsheet when each operations team member is brought into the project and at what level as Full Time Equivalents (FTEs). The monthly staff level in FTEs can then be determined by adding the values per month. From these totals you can produce a graph showing the staffing profile for the mission.

Although we have concentrated on the operations staffing so far in this step, the other part of the step is to identify other resources that will be required by the mission. These could include ground station coverage (utilization), computers, communications equipment, consoles and workstations, or software applications that are needed to support operations. Some of these are covered by other areas, such as the Ground Segment, but may come under the responsibility of Mission Operations or under joint responsibility. Once you have the staffing requirements done, as well as the communications and other mission requirements as designed into the current system architecture, you will be able to make estimates for these other resources. However, the resources include not only hardware and software, but also services, such as precision orbit determination, that might be required and will have to be costed.

Multi-mission operations can have different loading in both staff and resources. For example, a 0.2 FTE orbital engineer may be normal as that function maybe multi-mission. Likewise, a ground station is nearly always multi-mission, which a monitor and control tool

Table 29web-3. Example of a Work Breakdown Structure (WBS) for Mission Operations. This example is taken from the project WBS (which is why it begins with 6 instead of 1). Although this WBS consists of mostly the tasks required for developing mission operations, it also includes the tasks for conducting mission operations after launch of the spacecraft. In some projects, the WBS for the development and execution phases may be done separately**.**

X	FLIGHT OPERATIONS DEVELOPMENT	X.6.5	Conduct On-Orbit Rehearsals
X.1	***Operations Development Management***	X.6.6	Conduct Contingency Ops Rehearsals
X.2	***Ops Systems Engineering***	***X.7***	***Real-time Flight Operations***
X.2.1	Define and Detail Ops Requirements	X.7.1	Launch & Early Orbit Operations
X.2.2	Develop Ops Concept Document	X.7.2	Engineering Evaluation & Checkout Operations
X.2.3	Develop Ops Test Plan	X.7.3	Nominal Primary Mission Operations
X.2.4	Develop Commissioning (IOC) Plan	X.7.4	Contingency Primary Mission Operations
X.2.5	Determine Flight Rules	X.7.5	Nominal Secondary Mission Operations
X.2.6	Develop Flight Ops Handbook	X.7.6	Contingency Secondary Mission Operations
X.2.7	Support System I&T	***X.8***	***Timelines & Scripts Generation***
X.3	***Mission Planning & Analysis***	X.8.1	Design and Develop Timeline Generator
X.3.1	Develop EE&C Phase Activity Operations Plan (AOP)	X.8.2	Design and Develop Command Script Generator
X.3.2	Develop Primary Mission AOP	X.8.3	Test Timeline and Script Generation Process
X.3.3	Develop Secondary Mission AOP	X.8.4	Produce and Test Timelines and Command Scripts
X.3.4	Develop Mission Planning Process	X.9	Engineering Trending & Analysis
X.3.5	Design and Develop Encounter Planner	X.9.1	Develop Engineering Trending & Analysis Process
X.3.6	Modify & Implement Mission Plan	X.9.2	Design and Develop Engineering Analysis Tools
X.3.7	Schedule Mission Activities (including GS Passes)	X.9.3	Perform Engineering Analysis on Mission SOH Data
X.3.8	Plan Encounters and Activities for Implementation	X.9.4	Write and Distribute Engineering Analysis Reports
X.3.9	Analyze Flight Results & Generate Feedback to MP Process	***X.10***	***Data Processing, Archiving & Distribution***
X.4	***Orbit Analysis***	X.10.1	Develop Data Management Plan
X.4.1	Provide Analysis of Orbit	X.10.2	Develop & Test Data Management Tools
X.4.2	Develop Orbit Determination Process	X.10.3	Nominal Data Management Ops
X.4.3	Determine Orbit and Generate Ephemeris	***X.11***	***Operations Software***
X.5	***Procedures Development***	X.11.1	Determine Ops SW Requirements
X.5.1	Capture Commanding and Telemetry Parameters from I&T	X.11.2	Develop Ops SW Development Plan
X.5.2	Develop Nominal Flight Ops Procedures	X.11.3	Develop SW for Mission Planning & Analysis
X.5.3	Develop Anomaly Response Procedures	X.11.4	Develop SW for Orbit Analysis
X.6	***Training & Rehearsals***	X.11.5	Develop SW for Training & Rehearsals
X.6.1	Develop Flight Ops Training Plan & Materials	X.11.6	Develop SW for Timelines & Script Generation
X.6.2	Develop Rehearsals Plan	X.11.7	Develop SW for Engineering Trending & Analysis
X.6.3	Training and Certification	X.11.8	Develop SW for Data Processing, Archiving & Distribution
X.6.4	Conduct Launch and Early Orbit Rehearsals	X.11.9	Ops SW Maintenance

