Titan Science Return Quantification

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1 Introduction

Part of the procedure for submitting a proposal to NASA for a mission or an instrument to be included in a mission is to complete a Science Traceability Matrix (STM), which is intended to show that what is being proposed would contribute to satisfying one or more of the agency's top-level science goals. But the information included in this document is not traditionally in the form of quantities that can be used directly to compute anticipated results, and so evaluations and comparisons are often more subjective than might ideally be desired.

We added quantitative elements to NASA's Science Traceability Matrix and developed a software tool to process the data. We then applied this methodology to evaluate a group of competing concepts for a proposed mission to Saturn's moon, Titan.

Although we recognize that our methodology does not completely eliminate subjectivity since it relies on estimates based on the experience and knowledge of relevant scientists and engineers, it has the merit of clarifying and focusing attention on specific numerical values of significant importance and stimulating discussion about them.

2 Augmenting the Science Traceability Matrix

The STM that NASA has been using asks proposers to provide the following information, which forms a chain from top-level science goals down to the instruments that would be required to furnish the information needed to meet those goals:

1. Relevant NASA science goals (big, general questions such as those set forth in the planetary science decadal survey published by the National Research Council in 2011 [1])
2. Science subgoals (sets of specific questions, the answers to which would lead to answering each of the science-goal questions)
3. Science objectives (sets of more-detailed questions designed to answer each of the subgoal questions—e.g., whether a particular isotope exists on Titan)
4. Scientific measurement requirements (parameters of the measurements needed to answer the science-objective questions)
    a. Observables
    b. Physical parameters
5. Instrument performance requirements (specific measurements needed to meet the measurement requirements)
    a. Measurements
    b. Range and sensitivity of each measurement
6. Projected instrument performance (instruments proposed to make the required measurements)
7. Mission requirements (general description of the types of instruments and functions that would be required)

Our augmented STM adds two significant features to the standard STM:

- It enables a quantitative estimation of the impact of each key link in the STM chain on the next-highest link. Integrating over the entire chain serves to quantify, for each proposed measurement of each proposed mission, its contribution to a set of top-level science goals.
- It calls for listing the events that could degrade the value of the measurements, such as failure of one or more instruments or missing the targeted landing zone, and estimating the probability of each event occurring. Each combination of possible events (e.g., no instruments fail, only instrument #1 fails, only instrument #2 fails, both instruments #1 and #2 fail, etc.) constitutes an "event scenario" as discussed below.

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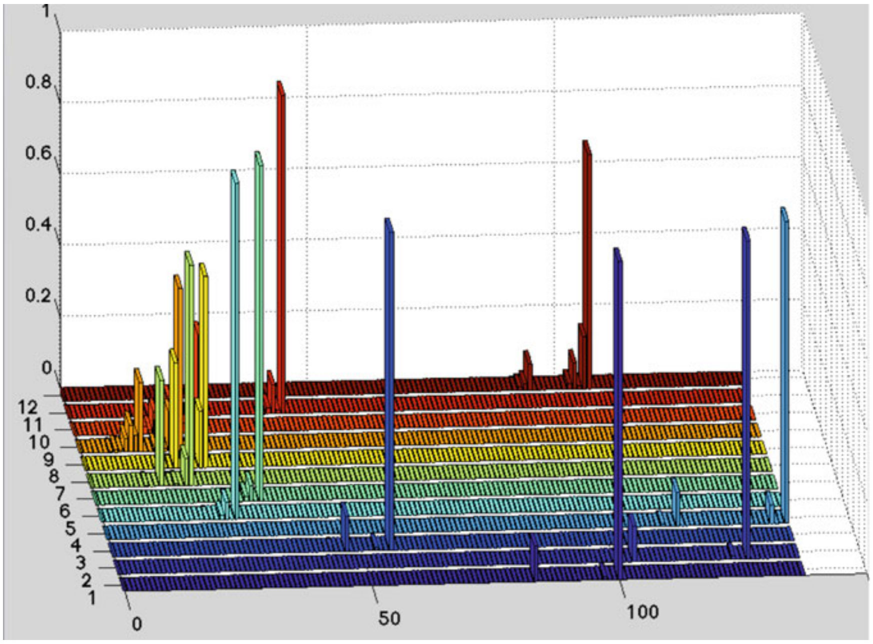

Fig. 1 Relative science value of 12 mission concepts (numbered 1 through 12 on the Z axis) given a particular set of facts and assumptions about each concept. Each bar represents the percentage of minimum acceptable science return (location along the X axis) that a mission concept achieves given a certain combination of conditions, such as unexpected environment or failure of one or more instruments, and the probability of that combination of conditions occurring (the height of the bar on the Y axis). Mission concept #1 is arbitrarily chosen as the baseline, which produces 100% of the minimum acceptable science return if nothing goes wrong

We believe that this augmented process enhances the ability of decision-makers to compare competing concepts objectively and to see clearly the inputs that lead to any given results. For the proposers of mission concepts, it also has the advantage of providing a forum for scientists and engineers to reach consensus on important numerical values, and encouraging the provision of specific information that enables decision-makers to evaluate their proposals in the clearest light.

