Conceptual Design Methods and the Application of a Tradespace Modeling Tool for Deep Space Missions

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Abstract—Concept studies for deep space missions are typically time-consuming and costly, given the variety of missions and uniqueness of each design. Yet, in an increasingly cost-constrained environment, it is critical to identify the most scientifically valuable and cost-effective designs early in the design process. While some spacecraft design models currently exist for Earth-orbiting spacecraft, there has been less success with deep space missions. Instead, these missions require a modified design and modeling approach to enable the same construction of a comprehensive, yet credible, mission tradespace. This paper presents an approach for efficiently constructing such a mission trade space. In addition to a proposed design and modeling approach, three case study missions are presented including a solar orbiter, a Europa orbiter, and a near-Earth asteroid (NEA) sample return mission.[12]

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1. INTRODUCTION

In the aerospace industry, it is believed that 80% of the total cost of large development projects is committed in the early phases of the design process [1]. This assertion is particularly true for deep space missions, where the destination, trajectory, and science payload decisions (often decided in the conceptual design phase) account for the majority of the cost. As the project matures, the management team quickly loses its ability to implement design improvements or cost-savings measures. Thus, it is vital to ensure an early and comprehensive exploration of the design tradespace.

Exploring the tradespace and determining an optimal design, however, is particularly difficult in the regime of deep space missions. Given the diversity of potential destinations such as the sun, inner and outer planets, moons, minor bodies, comets, and asteroids and the technical depth needed to ensure a credible design, it is time-consuming and costly to adequately develop a set of alternative designs. Instead, mission architects and spacecraft engineers often employ their intuition in identifying the most promising designs. While this intuition is generally adequate, it does not allow for slight design differences that can ripple through the larger design, often resulting in dramatically different mission concepts than originally envisioned.

The challenge, therefore, is to quickly develop a comprehensive mission tradespace. Figure 1 illustrates the necessary technical depth and breadth that is needed to select optimal designs. There are dozens of alternative design solutions, where each must be understood at the subsystem-level. The generation and evaluation of the dozens of alternative designs can be produced by tradespace modeling tools [2], [3], [4], [5], [6]. Key parameters must be evaluated, including science data returned, mass and power (at the subsystem-level), schedule, and cost. Once this tradespace is developed, parameters representing science value may be compared against cost to determine the optimal designs.

In this paper, an approach is described for efficiently developing a tradespace of mission concepts. Team-generated point designs are combined with model-driven parametric designs to establish both technical breadth and depth. The Systems Trades Model (STM) is used as a tool to develop a complete tradespace. Finally, three case studies are presented. The first is a solar orbiting mission that studies the far side of the sun from a distance of one AU. The second mission is one that would orbit the Jovian moon Europa at an altitude of approximately 100 km. The third mission collects a regolith sample from a near-Earth asteroid and returns the sample to Earth. The diversity of these three missions provides an effective context from

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[2] IEEEAC paper #1112, Version 2, October 12, 2007.

which to discuss the design and modeling of deep space missions.

