Science Traceability

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Abstract—Any comprehensive science mission[1,2] proposal must be able to simply explain why it is important to accomplish the goals of the mission and how it will be implemented. This can be accomplished through use of a Science traceability matrix, a construct that is becoming a required component of all NASA science mission proposals. The Science Traceability Matrix (STM) provides the overview of what a Mission will accomplish relative to high-level objectives suggested through Academy of science surveys, NASA Roadmaps, or Program Objectives. It provides a logical flow from these high level objectives through mission objectives, science objectives, measurement objectives, measurement requirements, instrument requirements and spacecraft and system requirements to data products and eventual publications. It is the one document that shows the relationship between all these key elements and the one document that provides the breadth needed to perform and document high level trades effecting science outcome and overall design.

The increasing detail in the requirements flow down represent results of considering underlying key parameters Some of the key parameters considered during requirements definition include: observation importance, ability to make a given measurement, constraints on all systems, number of measurements needed to complete an observation objective, complexity of required measurements, probability for success, measurement fidelity, data quality, community involvement, publishable findings, questions addressed. Parameters underlying instrument definition include: data requirements, pointing constraints, stability requirements, mounting constraints, thermal constraints, power constraints, mass, and volume.

The STM can be used as a gauge to determine the completeness of the definition of a proposed mission If the matrix flows effortlessly from high level objective to publishable science result then it has been carefully laid out. If the logic that ties one aspect to another is not clear then there is more work to be done prior to any proposal preparation.

The science matrix provides a basis for negotiating lower level requirements (typically tracked with tools such as Telelogic's DOORS® requirements tracking tool) and evaluating affects of the results of those negotiations on the ability to achieve objectives originating at higher levels. It also provides a succinct snapshot of those high level objectives – particularly important for high-level goals since there is often no objective algorithm to quantify the relative merits of the conflicting high-level goals. For this case, the matrix provides a convenient notation for assessing and arbitrating the impact on equal-valued objects caused by changes in available mission resources.

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1. INTRODUCTION

A science mission proposal must be able to simply, and quickly explain the importance of mission goals and how those goals are implemented. The Science Traceability Matrix (STM) provides such an overview of what a Mission will accomplish and relates it to high-level objectives suggested by program architecture statements such as the Academy of science decadal survey, NASA Roadmaps, or NASA Program Objectives. The STM provides a logical flow from these high level objectives through Mission objectives, measurement objectives, instrument requirements, spacecraft and system requirements to data products and eventual publications. It is the vehicle that summarizes the relationship between all these key elements and the one document that provides the breadth and scope needed to perform high level trades effecting science outcome and overall design.

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[1] "0-7803-8870-4/05/$20.00©2005 IEEE"

[2] IEEEAC paper #2.0402 version 3, Updated December 22, 2004

The process of developing an STM provides a forum for proposers to develop and document sound rationales for the design and implementation of their mission. The STM aids reviewers of a proposed mission by serving as a gauge to determine if a proposal is complete or not. If the matrix flows effortlessly from high-levels to publishable science result, then the science content of a mission has been carefully laid out. The logic that ties one aspect of the matrix to another is the key to its effectiveness and the parameter space by which key trades will be made. Finally, the STM has excellent potential for quickly determining the effects of low-level changes on high-level goals throughout the implementation and operation of a mission.

2. OVERVIEW

A good science traceability matrix (STM) contains all the high level information needed to understand why a given proposal is relevant, what it purports to accomplish for science, how it intends to accomplish it, and what expected products and knowledge will result from it's success. It also provides a template for trade studies by spelling out what is needed to accomplish any specific objective. If the objective is changed or the approach to achieving the objective is altered then the ripple effect is easy to determine for analysis and further iteration. For instance, if a particular instrument is not appropriate to achieve a given measurement objective then analysis of alternate instrument approaches can be compared readily to measurement requirements to meet the objective. If analysis shows that the over-all intent of the objective cannot be met, then it becomes a driver on the re-formulation of the mission. Alternately, if a primary objective is decided to be over-ambitious, the resource savings regarding instrument, spacecraft, and ground requirements changes are easy to determine. Additionally, the STM provides a tool for evaluating the scientific consequences of any reduction in objectives, yielding a clear indication of expected science return and establishing a new baseline for mission feasibility and importance. As a basic systems engineering tool, a good science traceability matrix provides requirements traceability from over-all mission and science objectives through expected delivered science products thus a trade space for adjusting to changing mission capabilities, requirements analysis, performance analysis, cost evaluation, and assessment of mission design. The traceability matrix also has applicability throughout the life cycle of the project, including mission formulation, proposal development and evaluation, implementation risk analysis and requirement trades, development analysis, operations analysis, public education, and data archiving.