Our additions to the STM call for the following quantitative information:

A. Relative value of each subgoal towards a top-level goal (i.e., estimate of the percentage of a particular top-level goal that will be satisfied if the subgoal is fully met).
B. Estimate of the percent completion of each subgoal, given full satisfaction of all contributing objectives.
C. Estimate of the percent completion of each objective, given full satisfaction of all contributing observables.
D. Capability-reducing events
   1) Event name
   2) Estimate of event probability
   3) Expected observational loss due to event occurring, from 0 for no loss to 1 for complete loss

Integrating over the quantities provided for A, B and C enables projection of the science return a candidate mission concept would produce, assuming it works perfectly as intended (which we report as a percentage of a baseline mission concept that produces the minimum acceptable science return). This performance is then reduced within a series of event scenarios (i.e., specific combinations of capability-reducing events) by factoring in the probability of the event occurring (D2) and its associated loss to science return (D3) to provide a probabilistic risk-adjusted performance for that specific scenario.

This provides a data point, which can be seen as any one of the bars in Fig. 1. Integrating over all the data points for a given mission concept gives the probability that the mission concept will produce a greater science return than the baseline mission concept.

We created a software tool called SCORE (Science Concept Optimization and Results Evaluator) to process the data collected in the augmented STM. It is capable of calculating the science return to be expected under each of the thousands of possible combinations of mission scenarios.

3 Example: A Study of Potential Missions to Titan

Titan is Saturn's largest moon and one of the most desired targets for further study among planetary scientists, who are eager to follow up on the discoveries made by the Huygens probe in 2005 and the Cassini spacecraft that is currently exploring Saturn and its moons.

The science team participating in this study identified 12 concepts for missions to Titan. Eight are landers, two would float balloons in Titan's atmosphere, and two would conduct their measurements while orbiting Titan. Within each of these three categories, the mission concepts differ from one another in terms of the instruments they would carry and the measurements they are designed to make.

Our study was directed toward analyzing how each proposed experiment of each proposed mission would help to answer one or more of the following questions (top-level science goals) set forth in the 2011 planetary science decadal survey [1]:

1. How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?
2. What were the primordial sources of organic matter, and where does organic synthesis continue today?
3. Beyond Earth, are there modern habitats elsewhere in the solar system with the necessary conditions, organic matter, water, energy and nutrients to sustain life, and do organisms live there now?
4. Can understanding the roles of physics, chemistry, geology and dynamics in driving planetary atmospheres lead to a better understanding of climate change on Earth?
5. How have the myriad chemical and physical processes that shaped the solar system operated, interacted and evolved over time?

The team of scientists and engineers participating in this study estimated all of the values required by our augmented STM as described above. This process was carried out for every measurement envisioned for every instrument proposed for each of the 12 mission-concept candidates. SCORE was used to process the thousands of combinations and to calculate the science return of each scenario (i.e., each combination of each mission concept's instruments and capability-reducing events) relative to the mission concept chosen to serve as the baseline.

A small excerpt of the augmented STM Excel data sheet follows. It has been modified from the spreadsheet format to increase legibility in this paper. Items in red show what we added to the standard STM in our augmentation process.

NASA science goals priority question 1: How did the giant planets and their satellite systems accrete, and is there evidence that they migrated to new orbital positions?

Science subgoal 1: Characterize the exchange process between the interior and the atmosphere; relate them to the original composition of Titan "satellitesimals," comets, other satellites.

Relative value of subgoal toward goal: 100%

Measurements: Mass spectroscopy

Science Objective question 1: Is there 22Ne on Titan, unlike other places?

Percent completion of subgoal given full satisfaction of all contributing objectives: 10%

Observables: Confirm tentative detection of 22Ne by Huygens GCMS. Physical parameters: 22Ne to ± 10% accuracy down to 10-20 ppb.

Percent completion of Objective given full satisfaction of all contributing observables: 50%

Science Objective question 2: Is there selective trapping of Kr and Xe relative to 36Ar by Titan processes (aerosols, clathrates, dissolution)?

Percent completion of subgoal given full satisfaction of all contributing objectives: 10%

Observables: 36Ar/Kr, 36Ar/Xe, Kr/Xe rations in atmosphere and surface liquids/solids. Physical parameters: Ar, Kr, Xe to ± 25% accuracy for mole fractions down to 0.1 ppb (in atmosphere) and 10 ppb (liquid/ground moisture/solids).

Percent completion of Objective given full satisfaction of all contributing observables: 95%

Science Objective question 3: Do noble gas abundances correspond to direct deposition, trapping in amorphous ice, clathration in the solar nebula, or a combination of processes?

Percent completion of subgoal given full satisfaction of all contributing objectives: 20%

Observables: 36Ar/Kr, 36Ar/Xe, Kr/Xe rations in atmosphere and surface liquids/solids. Physical parameters: Ar, Kr, Xe to ± 25% accuracy for mole fractions down to 0.1 ppb (in atmosphere) and 10 ppb (liquid/ground moisture/solids).