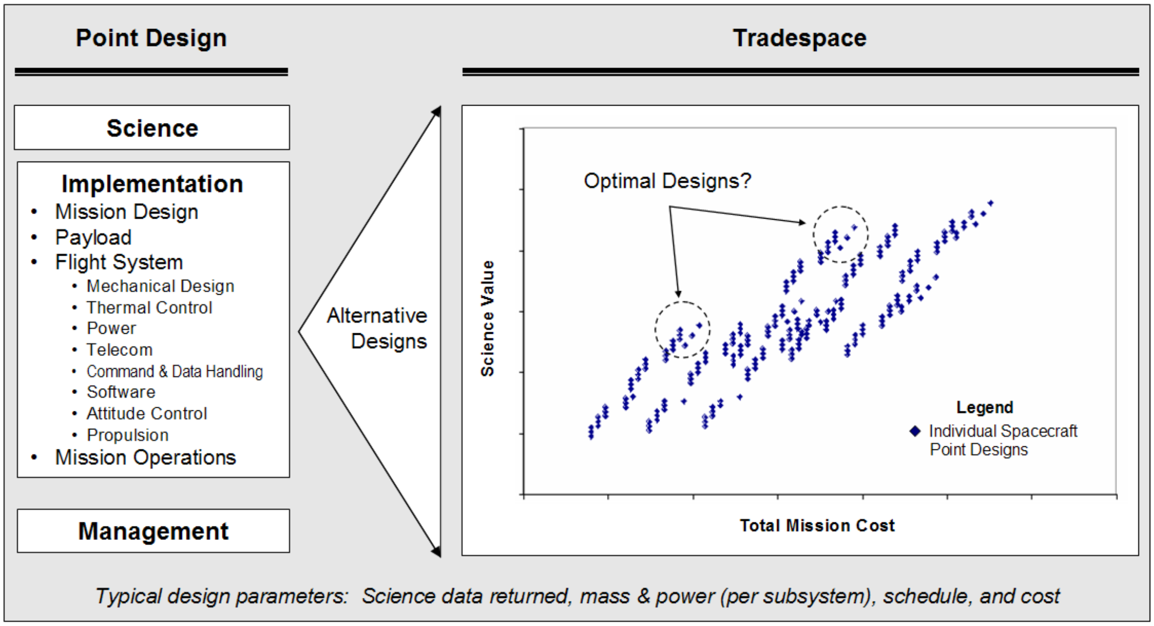

Figure 1 – Conceptual Design and Modeling

2. Design and Modeling Challenges

For Earth-orbiting missions, there have been a variety of successful approaches to modeling. For example, the book Space Mission Analysis and Design [7] includes software for modeling Earth-orbiting spacecraft. Additionally, the Jet Propulsion Laboratory has used the software GAJAT to study near-Earth missions [8]. This tool facilitates rapid mission architecture studies for missions in the vicinity of the Earth by calculating an array of design parameters for a mission based on user input. Changes in user inputs allow for multiple mission architectures to be examined in a relatively brief duration of time. Additionally, many spacecraft contractors have software for studying variations of their existing spacecraft designs. Using these tools, it is often possible to generate slight deltas from existing spacecraft designs. However, for deep space missions, the state of the art has not yet allowed this degree of sophistication. Instead, missions that travel beyond Earth orbit fall into a category that is more difficult to model. The reasons include:

1. Diversity of mission architectures
2. Importance of technical depth
3. System-/subsystem-level validation

While these reasons represent challenges (as described in the following sections), they also pose important requirements for a successful approach to the design and modeling of deep space missions.

2.1 Diversity of Mission Architectures

There are a plethora of potential missions that range from planetary fly-bys to sample return missions. They may last a few months in a high radiation environment or perhaps longer than a decade on a trip that spans the solar system. Furthermore, there is significant technology development that is occurring at this leading edge of deep space missions, such that within a short-time, new missions or architectures become possible that were not previously considered feasible. Given this breadth of destinations and rate of technology growth, it is unreasonable to expect a single tool to accurately model multiple types of missions.

Instead, the emphasis should be two-fold: (1) working with a dedicated spacecraft team to accurately model a mission concept, including at least one end-to-end point design, and (2) using a software tool that serves as a template for organizing mission-specific information and simultaneously links the system design to assess the impact of design trades and technical changes. This approach reinforces the ongoing industry paradigm shift from designing selected point designs to understanding the larger design space. Additionally, given occasional similarities between different types of missions, the tool should be modular to allow the re-use of similar portions. This methodology creates a library of missions from which existing modules may be pulled applied to new mission concepts as deemed technically appropriate. Hence, the standard of the modern design laboratory should be both an experienced design team and a library of software modules for use in tradespace modeling.

2.2 Importance of Technical Depth

At a high-level, it is often deceptively easy to design mission concepts or to propose an unreasonably high degree of heritage. However, as the design matures, numerous problems begin to surface. Examples from past flight missions include the redesign of an avionics system due to the unavailability of a single computer chip, significantly increasing solar array size due to higher-than-expected radiation degradation, and the loss of a mission from an unanticipated high-temperature gradient of a solid rocket motor. Each of these problems, as well as many others, occurred in the detailed design and significantly influenced the end-to-end architecture. While setting high mass and power margins can mitigate these problems to some extent, it is far better to incorporate higher levels of technical detail earlier in the process to ensure a credible and feasible mission concept.

This assertion reaffirms the need for a dedicated spacecraft design team. Furthermore, the parametric tool used in combination with the spacecraft team should provide the structure and information necessary to foresee and mitigate problems to ensure schedule and budget are not exceeded. For example, the tool should provide a 100- to 200-line mass and power equipment list for each mission concept, including sufficient flexibility to incorporate additional technical detail as the project matures in Phases A and B.