Science traceability has become a required component of all NASA science mission proposals. A proposal containing a carefully constructed traceability matrix can clearly communicate that the proposal has been well thought out, is technically complete, and is well organized for review. In today's world of fierce competition and change it is important to convey this message as strongly as possible, and to have proposed missions structured for adaptation to changing conditions. The science traceability matrix approach provides all these attributes.

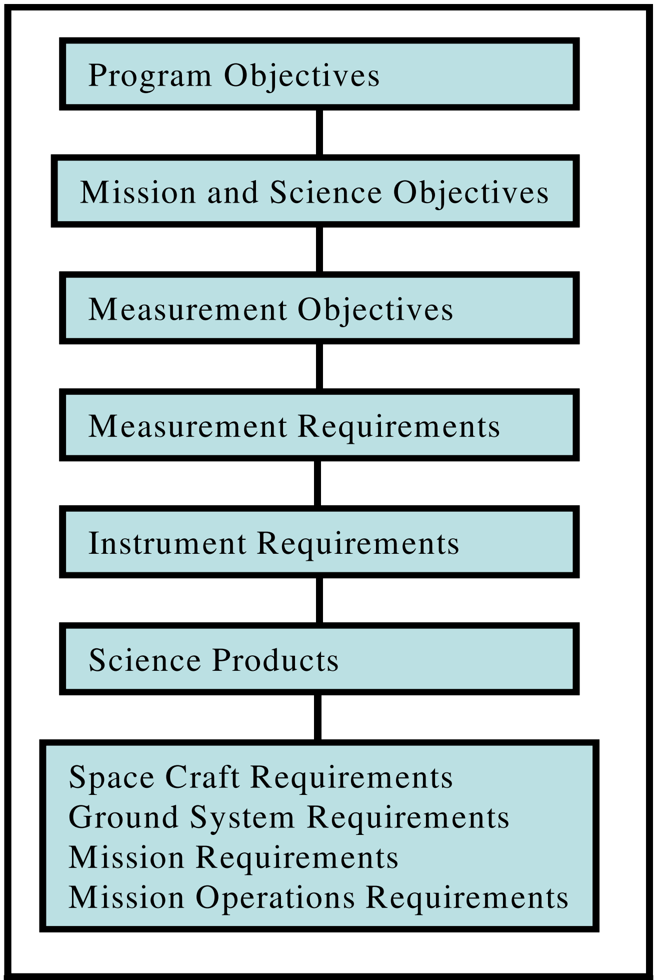


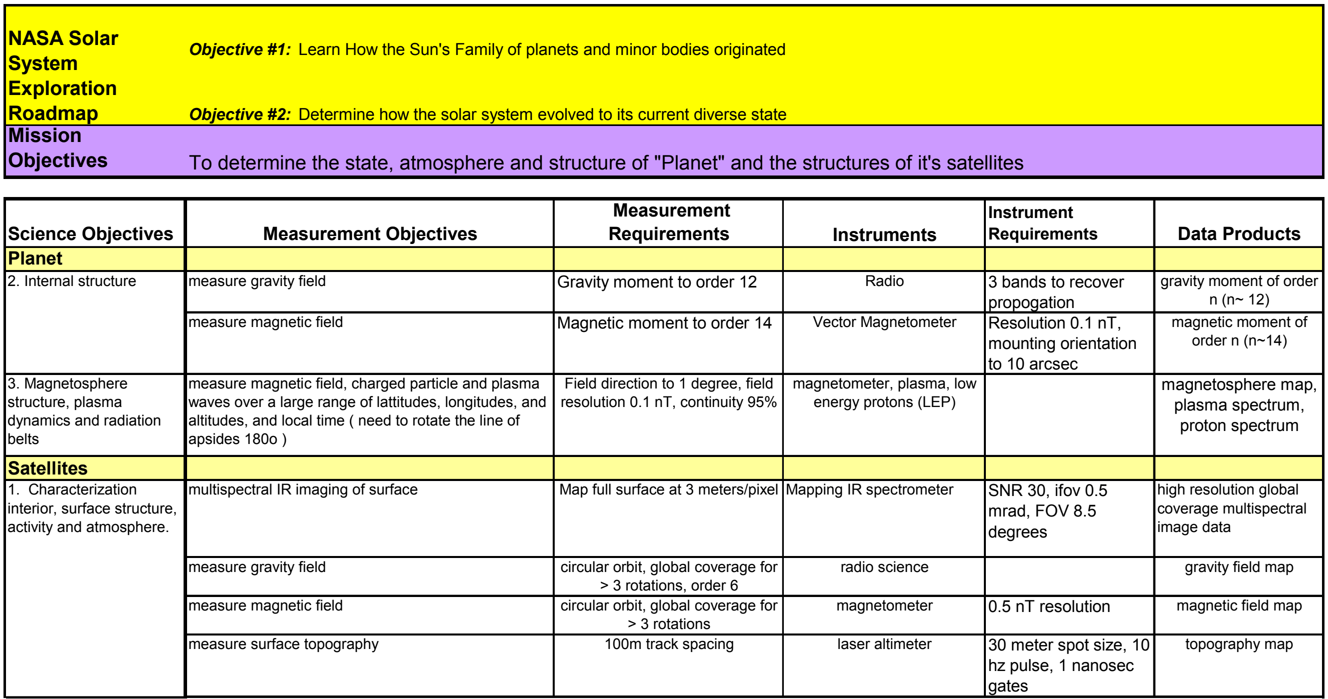
Figure 1. The contents of the science matrix include all science elements that affect resource trades for mission implementation –which is not part of the STM is summarized in the bottom box of this figure.

3. BASELINE CONTENTS AND RELATIONSHIPS

A baseline STM contains traceability from high-level objectives, usually taken from Programmatic Road Maps and/or stated explicitly in a given Announcement of Opportunity (AO), and relates those high-level science objectives to measurement objectives, which, in turn, quantify the observations necessary to acquire the needed data. In the simple case, each Measurement Objective is tied to a given Science Objective. Practical cases often have a many-many relationship (i.e. one science objective may require several measurement objectives and, conversely, one measurement objective may address several science objectives). The Measurement Objectives are written in such a way as to indicate what is seen as important to achieving a given Science Objective e.g. “Obtain magnetic moments “ (measurement objective) to “Better understand the internal structure of Neptune" (science objective). The measurement of internal structure may include measurements of the gravity field, the magnetic field, etc. The Science Objective leads to one or more Measurement Objectives which in than drive the measurement requirements, which in turn set sensitivity and range requirements on the instruments and