is probably mission specific (although within that mission it may control multiple satellites).

Step 9. Perform Trades to Determine Best Solution from Steps 5–8

At this point in the MOP development process, you will have identified the functions and level of automation required to complete your mission. You will also probably have identified several tools or packages (whether existing or not) that may work to accomplish these functions. The next step is to perform a trade study between the various candidate options to determine which would be best for your particular application. If this is being done early in the development cycle, then optimization is not expected, but rather obtaining a solution that is acceptable and will accomplish the mission. Later in the development cycle (i.e., a later iteration), then a more detailed analysis and comparison may be required to optimize your solution.

You must select the criteria that are best for distinguishing between the candidates in the trade studies. Typically these fall into the following four categories: performance, schedule, cost, and risk. These will be examined in turn.

Performance is probably the most important attribute in your trade study. This is a measure of how well the object being evaluated fulfills the functions for which it is being considered. Your selection must be able to function sufficiently well to accomplish the tasks needed to fulfill the mission objectives. If it will not do the job required, then it should be discarded. However, the selection cannot be made based on performance alone, but must be considered in light of the other selection parameters. When you score the attributes of the candidate solutions, performance is generally weighted the highest.

Schedule is important because no matter how well the candidate fulfills the other trade criteria, it is worthless if it cannot be available on time, especially if there is no flexibility in the project schedule. Schedule is also closely related to cost for elements that have to be developed for the project, because of the increase in labor cost as the time required increases.

Cost is critical for some projects, especially for universities and small programs, but inflated costs can kill even the high-end missions as well. For projects with tight budgets, cost becomes the dominant constraint and can even out-weigh performance as the primary selection parameter. In this case, "good enough" might be the selection mantra, even though it might cause reduction in mission objectives, lifetime, or increase in risk. Cost includes both the non-recurring costs for the pre-launch phases, and the recurring costs during the conduct of the mission. This is where automation can be a deciding factor—higher non-recurring costs for developing automation may lead to less overall project costs due to reduced recurring costs (e.g., fewer personnel required to operate the mission). When including cost as a selection parameter, it might be worthwhile dividing it into non-recurring and recurring costs, with possibly different weighting. This difference in weighting might not just be related to the total project costs, but could instead be tied to a funding profile for the project—plenty of funding during development but little funding for operations would put the weighting in favor of the non-recurring costs, while vice versa would put it in favor of the recurring costs.

Risk can encompass many areas, such as safety, probability of successfully completing the mission, political risk (e.g., high visibility projects may have high political risk—failure could have far-reaching consequences) and technology readiness level. Risks are identified using a process of risk management, and the willingness to accept the risks has to be determined. When using this as a trade selection parameter, you might want to differentiate between the different types of risk, because each may have different weighting for your project.

The simplest way to do the trade study may be to take the table you used to determine the functionality of the candidates in your trade space (e.g., Table29web-1) and assign numeric values to each of them for each of the four trade parameters instead of the simple "X" as shown in Table 29web-3. However, a more rigorous methodology for performing trades is presented in Section 5.3 and is applicable for use in operations as well.