2.3 System-/Subsystem-level Validation

Given the complexity of deep space missions, it is important for the design and tool results to be easily validated at the system and subsystem level by other members of the design team and by outside peer reviewers. Thus, both the mechanics and outputs of the design process must be easily accessible to the team responsible for validation. This requirement further implies that the type of software used must be in current use by the majority of spacecraft engineers and the outputs of the model are provided in a standard, comprehensible format.

3. FRAMEWORK FOR DESIGN AND MODELING

In the concept development phase of deep space missions, there are a series of steps that form a conceptual design and modeling framework (see Figure 2). These steps, combined with iterative feedback from the science community, describe an approach that leads to the selection and refinement of favorable mission architectures based on a set of mission requirements. The framework also shows how intuition plays a role in the design. Early in the process, experience and intuition guides the design of the baseline mission. Then, as more trade studies are completed, the design matures first at the subsystem-level and second at the system-level. It is at the system-level where incorporating a tradespace modeling tool contributes to a mature design architecture as the ripple effect of small changes at the subsystem level is assessed at the system level.

A framework for the concept development phase of a mission is outlined in Figure 2. The framework is set in the context of program requirements levied by the governing agency. For example, often budget, launch time frame, launch vehicle, and target body may be specified in an Announcement of Opportunity (AO) for a competed mission. Similarly, directed missions have a similar set of criteria that must be observed. Superimposed on this set of requirements are the desires of the science community (represented by a science team). This team is part of a six step iterative process that formulates, proposes, and designs the mission concept. Since science is nearly always the underlying driver for the mission [9], a fine balance must be struck between science return and technical feasibility. Thus, the process of creating a tradespace of design options maximizes the ability of the science team to winnow the list of options in a fashion managed by the engineering team. Then, as requirements and design drivers shift, the science team continues to play an active role in the direction of the design, augmenting the path suggested by the engineering team.

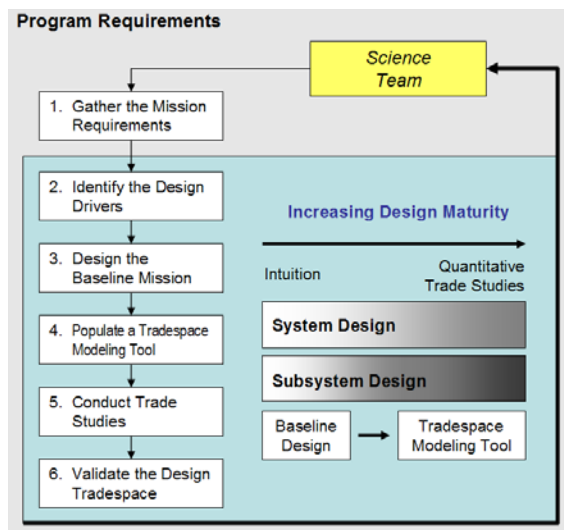

Figure 2 – Conceptual Design and Modeling Framework for Deep Space Missions

3.1 Gather the Mission Requirements

The mission requirements are the fundamental objectives that drive the entire design. These requirements include such questions as:

- What are the science objectives?
- What is the destination?
- What are timing requirements?
- What level of risk is acceptable?
- Is technology development required?

It is critical that these questions are fully understood early in the process, including the difference between the ideal requirements and the floor requirements. Floor requirements are those requirements that must be achieved in order for the mission to be worth flying. For example, while the scientific community would ideally like to remain in a fixed position to study the far side of the sun, they would tolerate a less expensive mission that drifts past the ideal location. Similarly, a mission to Europa would ideally last more than 90 days to collect the necessary science data. However, missions of less than 90 days are also possible, depending on the impact to science data and mission cost. Likewise, scientists ideally would prefer several hundreds of grams of sample from several locations on an asteroid. However, from a risk and cost perspective it may only be feasible to collect tens of grams from one location on an asteroid. Often, it is helpful to view the initial baseline design as the science floor, answering the question of "At what cost, can the minimum mission be achieved?" Then, further designs or trade studies can highlight the costs and benefits of pursuing additional science. At the conclusion of this step, the design team should fully understand the science requirements and their sensitivities.