sensors. In this example to measure the gravity field you may require three-band propagation for radio science experiments or precision pointing knowledge to determine the direction of the magnetic fields. The flow-down dictates the instrument complement to be supported by the chosen spacecraft and ground system. The flow chart in figure 1 illustrates the relationship of the flow. Note that high-level accommodation requirements, mission requirements, and ground system requirements are usually placed in separate constructs (for a proposal), to maintain brevity of the STM.

4. COMPLETING CONSTRUCTION OF THE STM

After determining what the driving Science Objectives will be, and establishing Measurement Objectives needed to achieve the science objectives, one determines the measurement requirements to achieve the measurement objectives and the instrument set required to achieve those measurement requirements. Following forward with our previous example there is a requirement to perform radio science measurements but in order to improve upon our previous knowledge the gravity moment measurement would have to be better than (say) order n (n~12). This requires a certain circular orbit around the planet along with both spacecraft and ground telecom capabilities to achieve the desired measurement fidelity. A circular orbit at a given height then becomes one of the mission accommodation requirements for radio science, as does the telecom configuration. Likewise, for each chosen instrument a set of measurement requirements would have to be established that specify the instrument performance as well as (potentially) drive the spacecraft and ground requirements. This establishes the traceability from Science Objectives to Measurement Objectives, to measurement requirements, to instrument selection, to measurement requirement to instrument performance specifications, to spacecraft and ground requirements. The finishing touch for the STM includes expected data and science products – which can be used to validate the sizing of the data analysis and science



