JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 33, No. 6, November–December 1996

Tradeoffs Between Science Objectives and Ground System Capability

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The most fundamental objective of all planetary missions is to return data. To accomplish this, a spacecraft is fabricated and built, software is planned and coded, and a ground system is designed and implemented. However, a systems engineering approach to determine how the collection of data drives ground system capabilities has received little attention. A technique by which science objectives can be quantitatively evaluated is defined. For illustrative purposes, it is applied to the Cassini mission. This mission, to be launched in 1997, is an international endeavor designed to orbit Saturn for four years. The results of this system's engineering approach will show which science objectives drive specific ground system capabilities. In addition, this technique can assist system engineers in the selection of the science payload during preproject mission planning, ground system designers during ground system development and implementation, and operations personnel during the mission.

Introduction

THE basic approach to analyzing the tradeoffs between science objectives and ground system capabilities has both the science community and the ground system define a set of matrices. The science matrices define the main objectives of the mission: 1) which instruments collect the data and 2) when in the mission the data collection occurs. The ground system matrices define the characteristics that drive ground capabilities and an estimate of when each service can be provided. Together, the set of matrices represents a powerful analytic tool.

To begin, the first matrix created (and the most fundamental) is the matrix that explicitly establishes which science objectives can be met by each investigation. This matrix, known as the science objectives vs investigation matrix,[1] ensures that the objectives of the missions can be met by the selected investigations.

Once the science objectives vs investigation matrix is completed, a second matrix that establishes the times during the mission (i.e., epoch) when each objective is captured is created. This matrix identifies the importance of each epoch based on the acquisition of science objectives. Epochs are determined either by orbital events (e.g., bow shock crossing, satellite closest approach, etc.) or by investigation characteristics (e.g., the time when the target body fills the narrow angle camera field of view).

The science community creates a matrix that defines types of observations the spacecraft must perform to obtain the desired science. The observation type represents only activity that is external to the science instruments. It is assumed that instrument internal commands can always be sent to the spacecraft when two-way communication has been established.

The last matrix generated by science defines which ground system resources are needed for each observation type. This matrix, known as the operations characteristics vs observation type matrix, allows the science community to evaluate, independently from the ground system (GS), which ground resources are needed by their investigation.

During the development of these matrices, the GS defines its own tables. The first of these defines the mission operation characteristics (i.e., those characteristics that drive mission operations cost) and their associated dynamic range.[2,3]

Received Sept. 28, 1995; revision received June 12, 1996; accepted for publication June 20, 1996.

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Next, the GS generates the operations characteristics vs orbital segment matrix.[2,3] This matrix is the GS's best estimate of how its ground resources will be used during the course of the mission. It shows what level of resources is needed for each segment of the mission. Once generated, the observation types (based on the GS's characteristics) are compared to this table. The results show which science objectives are in jeopardy by the current allocation of GS resources.

By identifying conflicts early, the GS and science community can negotiate how to reallocate resources to design a ground system that is within budget, consistent with mission plans, and responsive to the needs of the science community.

Science Matrices: Science Objectives vs Investigation

The first set of matrices captures the mission's science objectives. These objectives usually fall into one of four categories: atmospheres, magnetospheres, rings, and satellites. In some cases, categories may need to be added, removed, or modified. In the Cassini example, the addition of a Titan category is required. In each category there are approximately 5–10 explicit science objectives.

This set of matrices has one matrix for each category. Each matrix shows which objectives are captured by which investigation (Fig. 1). During preproject development, the proposed generic instrument payload (i.e., imagers, spectrometers, radiometers, mass spectrometers, magnetometers, etc.) is evaluated against its corresponding science objectives. This evaluation ensures that the proposed instrument payload captures all of the science that the spacecraft is designed for and confirms that no proposed investigation is redundant with another and that no investigation exceeds the scope of the mission.

During development, the selected payload is again evaluated against the science objectives. This evaluation confirms that between preproject design and project start (and the selection of investigations), the desired set of science objectives are indeed captured by the spacecraft's payload. Once evaluated, these matrices are placed under project change control to ensure that the contributions from

	CAPS	ISS	MAG	RPWS	UVIS	VIMS
ABUNDANCE	•				•	•
CHEMISTRY	•	•			•	•
CIRCULATION		•		•	•	•
MAGNETOSPHERE	•		•	•	•	

Fig. 1 Small component of the Titan matrix that describes which science objectives are captured by each investigation: CAPS, Cassini Plasma Spectrometer; ISS, Imaging Science Subsystem; MAG, magnetometer; RPWS, Radio and Plasma Wave Spectrometer; UVIS, Ultraviolet Imaging Spectrograph; and VIMS, Visual and Infrared Mapping Spectrometer.