Step 10. Determine ROM Mission Operations Cost

By this step you have determined the factors that are needed to develop a rough order of magnitude (ROM) cost estimate. These major factors include the tasks, staffing profile, hardware, software, facilities, and communications costs as well as maintenance/refurbishing and replacement cost for long-term missions. Detailed cost analysis methodologies are described in Chap. 11. See Cost Model (NICM) in Sec. 11.2.5.

The cost of operating a mission depends most on the number of personnel involved (people are very expensive as a recurring cost) and operations complexity. Both of these depend on the amount of automation employed both in the spacecraft and in the ground segment. Adding more automation probably increases the non-recurring costs during Phases A to D, but may allow for lower recurring operations costs during Phase E. The complexity of the operations depends on the mission objectives, the design of the spacecraft and payload, communications and ground segment design, and operational risk policies.

Step 11. Repeat Steps 4–10 for Development Phase (Mission Phases A-D as Appropriate)

The core of mission operations for any project is what is required to execute the mission after launch. This is the phase of the project that the mission operations are designed to fulfill—this is what accomplishes the mission goals. The operations development done prior to launch (Phases A to D) is just what is required to make the mission operations to run smoothly to accomplish the mission. That is why we look at the Phase E operations first to develop our Mission Operations Plan, and to size and cost these operations. However, to complete the MOP, we must go back and determine what needs to be done to evolve the operations into the efficiently functioning system required for flight operations. Now is the appropriate time to go back and repeat the steps of the MOP development to account for the operations development in Phases A to D. In some of your previous steps, you may have already included some of this early work (e.g., staffing profile), so now is a good time to go back and revise it if necessary based on your later determinations. At the end of this step you should have a revised ROM cost estimate and be ready to press on to the final steps of the mission operations plan development.

Step 12. Assess Mission Utility, Complexity, Cost Drivers

The mission utility of the operations (i.e., determining how well the operations help us meet the mission objectives) is calculated using the method outlined in Sec. 5.4. It is helpful if you have simulations that you can use for determining the performance and characteristics of the system and for which you can input a range of values for the design parameters to determine their effect on the cost and performance. Operational simulations such as these have been developed and used extensively [Rainey, 2004], and are available from various sources such as NASA. The development of the Mission Operations Plan is iterative, and as the plan becomes more mature, the differences in the mission utility parameters between iterations should decrease, and also helps provide confidence in the viability of your operations system design.

Mission operations cost depends largely on the complexity of the operations. To determine how the complexity affects the cost drivers, we can use a complexity model which expresses operational parameters in terms of FTE operations personnel. Each of the operational activities is graded as low, medium, or high complexity, using the analogous method (i.e., comparing with the same function on similar class missions that have been flown). This complexity factor is included in the algorithms of the model that can be used to evaluate the operations and to reduce operations cost. This model and method is described in detail in Squibb, et al. [2006].

Step 13. Repeat for Alternate Mission Concepts (Starting with Step 2) if Required

This step is used early in the life cycle of the mission design when trade studies are still being done to determine alternate mission concepts, but is skipped if the baseline mission concept has been selected. The purpose of doing operations concepts for alternate mission concepts is to determine how operations affects the performance, schedule, cost, and risk of each mission concept being evaluated. This becomes an important factor in deciding the baseline mission concept to be used.

Step 14. Identify Derived Requirements

In Step 1, the top-level requirements, both for the mission and for operations, were defined. However, to implement a design, requirements need to be specified that go to a more detailed level in each system element. Although this is particularly obvious with spacecraft subsystems, it is also important for operations as well. You need to know how you are going to meet the top-level requirements and there will be constraints or design factors that have to be considered as you get deeper into the design. These are captured in what are called derived requirements (see Sec. 6.1). Each *derived requirement*, as its name suggests, is derived, or allocated, from a higher level requirement. This means it has traceability all the way up to the mission objectives. Requirements also need some way to be tested or verified. It is important that requirements be numbered and tracked in the Mission Requirements Document, System Specification Document, or a similar document. In Table 29-7 is a simple example of top-level requirements and their first generation derived requirements.