NASA Solar System Exploration Roadmap	***Objective #1:*** Learn How the Sun's Family of planets and minor bodies originated ***Objective #2:*** Determine how the solar system evolved to its current diverse state
Mission Objectives	To determine the state, atmosphere and structure of "Planet" and the structures of it's satellites

Science Objectives	**Measurement Objectives**	**Measurement Requirements**	**Instruments**	**Instrument Requirements**	**Data Products**
Planet					
2. Internal structure	measure gravity field	Gravity moment to order 12	Radio	3 bands to recover propogation	gravity moment of order n (n~ 12)
	measure magnetic field	Magnetic moment to order 14	Vector Magnetometer	Resolution 0.1 nT, mounting orientation to 10 arcsec	magnetic moment of order n (n~14)
3. Magnetosphere structure, plasma dynamics and radiation belts	measure magnetic field, charged particle and plasma waves over a large range of lattitudes, longitudes, and altitudes, and local time (need to rotate the line of apsides 180o)	Field direction to 1 degree, field resolution 0.1 nT, continuity 95%	magnetometer, plasma, low energy protons (LEP)		magnetosphere map, plasma spectrum, proton spectrum
Satellites					
1. Characterization interior, surface structure, activity and atmosphere.	multispectral IR imaging of surface	Map full surface at 3 meters/pixel	Mapping IR spectrometer	SNR 30, ifov 0.5 mrad, FOV 8.5 degrees	high resolution global coverage multispectral image data
	measure gravity field	circular orbit, global coverage for > 3 rotations, order 6	radio science		gravity field map
	measure magnetic field	circular orbit, global coverage for > 3 rotations	magnetometer	0.5 nT resolution	magnetic field map
	measure surface topography	100m track spacing	laser altimeter	30 meter spot size, 10 hz pulse, 1 nanosec gates	topography map

Figure 2: Generic example of a fragment of a science traceability matrix for a planetary orbiter. In this extract the science objectives are geodesy and geophysics. Note the flow from the NASA roadmap to the mission objectives (stated in an AO) to science objectives through to data products. This example illustrates several of the issues that arise during matrix formulation. The gravity field measurements have different measurement requirements for the planet and the satellite. These different requirements should be tracked separately, but this can cause the matrix to grow too large for clarity. A single science objective may have multiple supporting measurements and/or a single measurement may support several science objectives. This potential many-many relation can make it difficult to enumerate all flow-down succinctly. Though there is a host of clever ways to multiplex the parent-child relationships, the matrix is easiest to comprehend quickly when the relationships are flattened through replication. To keep the figure small, this particular example does not include the important requirements on spacecraft implementation such as bus and telemetry data rates, fields of view, power, and operational requirements.

teams. The formation of the STM follows the flow summarized in figure 1.

At JPL we are developing a tool to aid proposers in the development of a complete STM. The tool uses databases containing information on what has flown in the past:, instruments, instrument performance, instrument requirements, spacecraft capabilities, ground system choices, and science goals. The tool includes look-up tables describing available instruments, their performance capabilities, and their interface requirements as well as road maps, spacecraft and ground system overviews. The tool is intended to provide proposers with rapid access to details of the components required to form the STM. Establishing the logical and quantitative relationships between these components remains, of course, an exercise for mission proposers.

5. KEY PARAMETERS

The STM requirements and objectives are based on assessment of key parameters underlying those requirements. Some of these key parameters include:

- Relative importance of an observation to achieve the desired science,
- End-to-end system ability to make a given measurement,
- Minimum number of measurements needed to achieve a given science goal,
- Over-all complexity of each required measurement,
- Measurement fidelity to acquire the required science,
- Probability for making the successful measurement,
- Over-all data quantity and quality,
- Technology and implementation constraints,
- Key science questions to be addressed.

Key parameters for instrument accomodation include:

- Data rate and volume requirements,
- Pointing and stability requirements,
- Mounting and structure requirements,
- Thermal, power, mass, and volume constraints.