Sci Obj \ Orb Seg	Probe	Fields & Particles	Occult	Sat
ABUNDANCE	1	N	N	N
CHEMISTRY	1	N	N	N
CIRCULATION	1	N	N	N
MAGNETOSPHERE	2	N	N	N

Fig. 2 Small fraction of the Titan matrix that identifies the importance of each epoch in the orbit based on science objectives: 1, major observation period; 2, minor observation period; and N, not applicable.

Science Objective	Prime	Obs Type	Commen
TITAN			
Atmospheric Abundances	CAPS	Roll	D/L FP&W
	UVIS	Mosaic	Auroral Sca
	VIMS	Mosaic	4 x 4
Chemistry	CAPS	Roll	D/L FP&W
	ISS	Mosaic	3 Filter

Fig. 3 Partial Titan matrix that defines activities that the spacecraft must perform to obtain the desired science.

each investigation are explicitly stated and that their requirements do not continue to grow.

Science Matrices: Science Objectives vs Orbital Segment

Once the science objective matrices have been developed, the times in the mission when the science objectives are acquired need to be established. For a swingby mission such as Voyager, the encounter period may be divided into segments and geometric events [e.g., approach, far encounter, near encounter, planet closest approach (C/A), satellite C/A, postencounter]. For an orbiter mission that studies temporal variations of a target for many years, orbital segments are created by the identification of geometric events. As an example, the Cassini mission starts with Saturn orbit insertion and then has its associated geometric events: 1) atmospheric (e.g., atmosphere occultations, phase angle, etc.), 2) magnetospheric (e.g., bow shock crossings, satellite wake, etc.), 3) ring (e.g., ring plane crossing, ring occultations, etc.), and 4) satellite (e.g., Titan encounters, targeted icy satellite encounters, nontargeted icy satellite encounters) events.

Once segments are defined from the geometric events, 0a matrix of science objectives vs orbital segments is developed (see example Fig. 2). Note that the sum of the segments defines the entire encounter or orbital tour. If it does not, then the addition of place holders may be necessary. Saturn orbital operations is an example of a Cassini orbital tour place holder. This place holder is needed because some high-priority observations are bound to orbital characteristics and not just particular geometric events. These high-priority events dictate that Saturn orbital operations be divided into high-activity and low-activity segments. Only high-activity periods contain high-priority events. The low-activity segments are for the remainder of the orbital tour.

An example of an observation that requires a high-activity period is a stellar ring occultation. This important observation is tied to both a geometric event and orbits with relatively high inclinations. For Cassini, these orbits occur early and late in the orbital tour. A low-activity period may contain periodic fields, particles, and wave (FP&W) measurements. These measurements are critical to the understanding of the magnetosphere but may be done anywhere in the orbit. The spacing of individual observations does not matter as long as complete coverage of the orbit is obtained.

Science Matrices: Validation of Orbital Segments

The science objectives vs orbital segment matrix is used to determine the times in the mission when the science objectives are achieved. A 1, a 2, or an N is placed in each cell of the matrix to identify the degree in which the objective was captured during the particular orbital segment. A 1 indicates that the objective was met during the particular orbital segment, a 2 indicates that some portion of the objective was met, and an N indicates that the objective could not be obtained at this particular time.

Once the entire matrix is finished, all cells with an N are shaded for readability. This matrix can now be used to validate that the set of orbital segments is complete. The validation process is first performed on the rows (i.e., science objectives). Each row must have at least one 1 or a 2 in it. If it does not, then the objective is not captured with the current set of orbital segments. This implies that either the objective should be removed or a new orbital segment (which would capture the objective) be added.

Next, the columns are checked for internal consistency. At least one 1 or a 2 should be in every column. If it is not, then the column (i.e., orbital segment) is unnecessary and should be removed from the matrix (in this case, some columns do not contain a 1 or a 2 because this table is only a part of the complete matrix). It is desired, for simplicity, that the final matrix have the fewest columns. The end result is a table that explicitly defines when in the mission specific science objectives are obtained.

Science Matrices: Define Observation Types

Science investigators next define observation types. An observation type is an activity needed by an investigation to capture a scientific objective. The investigator needs to define only those types of activities that impact ground system resources. Any activity that is performed internal to the instrument does not need to be considered, as it only drives the investigation's resources.