Step 15. Develop Training Plan

When you have identified the operations staff positions required by your mission and have determined the staffing profile, you need to develop a Training Plan (sometimes called a Training and Certification Plan). All operational positions require training but not all require certification. Although different organizations may have different policies and techniques for training and certification, the basic training plan and methodology described here is based on NASA-sanctioned Instructional Design Processes, and should work for most missions with little modification. However, it should be noted that some organizations do not want their satellite operators to "think" for themselves, but rather just to follow prescribed procedures. This is more common in satellite operations within organizations where the operators are there only as a temporary assignment and may be operating assets worth billions of dollars. There have been instances where an operator has jeopardized a mission by trying to solve a problem that was relatively benign to start with.

The most efficient method of training, especially for smaller organizations, is to use a "right level" on-the-job (OJT) style approach to training its operators where the emphasis is on position proficiency and not universal knowledge. Hands-on experience is emphasized far more than classroom instruction. This approach requires position cross-training, especially with limited staffing resources, while up-training is a privilege that must be earned. Personnel should be encouraged to learn the basics of performing higher level functions and expanding their technical worth to the program. In addition, those exhibiting high degrees of initiative and motivation can be up-trained as a career enhancing opportunity. However, positional up-training as a function of an operator's employment is not necessary and is not usually formally pursued unless the situation (e.g. imminent departure of ops team member) drives such a requirement. Within the mission operations team, the training and certification authority and administrator will vary depending on position. Basically training is divided into two distinct parts, new-hire basic training and mission specific training.

To effectively implement the classroom/hands-on and field training phases of the program, a variety of methods of instructional delivery should be used that yields qualified satellite operations personnel, cost effective implementation expenditures, and allow for a follow-on training program. A formal certification program is included to evaluate and ensure the proficiency of operations personnel thus mitigating risk and increasing the overall level of confidence in mission success. Training objectives are linked with skills required for certification to ensure operations personnel competence in all required mission related tasks.

The training process is designed to develop a spacecraft flight operations training and certification hierarchy that contains generic, as well as program and skill category specific training. At each stage, there are certification procedures that ensure knowledge bases and skill sets before a trainee is allowed to progress to the next stage of training. Figure 29-5 shows for this Training Program Process.

Phase I Training is an introductory level mission operations training and certification program. In this phase, trainees become familiarized with the fundamental concepts of the mission operations process: what are the component functions, how they fit together, and how they interact in the operations control room. Typically, all the space mission operations functions described in this chapter are covered in the Phase I training. Trainees also learn about the core spacecraft and ground systems

Table 29-7. Example of Derived Requirements *(Child Requirements)* Obtained from Top-Level Operations Requirements *(Parent Requirements)*.

Top Level Operations Requirements (Parent)	Derived Operations Requirements (Child)
The Mission Operations function (Mission Ops) shall provide management and control of the spacecraft and Ground Segment to help ensure the successful completion of the mission	• Mission Ops shall perform real-time contact support (monitoring and commanding) • Mission Ops shall perform mission planning • Mission Ops shall perform timeline and command script generation • Mission Ops shall perform orbit analysis and provide orbit ephemeris to mission users • Mission Ops shall perform spacecraft engineering trending and analysis • Mission Ops shall perform anomaly resolution and contingency operations • Mission Ops shall determine operations statistics • Mission Ops shall perform data management • Mission Ops shall provide operations report generation functions for the mission • Mission Ops shall be involved with the design of the spacecraft throughout the project life cycle • Mission Ops shall support spacecraft integration and test activities
Mission operations shall be designed for human control or autonomous "lights out" nominal contact support	• Mission Ops shall be automated to allow the option of "lights out" nominal contact operations after IOC

