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Matrix Evaluation of Science Objectives

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Introduction

The most fundamental objective of all robotic planetary spacecraft is to return science data. To accomplish this, a spacecraft is fabricated and built, software is planned and coded, and a ground system is designed and implemented. However, the quantitative analysis required to determine how the collection of science data drives ground system capabilities has received very little attention.

This paper defines a process by which science objectives can be quantitatively evaluated. By applying it to the Cassini Mission to Saturn, this paper further illustrates the power of this technique. The results show which science objectives drive specific ground system capabilities. In addition, this process can assist system engineers and scientists in the selection of the science payload during pre-project mission planning; ground system designers during ground system development and implementation; and operations personnel during mission operations.

1. Approach

The basic approach has both the science community and the ground system define a set of matrices. The science matrices define the main objectives of the mission, who will collect them and when. 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, 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, which establishes the times during the mission (i.e., epoch) where 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).

Next, the science community creates a matrix which defines "types of observations" the spacecraft must perform to obtain the desired science. The observation type only represent 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 communications has been established.

The last matrix generated by science defines which ground system resources are needed for each observation types. This matrix, known as the "Operations Characteristics vs. Observation Type" matrix, allows the science community to, independently from the Ground System (GS), evaluate 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 ops cost) and their associated dynamic range.

Next the GS generates the "Operations Characteristics vs. Orbital Segment" matrix. This matrix is the GS's best estimate of how its ground resources will be used during the course of the mission. It show what level of resources are 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.

2. 1 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 five to ten explicit science objectives.

This set of matrices have one matrix for each category. Each matrix shows which objectives are captured by which investigation (see fig. 1 "Cassini Titan Science Objectives"). During pre-project development, the proposed generic instrument payload (i.e., imagers, spectrometers, radiometers, mass spectrometers, magnetometers, etc.) are evaluated against their corresponding science objectives. This ensures that the proposed instrument payload captures all the science that the spacecraft is designed for, 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 confirms that between pre-project 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 each investigation are explicitly stated and that their requirements do not continue to grow.

2.2 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 needs to be established. For a "swingby" mission, like 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, post encounter). For an orbiter mission which 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 (SOI) 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 crossings, etc.)
3. ring (e.g., ring plane crossing, ring occultations, etc.)
4. satellite events (e.g., Titan encounters, targeted icy satellite encounters, nontargeted icy satellite encounters)

SCIENCE MATRICES

CASSINI TITAN SCIENCE OBJECTIVES

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

Fig. 1: This marix shows which investigations capture each science objective.

CASSINI
SCIENCE OBJECTIVES vs. ORBITAL SEGMENT

Sci Obj \ Orb Seg	Probe	F&P	Occult	Sa
TITAN				
ABUNDANCE	1	N	N	N
CHEMISTRY	1	N	N	N
CIRCULATION	1	N	N	N
MAGNETOSPHERE	2	N	N	N

1 - Major Observation Period
2 - Minor Observation Period
N - Not Applicable

Fig. 2: This marix identifies the importance of each epoch in the orbit based on science objectives.

CASSINI
SCIENCE OBJECTIVES vs. OBSERVATION TYPE

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: This marix defines activities that the spacecraft must perform to obtain the desired science.

CASSINI
OPS CHARACTERISTICS vs. OBSERVATION TYPE

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: This marix allows the science community to independently evaluate Ground System resources.

Once segments are defined from the geometric events, a matrix of science objectives vs. orbital segments is developed (see fig. 2 "Cassini Science Objectives vs. Orbital Segments"). It is important to 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 Ops" 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 Ops" 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 which 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 & wave measurements. These measurements are critical to the understanding of the magnetosphere but may be done anywhere in the orbit. The spacing of individual observations do not matter as long as complete coverage of the orbit is obtained.

2.3 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", "2" or "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 "2" should be in every column. If it does 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 figure is only a part of the complete matrix). It is desired for simplicity that the final matrix have the least number of columns. The end result is a table that explicitly defines when in the mission specific science objectives are obtained.

2.4 Science Matrices: Define Observation Types

Science investigators next define observation types. An observation type is an activity needed by an investigation in order to capture a scientific objective. The investigator only needs to define 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 drive 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 x 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, investigation that provide "notable contributions" (a.k.a prime investigations) and then defining the proposed observation type (see fig. 3 "Cassini Science Objectives vs. Observation Type"). 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 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), than a cost savings will be realized.