Percent completion of Objective given full satisfaction of all contributing observables: 30%

Science Objective question 4: What is the influence of atmospheric processes (photochemistry, escape) on carbon, nitrogen, and hydrogen isotopes?

Percent completion of subgoal given full satisfaction of all contributing objectives: 20%

Observables: 13C/12C, 15 N/14 N, and D/H profile in atmospheric volatiles, condensates, and surface liquids or solids. Physical parameters: Carbon, nitrogen, and hydrogen isotopes in nitrogen, hydrocarbons, etc. to ± 5%.

Percent completion of Objective given full satisfaction of all contributing observables: 50%

Science Objective question 5: Is Titan's methane primordial or formed by internal or nebula processes from CO/CO2?

Percent completion of subgoal given full satisfaction of all contributing objectives: 20%

Observables: C isotopes in CH4, CO, CO2. Physical parameters: 13C/12C to ± 5% accuracy down to 1 ppm total CO/CO2.

Percent completion of Objective given full satisfaction of all contributing observables: 30%

Potential Capability-Reducing Events

Event: Poorer detection threshold or calibration issue.

Event probability: 0.1

Expected observation loss: 0.2 (where 0 = no loss and 1 = complete loss)

Measurements: Images

Science Objective question 6: Do materials currently vent from Titan's surface?

Percent completion of subgoal given full satisfaction of all contributing objectives: 20%

Observables: Search for ground fogs correlated with fractures or vents, if any. Physical parameters: Surface feature, morphology, mists.

Percent completion of Objective given full satisfaction of all contributing observables: 20%

Potential Capability-Reducing Events

Event 1: Interference from low-lying hazes

Event probability: 0.1

Expected observation loss: 0.5

Event 2: Lack of wind results in lack of movement

Event probability: 0.1

Expected observation loss: 0.5

Science subgoal 2: Determine origin and evolution of Titan's atmosphere.

Relative value of subgoal toward goal: 10%

Measurements: Mass spectrograms

Science Objective question 1: What are the escape rates of N2 and CH4 from Titan?

Percent completion of subgoal given full satisfaction of all contributing objectives: 100%

Observables: Isotopic ratios in N, C, and H. Physical parameters: 14 N/15 N in N2, 12C/13C in HCN, and D/H in CH4 to 2%.

Percent completion of Objective given full satisfaction of all contributing observables: 75%

Potential Capability-Reducing Events

Event 1: Issue with data acquisition during aerocapture

Event probability: 0.1

Expected observation loss: 0.1

The STM also includes the range, sensitivity and instrument projected to be used for each measurement. Our enhanced version indicates which measurements apply to which of the candidate mission concepts.

4 Results

One of the lander concepts (#1 in Fig. 1 and Table 1) was designated the baseline mission, which by definition would produce 100% of the minimum acceptable science return if nothing goes wrong. Two of the other lander concepts (#2 and #4) were found to exceed the baseline science return under all of the scenarios that were considered, while one of the orbiter concepts (#12) was found to have a 91% probability of doing so. The remaining eight mission concepts were found to fall short of the baseline and would not need to be considered unless further analysis showed that the cost and/or risk of the baseline and three higher-scoring concepts were unacceptable.

Participants in this study reported that the quantification process provided clarity and focus to the science discussion of mission concepts.

We conducted this study with a neutral attitude toward risk. However, the formulas could be adjusted to reward or penalize missions that have higher probabilities of exceeding the baseline under some scenarios and of falling short of the baseline under other scenarios, depending on the preference of the decision-maker.

As noted above, the analysis cited here used the science goals set forth in the 2011 planetary science decadal survey as the top-level science goals. The same methodology would apply to an analysis based on any set of top-level science goals, but of course the results might differ.

Table 1 Results calculated when nothing goes wrong (column 2) and when projected science return for each mission concept is integrated across all of the capability-reducing events that were considered in this study (column 3). The results shown in red are for mission concepts that meet or exceed the baseline science return

Mission Concept	% baseline science return achieved with no capability-reducing events	Probability of exceeding baseline, integrated across capability-reducing events
1 (baseline)	**100**	**0.50**
2	**127**	**1.00**
3	56	0.00
4	**137**	**1.00**
5	27	0.00
6	33	0.00
7	20	0.00
8	24	0.00
9	20	0.00
10	26	0.00
11	43	0.00
12	**106**	**0.91**

5 Next Steps

It would be a straightforward matter to conduct sensitivity analyses of the various inputs to identify which ones are most significant in determining a mission concept's science return. Those inputs could be subjected to greater scrutiny if desired.

We note that cost was not taken into account in this study. However, a comparative cost-benefit analysis of the various mission concepts could easily be done. Ultimately, the mission concepts could be compared in a science-cost-risk space for the most meaningful relative ranking.

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Reference

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