3.2 Identify the Design Drivers

Based on the mission requirements, the process of identifying technical parameters, including the key design drivers, begins, often in parallel with designing the baseline mission. At the system-level, the science payload and trajectory tend to drive the design, since these parameters significantly affect both science and cost. Beyond these design drivers, the next class of design drivers is subtler, usually dependent on the required capability versus availability of individual subsystem designs. For example, the solar range and high radiation environment of Jupiter require more capable power and data storage systems than are commonly found in other spacecraft. Similarly, the trajectory requirements to reach an asteroid or comet may eclipse the capability of a bipropellant propulsion system, resulting in the use of electric propulsion. Identifying these and other design drivers early is often based on the intuition and experience of veteran spacecraft engineers. In this context, it is helpful to poll the design team to surface and manage the principal drivers. Then, as the design concept is iterated, new drivers surface, often evolving into a series of trades studies.

3.3 Design the Baseline Mission

Given the set of programmatic and science constraints, a baseline mission may be conceptually designed by a spacecraft design team. Usually, space agencies use dedicated design teams, such as JPL's Advanced Projects Design Team (Team X) or Goddard's Mission Design Center (MDC). These teams are comprised of five to thirty engineers who have a variety of flight project experience, along with access to many types of analysis tools useful in the formulation of a concept.

The design team generally begins with a sketch or vision of the overall mission architecture, including the trajectory and science payload requirements. Using this information, the trajectory and science instrument engineers begin preliminary work ahead of the larger team. Then, as part of the first official design session, the trajectory and science engineers present the results, which initiate numerous analyses that run in parallel. Based on the initial mission sketch (supplemented by the trajectory and science analysis), each subsystem engineer creates a design to meet the perceived requirements. The system engineer(s) gathers these designs to produce mass, power, data rate, and cost reports that define the design margins and risk of the system, resulting in new work by the subsystem engineers. This iterative process continues for three to four design sessions, until a consensus is achieved with respect to the design.

Within this iterative process, the principal design drivers play a critical role, since their selection often determines major aspects of the design. Furthermore, there is often insufficient time to evaluate these design decisions within one or two design sessions, resulting in both the need to judiciously select these design trades in advance and to provide a forum for the continued evaluation of these decisions.

3.4 Populate a Tradespace Modeling Tool

While the prior design steps are in general agreement with current practice, this paper would like to add this step to emphasize the construction of a tradespace modeling tool. Specifically, after the baseline mission is complete, the data and relationships generated may be used to populate a tradespace modeling tool, such as the one described in more detail in Section 4.0. The tool should allow the addition of many types of data in standard formats, such as mass, power, and costs for each subsystem. Additionally, key relationships should be maintained within the tool, such as the rocket equation (for missions requiring chemical propulsion) and system margin calculations. Thus, the combined storage of design information and an underlying set of key relationships provide a dynamic forum for continuing to study both the baseline mission and a larger tradespace of options.

The tool may then be validated against the baseline design to ensure that the same results are produced. Once the tool is validated against the baseline mission trade studies can be added (see Section 3.5). The tool can now generate a graph of all the combinations within the tradespace similar to that shown in Figure 1. A first order validation of the complete set of results can be obtained by taking a detailed look at the missions that are of most interest. Determining the optimum mission option can be complex and is outside the scope of this paper but methods for selecting the optimal mission can be found in the following references [2], [7], [10], [11].

Mass		Unit	# of units	CBE	Contingency	MEV
Subsystem	Component/Part	kg		kg	%	kg
Thermal -Mass	Architecture 1: Heat Pipes		Total	30.0	28%	38.4
	PPU & Telecom Louvers		3	-	10%	-
	PPU Louvers	0.80	2	1.6	10%	1.8
	Telecom Louver	0.40	1	0.4	10%	0.4
	Heat Pipe Assemby		3	-	30%	-
	Heat Pipes	1.40	2	2.8	30%	3.6
	Heat Pipe Saddle	4.00	1	4.0	30%	5.2
	Heaters, Sensors, & Other Hardware		106	-	29%	-
	Thermal Surfaces	0.50	1	0.5	30%	0.7
	Thermal Conduction Control	2.12	1	2.1	30%	2.8
	Thermostats	2.85	1	2.9	30%	3.7
	Heaters	2.35	1	2.4	30%	3.1
	Temperature Sensors	0.01	100	0.7	10%	0.7
	Xenon Heaters	0.60	1	0.6	30%	0.8
	Hydrazine Heaters	1.60	1	1.6	30%	2.1
	Multilayer Insulation	10.50	1	10.5	30%	13.7