The observation types are used to ensure that the GS has the correct resources in place as determined by the investigators. An example of an observation type is a mosaic. The shuttering of a single image, a uv atmospheric occultation observation, and a mass spectrometer sample of the atmosphere (by orienting the spacecraft into the ram direction) all fall under the same observation type (i.e., 1×1 mosaic). In each case, the investigation needs to orient its field of view in only one specific direction.

Observation types are determined by creating a table of science objectives and investigations that provide notable contributions (also known as prime investigations) and then defining the proposed observation type (Fig. 3). The first Titan science objective, atmospheric abundances, lists the investigations that were identified as prime in the science objectives vs investigation matrix (see Fig. 1). For each investigation in a particular science objective, an observation type is identified.

While identifying observation types, it is important to remember that the number of types should be kept to a minimum. This is driven by the fact that the larger the number of types, the more resources have to be spent by the GS to capture them. Thus, if Titan spiral radiometry scans and Saturn limbtrack maneuvers can both be performed by the same spacecraft routine (i.e., maneuver observation type), then a cost savings will be realized.

Once all of the objectives have been assigned an observation type, a summary of the different types is compiled. In this case, Cassini has six basic observation types: 1) articulation—mechanical motion of Cassini Plasma Spectrometer, Cosmic Dust Analyzer, and Magnetic Imaging Instrument; 2) Langmuir Probe operations—Radio and Plasma Wave experiment; 3) maneuver—radar radiometry and radio science limbtracks; 4) mosaics ($m \times n$)—1×1 (e.g., imaging, integration, or stare), $1 \times m$ (i.e., scan), and $n \times m$ (i.e., mosaic); 5) roll—spacecraft roll at 0.26 deg/s for FP&W, and 6) sounder mode operations—Radio and Plasma Wave experiment.

This list contains all activities that the GS has complete or partial responsibility for so that the investigations achieve their science objectives. In addition, this list begins to define the fundamental activities that could be built into the ground system prior to the orbital tour. With good system engineering, these activities should only require changes to their parameters to be used during the mission.

Ground System Matrices: Operations Characteristics vs Dynamic Range

The GS, in turn, must define which characteristics during operations drive its resources. For each characteristic, a range of values is defined to establish its dynamic range. As an example, the repetitiveness of a sequence directly drives the amount of resources (i.e., dollars) that must be utilized to develop command loads. The range extends from none, where each sequence is used only once (i.e., unique), to high, where each sequence is used many times. Obviously the more frequently a sequence can be used, the greater the cost savings during operations.

For the Cassini mission, operational characteristics fall into five areas; sequencing, spacecraft, navigation, systems, and real-time operations.[2] In each area, characteristics that drive operation costs and their associated dynamic ranges are identified. Note that each mission has its own unique cost drivers. As such, operational characteristic tables must be generated for each mission.

Ground System Matrices: Characteristics vs Orbital Segment

Once the GS establishes its operations characteristics, an operations characteristics vs orbital segment matrix is produced. This matrix allows the GS to scope where in the mission specific resources are necessary, based on the relative importance of each orbital segment. The level of resources placed in each cell is determined based on the mission plan and in accordance with the available GS resources. The final matrix represents the GS's best estimate of when specific capabilities must be in place to achieve the objectives of the mission.

In actuality resources cannot be added and subtracted as frequently as indicated by the change of orbital segments. Personnel must be trained in advance of their need date and must remain at their task for at least a number of months. An employee cannot be hired for a task for five days only to be removed for the next three weeks. However, the allocation of ground resources does identify the ebb and flow of resources and, thus, helps determine the level of effort that must be applied at different times in the mission.

Science Matrices: Characteristics vs Observation Type

With the generation of the GS's operation characteristics, the science representatives (i.e., project scientist, principal investigators, experiment representatives, investigation scientists, science coordinators, etc.) produce the operations characteristics vs observation type matrix (Fig. 4). This matrix, endorsed by the science community (independent from the ground system), establishes what resources are needed by the investigations to capture a specific type of activity. It is this matrix that will be used against the GS's estimate of the availability and allocation of its resources.

Application

As an example of the application of these matrices, Cassini radar scans will be analyzed. First find which objectives require radar scans. To do this, look at Fig. 5. Determine the objective(s) for which radar is the prime investigation and the observation type is scans. For this particular case, radar scans are only needed at Titan to determine the state/composition of surface.