For each of these key accommodation parameters there are implementation requirements that result in spacecraft and ground architecture drivers. For data products there are formatting and delivery requirements; there are timing requirements regarding when the data was taken and when the data will be available for analysis. There are also requirements pertaining to what information will be appended to the different data products consisting of pointing direction and stability, thermal and power conditions, a list of other instruments taking simultaneous data, and a host of other concerns all of which could cause conflicts and design considerations.

Each instrument will have its own unique accommodation requirements as well. Examples of unique requirements include: magnetic cleanliness for magnetometers, radiation protection if orbiting Jupiter, reflected light for cameras and spectrometers, etc.

Continuing the gravity measurement example, the Traceability Matrix fragment in figure 2 shows the result of considering key parameters: This example shows the top level driving objectives from the Solar System Exploration Roadmap as the rational for the mission followed by step-wise delineation of what is needed to accomplish these given objectives. For the science objective to determine the internal structure of the planet, it is clear that specific measurements need to be made with qualified instruments capable of delivering the data quality and resolution desired along with the requirements this approach would place on both the spacecraft and ground systems needed to carry it out. If all this is accommodated then there are specific resultant products that would be delivered to the appropriate science archive for distribution to scientist who would perform the required analysis and publish the papers that represent the findings.

Figure 3 shows a more complete STM example based on a fictitious, but representative, Europa orbiter mission dedicated to the characterization of potential oceans. Instead of multiple objectives (observations of both primary planet and its satellites) as in the earlier example, this second mission has a single objective, Europa. Figure 3 clearly illustrates the (common) multiple relationship structure arising in STMs. Science objective 1A maps to 4 instruments (altimeter, radar sounder, radio science and magnetometer) while a single instrument, e.g. the laser altimeter, could contribute to the measurements of surface topography (1A) and characterization of surface morphology (1C).

There are also cross-dependencies among different requirements. In this example, the performance of the laser altimeter correlates directly with the precision of the orbit determination, which is determined by the radio science requirements; the pointing stability requirements of NAC should agree with the altimeter pointing requirements; the data collection scenario for imaging is constrained by the resolution of the imagers and the telecom capability.

6. SYSTEM ENGINEERING TOOL

Science traceability is becoming a required component of all NASA science mission proposals. It has high utility in improving proposal organization, facilitating reviews, and in negotiating and documenting arbitration of mission implementation and resource utilization. What is required differs from discipline to discipline but the basic form of the science traceability matrix has been well established. A proposal containing a carefully constructed traceability matrix can clearly communicate that the mission proposal has been well thought out, is complete, and is well organized for the reviewer. In today's world of fierce competition and change, it is important to convey this message as strongly as possible, and to propose missions structured for adaptation for changing conditions and resource availability. The science traceability matrix approach provides all these attributes.

As a basic systems engineering tool, a good science traceability matrix provides requirements traceability from overall mission and science objectives through expected delivered science products; thus providing a trade space for adjusting to changing mission capabilities, requirements analysis, performance analysis, cost evaluation, and assessment of mission feasibility. Fundamental to all mission development work is a straightforward means of evaluating the end-to-end system in terms of the effects on NASA and mission objectives, cost drivers, technology risks and system drivers. The science traceability matrix can be used to evaluate the consequences of system changes on science through analysis of resultant requirement modifications. Taking our previous example, if it is determined that the given spacecraft and ground configuration can produce the desired resolution yet the expense of doing so would be prohibitive then the effects of a reduction in capability on the measurement and science objectives can be assessed conveniently. Likewise if a given system configuration is determined to be insufficient to meet science objectives, the science traceability matrix can be used to evaluate the cost-effectiveness of a range of possible upgrade alternatives each of which would be analyzed with respect to implementation feasibility, cost effectiveness and impact on the end-to-end system.

7. APPLICATION OF THE TRACEABILITY MATRIX

The traceability matrix has application throughout the life-cycle of a project, including formulation, proposal, evaluation, implementation requirements development, implementation, operations, public education, and data archiving. The matrix is normally presented in several formats to improve the utility of the matrix to a particular application. However, the underlying flow and content remain constant, as seen in the following descriptions of use of the matrix.

a. Formulation stage

The formulation stage of missions includes defining goals for NASA and NASA programs, defining missions that meet those goals, and defining science investigations that meet mission objectives. This stage also includes proposing missions and science goals and assessing those proposals.