Figure 3 – Example of Thermal Subsystem MEL Produced Using the STM

Power Modes Summary		Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7
		Telecom@ Cruise	Telecom	Thrusting	Reconnaissance	Sample Collection	Launch	Safe
Subsystem	Mode Selection:	Nominal	Nominal	Nominal	Nominal	Collect	Launch	Launch
ACS -Power Modes	**Power MEV:**	**40.4 W**	**40.4 W**	**40.4 W**	**40.4 W**	**42.1 W**	**13.7 W**	**13.7 W**
Architecture 1: Thrusters Only	**Contingency**	**38.5 W**	**38.5 W**	**38.5 W**	**38.5 W**	**40.1 W**	**13.0 W**	**13.0 W**
Sun Sensors (Pyramid)	5%	1	1	1	1	1	1	1
Star Trackers (A-STR)	5%	15.5	15.5	15.5	15.5	15.5	0	0
Inertial Measurement Unit (LN200)	5%	12	12	12	12	12	12	12
Solar Array Drives (type 2)	5%	5	5	5	5	5	0	0
Solar Array Drive Electronics	5%	5	5	5	5	5	0	0
Radar Altimeter (RAS) Electronics	5%	0	0	0	0	1.6	0	0
Radar Altimeter Antenna	0%	0	0	0	0	0	0	0

Figure 4 – Example of ACS Subsystem PEL Produced Using the STM

3.5 Conduct Trade Studies

Throughout the previous steps, a list of potential trades quickly accumulates. While some analysis should be done prior and in parallel to the baseline design, the location for conducting the majority of trade studies is following the design of the baseline mission and using the tradespace modeling tool from the previous step. The desired trade studies generally evolve from the list of design drivers, although less significant trade studies are also conducted to fine-tune the design with respect to maximizing science return and minimizing mission risk and cost.

Typical trade studies include trajectory trades (ballistic versus low thrust), propulsion trades (electric versus chemical), payload trades (number and type of science instruments), and subsystem trades (type of thrusters, solar arrays, attitude control system, etc.). Additionally, trade studies may also consider necessary levels of redundancy, perhaps swapping hardware components for increased software sophistication or vice-versa.

These trades must be analyzed and compared to determine the best option for the given mission. Typically, this process is completed by determining the impact to system-level science return, key margins, mission risk, and overall cost. This is where a tradespace tool, such as the STM described in Section 4.0, becomes particularly powerful. A tradespace modeling tool has the capability to organize and track multiple architecture options at the component level and can assess multiple trades at the system level. Additionally, a modeling tool should have the flexibility to incorporate trades that were not initially considered or reevaluate trades as the design changes.

3.6 Validate the Design Tradespace

Validation is a critical part of the process to ensure that the mission concepts are represented and modeled accurately. The process begins with the verification of individual subsystems, where cognizant engineers walk-through their respective baseline designs and modeling approach. In this review, it is important to recognize the applicability of the design through the range of potential limits of the relevant parameters. Following these verification reviews at the subsystem level, individual point designs (produced by the model) are selected for independent validation by a design team. Along with the validating the relative accuracy of the model, this process usually identifies several issues that further complement the model capability.

4. SYSTEMS TRADES MODEL (STM)

Development of the Systems Trades Model (STM) began in 2005 for use in concept studies where multiple tradespace options exist. The tool has undergone several iterations of development through use on case studies, three of which are presented in this paper, to improve the underlying structure of the tool and user functionality. The principal capability of STM is its ability to store component-level designs and use this information to assess the impact of trades at the system, subsystem, and component-level. The principal strength of STM is its underlying architecture for organizing subsystem analyses, capturing component-level mass equipment lists, power mode variations, Work Breakdown Structure (WBS) based costs, and the relationships between these mission parameters.

4.1 Model Requirements

One of the primary requirements for a tradespace modeling tool is for the tool to be easily accessible by the engineering team. This requires that the software used to run the tool is readily available and reasonably user friendly. The STM is an Excel based tool, providing a straightforward method to access each specific subsystem and the information for the subsystem is displayed in an organized manner set up by a standard template that can be used for each of the subsystems. The standard organization and subsystem allows effortless verification.

Due to the nature and diversity of deep space missions, the tradespace tools developed for deep space missions must have a good deal of flexibility built into them. It is important to have the capability to add new modules or elements as required to the model to do additional tradespace analyses. The analyses performed should not be constrained to those initially built into the tool but should have the flexibility to incorporate new analyses. Therefore, the focus should be on the overall tool structure and not one time needs.