Ops Charact \ Obs Type	Limbtrack	Mosaic	Roll
Adaptability	Low	Low	Lo
Dev. Time/Execute Time	3	1	1
Concurrent Activities	2	1	1
Repetitiveness of Sequence	Unique	Blocks	Bl
Simultation Effort	Most	None	N

Fig. 4 Small portion of the Titan matrix that allows the science community to independently evaluate GS resources.

Science Objective	Prime	Obs Type	Comment
TITAN			
Atmos. Circulation & Physics	RSS UVIS VIMS	Limbtrack Movie Mosaic	2-Frequencies Feature Track Feature Track
State/Comp. of Surface; Interior	RADAR RSS	Scan Limbtrack	Radiometry X- and Ka-B
Upper Atmos. Relation	CAPS INMS	Articulation Integration	Ram Direc

Fig. 5 Only Titan "State and Composition of Surface" objective requires radar scans. RSS, radio science subsystem.

Sci Obj \ Orb Seg	Probe	F&P	Occult	Ti
TITAN				
ABUNDANCE	1	N	N	N
CHEMISTRY	1	N	N	N
CIRCULATION	1	N	N	N
STATE/COMP SURF	1			1
MAGNETOSPHERE	2	N	N	N
SATURN				

Fig. 6 Titan surface composition only measured during Probe and Titan orbital segments: 1, major observation period; 2, minor observation period; and N, not applicable.

Observation Type \ Ops Characteristics	Articulation	Mosaics	RADAR scans	Sounder
Adaptability	Low	Low	Low	Low
Dev. Time/Execute Time	2	2	3	2
Concurrency	2	2	1	2
Repetitiveness of Sequence	Blocks	Blocks	Unique	Blocks
Simultation Effort	None	None	All	None

Fig. 7 Investigators generate the ground capabilities needed for each observation type.

Ops Charact \ Orb Seg.	Probe	Occult	Titan	RADAR scans
Adaptability	Low	Low	Low	Low
Dev. Time/Execute Time	3	2	2	3
Concurrency	2	1	1	1
Repetitiveness of Sequence	Blocks	Blocks	Blocks	Unique
Simultation Effort	Most	None	None	All

Fig. 8 Ground System capability compared with the science requirements needed to capture objective.

With the science objective known, use the Cassini science objectives vs orbital segments matrix (Fig. 6) to determine when the particular objective may be acquired. Figure 6 indicates (by the presence of 1 or 2) that scans are only needed during the probe and Titan orbital segments. When we apply the fact that radar will not be used during the probe mission, we realize that the GS only has to provide the capability for radar scans during Titan swingbys.

Next, return to the Cassini operations characteristics vs observation type matrix (Fig. 7). From this matrix, remove the radar scan column and compare to the Titan column from the Cassini operations characteristics vs orbital segment matrix (Fig. 8). For ease of review, the orbital segments not needed for radar scans have been shaded gray.

The requirements of the radar scan are then compared with the capability provided by the GS. For this example, areas in the radar column that require more capability then the ground has provided are shaded gray. In this example, three areas (i.e., development time/execute time, repetitiveness of sequence, and simulation effort) are in conflict. If we look at the simulation effort row in Fig. 8, we see that the GS does not plan to simulate radar sequences. However, from a science point of view, all radar sequences must be simulated. This apparent discrepancy results in one of the following: 1) GS reallocates resources to simulate all radar scans; 2) the radar team uses its resources to simulate scans prior to submitting their sequences to the GS; or 3) nothing is changed and the project accepts the greater risk of science data loss during radar scans.

Conclusion

The use of these matrices by the science community and the project's ground system allows both groups to understand what and when types of observations can be performed. The results make the science community sensitive to the limits of the ground resources and thus reduce the amount of creeping science requirements. In turn, the GS will be more responsive to the needs of the investigators to return the primary science objectives of the mission.

Once the matrices have been developed and analyzed, potential misallocation of resources will become evident. The areas where investigator's requirements are greater than the available resources will drive the GS and science commnity to one of three possibilities: 1) reallocate GS capability to meet the observation; 2) decrease the observation type's complexity by transferring the responsibility to the investigator; or 3) leave resources as is and accept the greater risk of data loss.

The technique may be applied to any science mission from any country. When applied to planetary exploration, mission planners may use it to select a spacecraft's science payload; ground system engineers may use it to ensure the ground system's compatibility with the science investigations; operations personnel may use it to quantify where ground resources need to be applied to return the quality of science data demanded by a first-rate planetary exploration program.

Acknowledgment

The research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

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