Depending on the application, the science traceability matrix may be used as a tool to assess approaches to i*mplementing NASA programs near-term goals*, a tool to assess alignment of *proposed mission* with previously defined NASA program goals (typical of Principal Investigator (PI) defined missions such as the NASA SMEX, Discovery, and New Frontiers programs), or as a tool to assess the alignment of a *science investigation* with previously defined mission goals (typical of large flagship missions) or as a tool to assess the science utility of a proposed technology development demonstration and validation (typically a New Millennium-class mission).

Proposed missions utilize the science traceability matrix to validate that the mission goals are consistent with long-term program goals – termed variously "decadal surveys" and "roadmaps" that have been delineated by national working groups populated with scientists representing a wide range of planetary and astrophysical disciplines. The tool is also used to demonstrate (and, for reviewers, validate) that the mission objectives can be achieved within the mission plan and payload capabilities and that the planned measurements represent significant advances over existing measurements.

Science investigations, proposed to flagship missions, can use the science traceability matrix to summarize alignment with the stated mission goals. Typically, a program implementation plan (PIP) that accompanies an AO for a flagship mission will already include a STM, created by a mission development team and based on mission objectives and a strawman payload. The proposed science investigation would typically demonstrate how elements in the matrix would be met or enhanced with this particular investigation and, perhaps, how the mission objectives can be enhanced.

Technology development and *NASA goal development* populate the matrix in a somewhat different way. These applications provide specific technologies or specific goals, and then assess a variety of potential missions that would utilize the technology or implement the goals. In these cases, the traceability matrix is populated from existing databases of science needs (typically from experts and literature), previous results, and existing and near-term technologies (typically information from previous missions and current technology programs). The resultant matrices can then be used to compare the relative value of proposed new technologies or the feasibility of implementing specific goals. At this point in time, the information used to populate matrices for these applications is relatively diffuse. This results in a labor intensive, and time-consuming process to evaluate technologies and goals. There has been, however, recent significant progress in forming summary databases of instrument capabilities, characteristics, and applications, and developmental effort in forming similar summaries of NASA goals and mission goals, capabilities, and results. These can be used to both populate and assess STMs. STMs populated from these databases cannot substitute for the value of using experts with current knowledge of the field to evaluate goals and technologies, but have the potential to provide both speed and scope for identifying which are most viable

b. Requirements Development phase

Mission implementation requirements development occurs early in phase B of a mission. This is the mission stage when resources and design are matched with all of the elements of the science traceability matrix in detail. It is very typical to discover at this stage, when sufficient resources are available to calculate the implications of various science requirements for all subsystems and resources, that some performances could be improved within the given resource envelope, and that some requirements are simply unachievable. The requirements and capabilities are negotiated and typically entered into a requirements tracking tool (such as DOORS®), which, in theory, provides the ability to assess the effects of changes on all subsystems. The role of the STM in negotiations leading up to agreements on capabilities is to provide a useful notation for assessing and tracking the effects of these negotiations on mission, science, and measurement goals. It also provides a convenient way to assess alternative approaches toward achieving a given goal.

c. Mission Implementation phase

During the implementation phase of a mission, it is common to discover that there are insufficient resources to implement all planned capabilities. The STM can be particularly useful when these resource limits affect the basic science plan. There are generally several science measurements of approximately equal priority and disparate value functions. Changes in these measurements are generally assessed by criteria other than relative value, frequently in acrimonious debate. The STM provides a tool that can be used to evaluate the effects of modifying one or both of these measurements on mission and NASA goals – perhaps clarifying, focusing and ameliorating the duration of the debate over changes to the mission.

d. Mission Operations Phase

During the mission operations phase, changes to the science plan can arise from unforeseen resource changes (such as budget reductions), failures of subsystems, or unforeseen events (weather and DSN outages). The STM can be used as a basis for negotiating sequencing and data return priorities in such cases

e. Outreach

The science traceability matrix provides a compact overview of the purpose and implementation of a given mission. While the notation is frequently too terse for public consumption, and the complexity of the matrix too high for presentation in its native state, it can provide an excellent basis for explaining the purpose and implementation of the project in outreach products.