At a more in-depth level, STM requires the trajectories studies for mission design and the costs for mission design and navigation wherever possible. Alternative payload suites including mass, average power, average science collection data rate, and cost are needed. Each subsystem must have a mass equipment list (MEL), power, and cost for each option desired by the customer. Additional options that include new technologies may be added as appropriate. Alternative ground systems options with cost also need to be incorporated. Cost by WBS for all options desired by the customer are also necessary. As described in the previous section, this data is generated by the design team that creates the baseline conceptual design.

4.2 Model Architecture and Worksheets

STM is composed of two primary templates for data entry. The first template is used to create separate worksheets for each subsystem (e.g., payload, propulsion, thermal, ACS, C&DH, power, telecom, structure, and other elements as needed). This allows for uniformity in how data is entered for each subsystem and supports validation exercises. Each subsystem worksheet consists of six tables:

1. **Inputs Table:** List of inputs (including their expected ranges) that are required from other worksheets.
2. **Key Parameters Table:** List of key parameters that are distributed to the workbook.
3. **Analysis Table:** A single table or set of mission-specific tables for conducting relevant subsystem analyses.
4. **Mass Equipment List*:** List of hardware component masses and contingencies.
5. **Power Modes Table*:** List of hardware power levels for different spacecraft modes.
6. **WBS-based Cost Table*:** List of costs.

   * *Separate lists may be created for alternative subsystem architectures, allowing the flexibility to swap architectures with respect to given trades.*

The second template has a more basic format designed to accommodate the information desired for mission design and ground systems. This template consists of an input section at the top of the page where key parameters can be brought in from other worksheets, a key parameters table where parameters can be listed that can be output to other worksheets, and a calculations section. This template has the flexibility to add tables if necessary such as in the case of mission design where a separate table listing all the trajectories and their characteristics may be necessary.

The culmination of all the worksheets can be found on the systems page. In the systems trades table, all of the key trades for the mission can be summarized in the table and the tradespace can be explored by selecting different trade options. In the selected key parameters table, all of the most important key parameters can be listed in this table to enable easy viewing of how these parameters change as trades are made at the system level. Additionally, all of the key parameters from the workbook are linked to this page and automatically summarized in a table below the selected key parameters table for viewing any parameter of interest that may not have been included in the selected key parameters table.

The results of selecting different trades can be seen on the mass equipment list (MEL), power modes (including a power equipment list (PEL), and cost worksheets. These pages are linked directly to the necessary information on the other worksheets to automatically generate the tables found on these sheets. The tables are updated each time a different trade option is selected. These worksheets also have summary tables that allow for selection of information to be summarized at the top and have the flexibility for modification as the missions being entered into the tool change.

4.4 Products

The standard products created by the model include a component-level MEL, PEL including a power modes summary table, cost and a list of key technical parameters. As an example, Figure 3 shows the thermal subsystem portion of a MEL for the asteroid sample return case study. The MEL (Figure 3) produced using the STM has the ability to store this component level information and track current best estimates (CBE) masses for all units required as well as maximum expected values (MEV) for masses. An example of the PEL for the ACS subsystem is shown in Figure 4.

5. SOLAR ORBITER CASE STUDY

The solar orbiter case study is based on design effort for the Farside Sentinel mission study [12]. This mission is designed to complement the Inner Heliospheric Sentinels (IHS) tasked with probing the characteristics of the solar environment as deep within the heliosphere as possible. The four IHS spacecraft will conduct detailed in-situ investigations, whereas the Farside Sentinel mission will provide a global context for these local measurements by studying the sun from near 1.0 AU in conjunction with observations from Earth. Thus, the more comprehensive view provided by this mission will contribute to an improved understanding of the overall solar dynamics. An overview of the trajectory for the Farside Sentinel mission is shown in Figure 5.