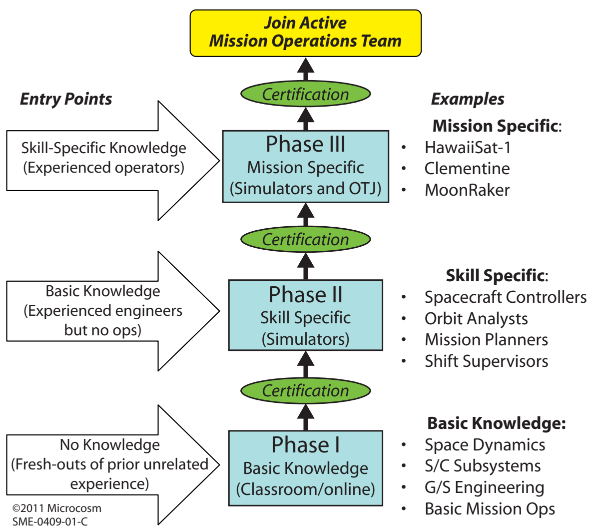

Fig. 29web-1. Training and Certification Process. This is an example three-phase process that takes operator trainees from basic knowledge needed for mission operations, through learning the skills needed for their particular position (with cross-training if desired), to the special skills needed to operate a particular mission. Experienced engineers or operators can enter the process at a higher phase. Phase II may include OTJ training or just simulators, depending on the situation and resources of the organization.

and subsystems, their functions within themselves, how they operate, how they interact with each other, and how one function/process is dependent upon others for proper, safe operation. Phase I should be completed by all mission operations personnel. The training should consist of a standardized set of courses so that all graduates have the same knowledge based upon which to build specific skills, so they all appreciate the roles and responsibilities of each member of the mission operations team. In this manner, we forge team attitudes from the beginning which in the long run leads to a smoother overall operation on the job. Where possible, the trainees should also have on-console training using an operational test bed or simulators to provide realistic mission environments. As part of the simulations, command sending and telemetry monitoring skills are taught. At this stage we initiate quality assurance programs and impart to the trainees, the organizational philosophies and constructs for insuring continuous improvement of processes.

Phase II Training is a skill category (i.e., operations position) specific spacecraft training and certification program. In this phase, trainees gain the knowledge depth and skills to perform mission operations functions. High fidelity mission simulations are provided to hone those skills for real-time operations including launch and early operations, routine, and anomalous operations. Special emphasis is placed on fault detection, identification, and resolution. In the later phases of the Phase II Training, the trainees get OTJ training inside the MOC during actual spacecraft operations, shadowing the certified operator conducting the mission. Under the supervision of the veteran operator, the trainee can then take over routine operations. The training operator has to certify the trainee's satisfactory progress and performance in actual operations.

Phase II Training is to be completed by those Phase I graduates who will be working in operations functions requiring a deeper knowledge set and skill set, such as spacecraft engineering where a detailed knowledge of spacecraft subsystems is required, orbit analyst, planning and scheduling, and shift manager. The training in Phase II involves operations development and higher fidelity simulations of operations scenarios including nominal and anomalous real-time operations. A major product of these simulations is ingraining team interaction and cooperation aspects of operations which are critical at all times but are especially required during the launch and early operations and anomaly operations phases. Reiterate and reinforce the policy of the organization in working independently and in teams using process improvement techniques to reach the customer's goal.

NOTE: Not every engineer or technician is suitable for real-time operations. There have been cases where an operations engineer is outstanding in planning and implementing time-delayed spacecraft operations (with no ground contact), but when faced with the pressure of real-time operations, they "freeze" and cannot act as required. Sometimes repeated training will take care of this, but not always. Some people are not suited for real-time mission operations and should be utilized in other areas such as mission planning and scheduling, mission analysis, or flight dynamics. It is important that your training and certification process is able to differentiate between the different capabilities of the trainees and does not certify people into an area for which they are not suited. Probably the best way to do this is to put your trainees into as realistic high-stress simulated scenarios as possible and see how they perform. This should be done several time with different scenarios to see if their performance improves with experience.