The STM can have similar utility in explaining the mission, and inevitable mission changes, to program and higher-level managers charged with monitoring progress of the mission and with obtaining resources for future missions.

f. Data Archiving and mission documentation

The STM includes a column summarizing expected data products associated with each measurement. This can be used as a basis for planning what types and how much data will be included in archives such as the Planetary Data System (PDS) and tracking completion of the data deliveries.

The content of the STM can also serve as a mission documentation tool. Science traceability matrices contain the information required to succinctly describe the purpose and science implementation of prior missions. It, in fact, contains the mission and instrumentation information in compact format, required to populate databases needed to assess planning and proposal for future missions.

g. Formats and other practical matters

One of the largest challenges in developing a science traceability matrix is to place it in a form that is logical, readable and rapidly comprehensible. The challenge arises from the many-many (rather than parent-child) relationships that are endemic to the STM content, and from the space limitations that are extant, particularly in proposals. Many formats have been utilized to address this challenge in proposals, including indexing, mapping with color, separate but related tables and so on. The page limitations typically imposed on proposals (as well as workforce resource limits) dictate against completely populating the matrix at the time of a proposal – even though most of the information is based on current knowable available at that time. The result of the space limitation on the STM is unfortunate and perhaps should be changed for the proposal process, since historically there are insufficient workforce resources to update the STM in later phases of the mission. The overall result is typically a longer, and more expensive than necessary, requirements development phase, higher difficulty in reallocating resources during the mission and operations phase, and inconsistency in documenting the mission during archiving.

8. CONCLUSIONS

A science traceability matrix provides a valuable tool for assessing both mission and systems engineering requirements. The science traceability matrix additionally provides a clear means for proposal evaluation and system resource trades. It is concise, complete, and straightforward. The STM supports analysis from either a top down or bottoms up approach providing flexibility and end-to-end visibility. The effort to create a science traceability matrix is small compared to the benefits generated, including a quick means of determining mission feasibility, illustration of implementation complexity, clear presentation of potential advantages of an investigation, and a strong basis on which to perform resource trades. If fully implemented in the formulation stages of a mission, it has high potential for expediting the negotiation of level 3 requirements; resource trades during implementation and operation; and providing a concise summary of the mission for public outreach and mission archiving. Under the guidance of JPL's Team X a semi-automated form of this useful tool is being developed to fit a wide variety of missions types and applied to mission proposal development and evaluation.

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Biography

Jim Weiss is the Chief Engineer for the Earth and Space Sciences Division at the Jet Propulsion Laboratory. In this role he serves as Science Chair for JPL's Team X, Proposal Coordinator for Earth and Space Sciences, science systems engineer for the Division and Engineering representative for science to most high level engineering and mission development efforts. He served five years at NASA HQ as a Program manager developing science systems engineering approaches for distributed data systems, science support to missions, and advanced planning. He has held science support and science management positions on 17 different NASA flight missions serving as every thing from science coordinator to Program Manager. He has graduate degrees in both applied mathematics and systems engineering.