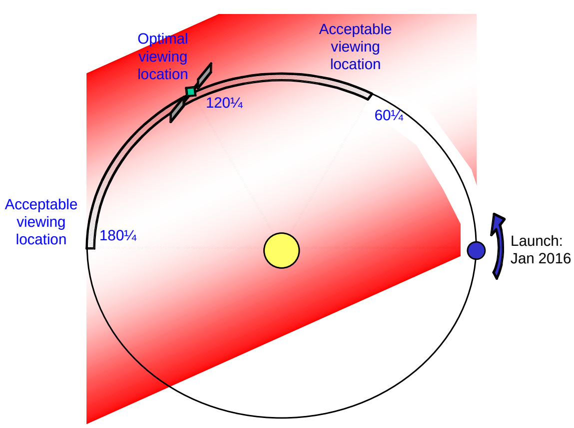

Figure 5 – Solar Orbiter Mission Overview

5.1 Key Design Drivers

A primary design driver for this mission is science payload, arising in part from the addition of a guide telescope that is required by several instruments and adds complexity from the need for precise pointing knowledge. Another principal driver is the set of derived requirements from the trajectory. The trajectory design process must balance the viewing requirements, including overlap with IHS, while trading launch vehicle size, flight times, magnitude of delta-V, and type of propulsion. Combined, the instrument payload and trajectory design directly account for a majority of the flexibility within the mission budget, without considering secondary effects on the flight system design. Table 1 shows a summary of the design drivers, the baseline mission, and alternative options that were considered. Each of these trades were modeled and analyzed using the STM.

Table 1. Design Drivers, Trade Options, and Baseline Mission for Solar Orbiter Case Study

Design Driver	Baseline Mission	Other Options
Instrument Payload	6 Instruments: Magnetograph + Coronagraphs + In Situ + Engineering	• Magnetograph Only • Helioseismology • Magnetograph and Coronagraphs
Trajectory	0 to 180 degrees Drifting with Lunar Gravity Assists	• 120 degree Fixed • Optimal 60 to 180 degrees • 0 to 180 degrees Drifting (slow) • 0 to 180 degrees Drifting (fast)
Science Data Collection Rate	115.6 kbps	• 37.3 to 500 kbps

Although data acquisition is not a principal design driver, it provides the opportunity to optimize the flight system design. Optimization can occur by adjusting the mass and cost of the telecom subsystem to maximize the data rate while fitting within the available mass allocation. Thus, depending on the launch vehicle margin, the data rate can slightly increase or decrease to either use excess launch capability or help accommodate a smaller launch vehicle. This optimization should be completed in concert with the t the telecom/ground-system design for a given data rate. Consequently, the transmitter size, high gain antenna (HGA), length and number of DSN passes, and DSN array may all be traded, selectively emphasizing reduced mission operations, low flight system mass, and/or limited data volume availability.

5.2 Systems Trades Model

The solar orbiter case study was the first test of the STM software. The spacecraft design team had established four point designs that provided a wealth of data to use for the population of the model. Then, in concert with adding this data, additional relationships and trade studies were incorporated, providing an in-depth analysis of the mission tradespace, as described in the following subsections.

5.3 Verification and Validation

Using the combination of the four point designs and a handful of selected trade studies, more than 1,000 permutations were generated as shown in Figure 6. These included the primary trades listed in Table 1, along with additional, less significant variations. This work, however, required verification and validation by the design team.

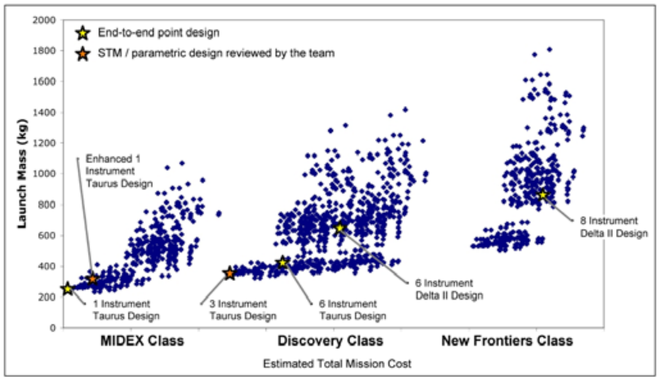

Figure 6 – Solar Orbiter Model Validation

Verification by the team was accomplished via a brief subsystem walk-through by the engineering team of the model worksheets. The accessible nature of the model worksheets proved to be a valuable design feature, allowing the team to provide feedback and improve the modeling capability. Additionally, validation exercises were accomplished by studying two additional designs. Specifically, a set of subsystem and system level products were generated by the model and reviewed by the team. These products were found to be consistent (within 5%) of the most likely design. In this validation exercise, the emphasis was placed on reviewing possible design alternative (that is, low mass and cost options) rather than a comprehensive validation of the tradespace envelope (see Figure 6). This is useful approach since often resources are limited, and it is generally unnecessary to examine options that are less likely to be utilized.