Once all 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 & Magnetic Imaging Instrument
2. Langmuir Probe Operations - Radio & Plasma Wave Science Experiment
3. Maneuver - RADAR Radiometry & Radio Science Limbtracks
4. Mosaics (m x n) -
    a. 1 x 1 (e.g., Imaging, Integration or Stare)
    b. 1 x m (i.e., Scan)
    c. n x m (i.e., Mosaic)
5. Roll - Spacecraft Roll at 0.26 deg/s for Fields, Particles & Waves
6. Sounder Mode Operations - Radio & Plasma Wave Science Experiment

This list contains all activities that the GS has complete or partial responsibility for in order for the investigations to 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 in order to be used during the mission.

2.5 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 are 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. In each area, characteristics which drive operation costs and their associated dynamic ranges are identified. It is important to note that each mission has its own unique cost drivers. As such, operational characteristic tables must be generated for each mission.

2.6 Ground System Matrices: Operations 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 are done 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 in order to achieve the objectives of the mission.

It must be mentioned that in actuality resources can not 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 can not 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 help determine the level of effort that must be applied at different times in the mission.

2.7 Science Matrices: Operation 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 ops characteristics vs. observation type matrix (see fig. 4 "Cassini Operation Characteristics vs. Observation Type"). This matrix, endorsed by the science community (independent from the ground system), establishes what resources are needed by the investigations in order 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.

3.0 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, "Cassini Science Objectives vs. Observation Type". 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".

With the science objective known, use the "Cassini Science Objectives vs. Orbital Segments" (see fig. 6) to determine when the particular objective may be acquired. The table indicates (by the presence of "1s" or "2s") 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, then we realize that the GS only has to provide the capability for RADAR scans during Titan swingbys

Next return to the "Cassini Ops Characteristics vs. Observation Type" matrix (see fig. 7). From this matrix remove the RADAR scan column and compare to the he "Titan" column from the "Cassini Ops Characteristics vs. Orbital Segment " matrix (see fig. 8)". For ease of review, the orbital segments not needed for RADAR scans have been shaded gray.

The requirements of the RADAR scan is then compared with the capability provided by the GS. For this example, areas in the RADAR column which require more capability then the ground has provided were shaded gray. In this

RADAR SCAN EXAMPLE

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SCIENCE OBJECTIVES vs. OBSERVATION TYPE

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 Dire

Fig. 5: First find which science objectives require RADAR scans. In this case, only "State/Comp. of Surface" of Titan.

CASSINI
SCIENCE OBJECTIVES vs. ORBITAL SEGMENT

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	N	N	1
MAGNETOSPHERE	2	N	N	N
SATURN				

1 - Major Observation Period
2 - Minor Observation Period
N - Not Applicable

Fig. 6: Titan surface composition measured during Probe and Titan segments. However, during the probe mission, the main antenna will be used for data relay not RADAR. Thus, RADAR scans only needed during Titan passes.

CASSINI
OPS CHARACTERISTICS vs. OBSERVATION TYPE

Ops Characteristics \ Observation Type	Articu-lation	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, independent from the GS, generate the ground capability needed for each observation type.

CASSINI
OPS CHARACTERISTICS vs. ORBITAL SEGMENT

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

RADAR scans
Low
3
1
Unique
All

Fig. 8: Compares GS capability with the science requirements needed to capture science objectives. Identifies which activities need to be simplified, which GS capabilities needs to be reallocated, or which activities may be at risk.

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 on this table, 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, or
2. The RADAR Team uses its own resources to simulate scans prior to submitting their sequences to the GS, or
3. Nothing is changed and the projects excepts the greater risk of science data loss during RADAR scans

4.0 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 in order 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 community to one of three possibilities:

1. Reallocate GS capability to meet the observation, or
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 approach stated in this paper may be applied during advanced mission planning in order to select a spacecraft's science payload; during ground system design to ensure the ground system's compatibility with the investigations; and during operations to quantify where ground resources need to be applied to return the quality of science data demanded by a first rate planetary exploration program.

5.0 References

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Systems Engineering

6. Systems Operations

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