Science Objectives	Measurement Objectives	Measurement Requirements	Instruments	Instrument Requirements	Mission Requirements	Data Products
A .Determine the radial structure of Europa, specifically the ice/water interface and ice shell structure	strength of ice shell	1m accuracy of tidal bulge;+/- 0.04 tidal love number (h2);	laser altimeter	frequency 10Hz, FoV 1mrad; 50m spot size; footprint spacing between 100m to 2 km depending on scanning	2 weeks of observation	topographic map with 90% coverage
	radial structure of ice shell and depth to brittle/ductile transition	100m vertical resolution near surface,10% depth of depth	radar sounder	Frequency 50 MHz,(6m in vacuum and 3.5m in ice); pulse width 500µm; PRF 400 Hz; bandwidth 0.85 MHz; 3dB beam width: 20^o across/100^o along track; footprint w/ 100 km orbit: 35 km across/238 km along track; resolution: vertical 10% of depth at depth; horizontal 1 to 2 km.	2 orbital passes during Jupiter occultation	ice shell depth map with 56% coverage
	internal structure and orbit determination	gravitational love number (k2) to an accuracy +/-0.001	Radio Science	radial position knowledge: 1m; Non-radial position knowledge ~ 100m; Doppler shift accuracy: 0.1mm/s	2 weeks of observation	gravity map with 90% coverage
	signature of global liquid water	0.03nT magnetic field strength variation	magnetometer	3-axis ring core fluxgate magnetometer; range +/- 1024 nT; sampling rate 40 Hz maximum	2 weeks of observation	spatial and temporal varying magnetic field tracks
B.Characterize and locally map the surface composition, especially compounds of interest to prebiotic chemistry	Distribution of water ice bands, hydrated salt minerals, and trace constituents on the surface	900-3700nm spectral analysis of surface;5 nm spectral resolution, 512m & 5km spatial resolution	NIR Imaging Spectrometer	spectral range: 900-3700 nm; spectral resolution: 5nm (560 channels); High resolution mode at 512 m/pixel; survey mode (factor of 10 summation) at 5.12 km/pixel	High resolution mode: 0.5% per orbit during day time; 1% coverage; Survey mode: 25% per orbit, day time; ~50% coverage	hyper-spectral map with 50% coverage in survey mode, <1% coverage in high spatial resolution
C. Understand the formation of surface features, including sites of recent or current activity, and identify candidate landing sites for future lander missions	Characterize morphology and correlate with surface composition	150m/pix & 2m/pix spatial resolution	Imaging Camera: monochromatic wide-angle camera and narrow-angle camera images	WAC: 1.5 mrad ifov; 1.31rad fov; 150-300 m/pixel at 100km; swath width 150km; NAC: 100 mrad ifov; 0.021 rad fov; 2m/pixel at 100km; swath width 2km	WAC: 15 images per orbit; NAC: 7 images per orbit	surface map with 90% coverage at 150m resolution, <1% coverage at 2m resolution
		900-3700nm spectral analysis of surface;5 nm spectral resolution, 512m & 5km spatial resolution	NIR Imaging Spectrometer	spectral range: 900-3700 nm; spectral resolution: 5nm (560 channels); High resolution mode at 512 m/pixel; survey mode (factor of 10 summation) at 5.12 km/pixel	High resolution mode: 0.5% per orbit during day time; 1% coverage; Survey mode: 25% per orbit, day time; ~50% coverage	hyper-spectral map with 50% coverage in survey mode, <1% coverage in high spatial resolution
		surface topography to 0.3m	laser altimeter	frequency 10Hz, FoV 1mrad; 50m spot size; footprint spacing between 100m to 2 km depending on scanning	2 weeks of observation	topographic map with 90% coverage
D. Characterize the 3-D distribution of any subsurface liquid water	Find ice/liquid water boundary	100m vertical resolution near surface,10% depth of depth	radar sounder	Frequency 50 MHz,(6m in vacuum and 3.5m in ice); pulse width 500mm; PRF 400 Hz; bandwidth 0.85 MHz; 3dB beam width: 20o across/100o along track; footprint w/ 100 km orbit: 35 km across/238 km along track; resolution: vertical 10% of depth at depth; horizontal 1 to 2 km.	2 orbital passes during Jupiter occultation	ice shell depth map with 56% coverage
E. Characterize the radiation and magnetic field environment with spatial and temporal	Quantify magnitude of energy transferred to detectors by charged particles in European orbital environment		Heavy Ion Counter; Energetic Particle Detector	Detect range 6-200 MeV /nucleon; Time resolution 0.7s ~ 2.0s; aperture angle: 0.436 rad narrow; 0.803 rad wide model	2 days of observation	energetic particle counts for Europa environment

Figure 3: Example of a traceability matrix for a Europa Orbiter mission. In this example, Science requirements A-C form the science floor – a reduction from the full A-E mission objectives. The same instrument is used to address several mission objectives (though with different performance requirements), and some mission objectives require more than one instrument for complete fulfillment. Further, reduction of one available resource may affect the ability to achieve mission goals by different degrees. The science traceability matrix is invaluable for summarizing and assessing these often-complex relationships.