Phase III Training is detailed spacecraft and ground system specific training such as is required for a specific mission. After completion of this phase, trainees are qualified to operate the customer's spacecraft and ground station and systems. They are fully qualified for mission operations performance. Phase III is to be completed by those certified graduates of Phase II (and Phase I in the case of satellite operators who require no Phase II training). This is mission specific training. The training is usually developed in consultation with the PI or mission customers.

For some small spacecraft missions and operations organizations, it might not be practical to do this three-phase training, a two or even single phase training program is sufficient. There may also be a need to periodically do refresher courses, especially anomaly resolution training in the OTB and simulators, for even veteran operators. This is especially true for missions where the spacecraft has had a long dormant or cruise period and is approaching a major event or phase, such as entering orbit around the target planet.

One aspect of the training plan that we have not yet covered is—who are the trainers? In some large organizations, such as the NASA Johnson Space Center, mission training is a complete organizational entity with its own administration and personnel, who are professional trainers. These are typically engineers who have been trained extensively in the various systems and subsystems and often develop the training materials and scenarios for the training program. There usually are experienced operators or engineers who form the core of such a dedicated training organization and train the trainers.

However, many organizations and missions cannot afford the luxury (expense!) of dedicated full-time trainers, and so current veteran operators are used for this function. What if you are starting up a new operation and have no veteran operators? In this case, it is best to use your spacecraft engineers, who develop procedures and tests to be used during the spacecraft I&T activities, to put together a draft training course (e.g., some presentation slides) and criteria for certification in their area of expertise. These spacecraft engineers could be used as the operators during the EE&C phase and provide the OTJ training for the operators who will be taking over from them after IOC. Typically, the training and certification is not as formal or rigorous for new operations organizations, but should be developed and matured with time and experience of the operations team.

The Training Plan is a project document under configuration control where the methodology, processes, course topics, personnel, schedule, and certification process and criteria are captured. For some organizations, especially the smaller ones, the Training Plan may not be a separate document, but incorporated instead into the Mission Operations Plan or a similar document. It is important that the Training Plan is kept up-to-date and actually used by the operations team. It helps to have someone designated with this responsibility.

Step 16. Generate MOP That Includes Technology Development Plan, Personnel Staffing & Training Plan, and Documentation Plan

If this is the first time through this process, then you now have all the pieces to put together a basic Mission Operations Plan. You should include in this document the background description of the mission, the mission statement, mission objectives, and the top-level requirements and constraints*, the mission architecture, the operations concept (description), operations architecture and functional flow block diagrams, operations organization, WBS, staffing plan, schedule, training and certification plan, technology development plan, and the documentation plan. For large and complex projects, some of these parts of the MOP are standalone documents (e.g., Training and Certification Plan or Technology Development Plan), but they would be summarized in the MOP. For smaller projects, these parts would appear in the entirety in the MOP as separate sections or maybe appendices.

The Documentation Plan lists and defines the various operations documents to be used for the project (see Table 29-3), who will be responsible for producing the document, when and how it should be developed, and its intended usage. This includes all the procedures to be used to conduct and support operations.

If this is not the first iteration of this MOP process, then this step is where you review, revise, and improve the MOP based on new information obtained in the previous steps of this iteration. This is the primary document of mission operations development and is very impor-

* For large and complex mission you may want to just include the top-level mission operations and constraints and refer to the Mission Requirements Document (or equivalent) for the remainder.

tant. Remember that the MOP is the blueprint to develop and successfully conduct operations for your mission.

Step 17. Document and Iterate/refine as Needed

This is the final step of the mission operations development process, where you publish the base (or revised) MOP that you have developed in the previous steps. If this is early in the life-cycle of the project, then the base MOP will probably not be complete or at least not mature, and one or more iterations through the steps will be needed to finish the MOP sufficiently for extensive use and reference by the project. The various iterations of the MOP should be made accessible and reviewed by other members of the project so that their input and feedback can be used to improve the plan.