5.4 Results

The results from modeling design variations provide insight of the respective sensitivities of the design drivers. While an experienced design team will usually predict these results, the visual representation (as displayed in the following graphs) provides confirmation on the design behavior, the potential to optimize the design, and the capability for risk assessment across an array of alternative designs.

In Figure 7, the mass and cost impact of the payload selection is shown. Clearly, the payload selection has a considerable impact on the design. This result is due to the combination of a wide-range of payload options combined with, for the most part, an otherwise straightforward spacecraft design. Thus, this relationship both places the onus on the science team to determine their science requirements relative to the budget and allows them the flexibility to negotiate for additional science benefits.

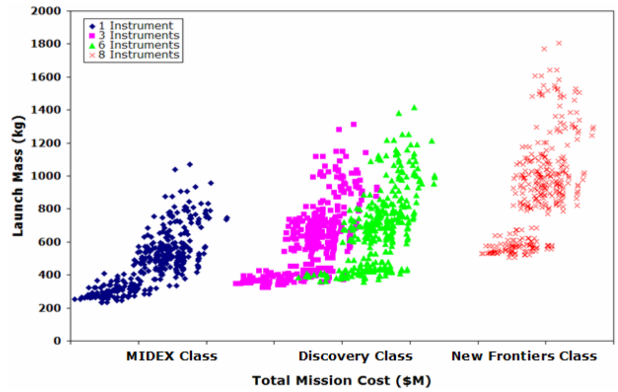

Figure 7 – Impact of Payload Options

The second principal driver is the type of trajectory that is desired, which is also directly related to science requirements (Figure 8). Specifically, while the science team would ideally like a 120-degree viewing angle of the solar farside, the additional cost of this option may not be sufficiently worthwhile. Instead, orbits that slowly drift past the desired viewing location may be sufficient. Additionally, the science team may use this information together with the evolving IHS timeline to determine which option best meets the overall science requirements while minimizing cost.

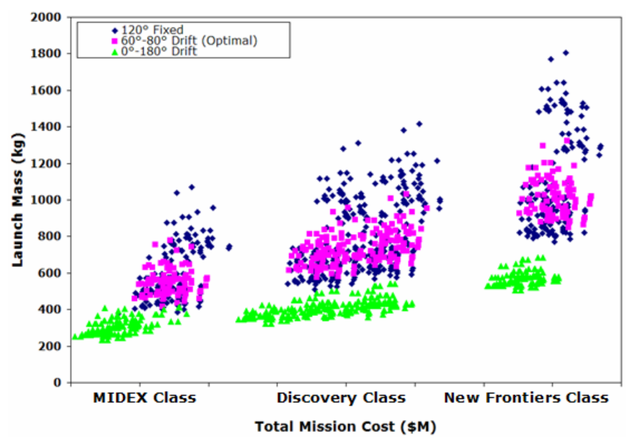

Figure 8 – Impact of Trajectory Options

In Figure 9, the impact of varying the data rate from 50 to 500 kbps is shown. From the chart, the data rate is not a primary driver, suggesting that science team can select a high data rate to maximize their science return. Additional results from this trade study, also suggest that the engineering team may further optimize the design to complement the final design, ensuring that excess launch mass is used to both maximize data return and minimize cost.

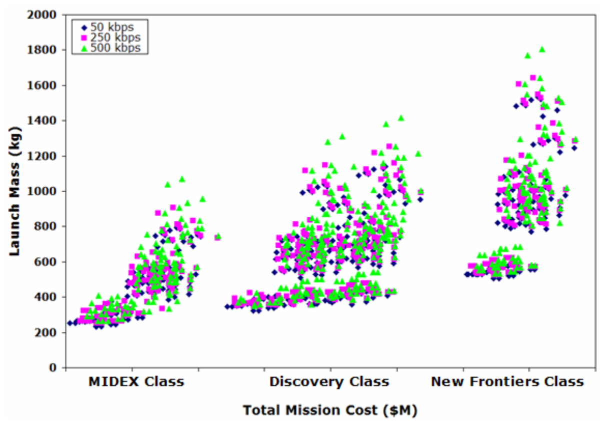

Figure 9 – Impact of Data Acquisition

Figure 10 illustrates the launch vehicle selection in the context of the former design drivers. As expected, the lowest mass and cost options utilize the smaller Taurus launch vehicle, whereas the majority of options use the more expensive Delta II launch vehicle. Additionally, a limited number of options at the very high end employ the Atlas V launch vehicle. These architectures were not validated, since they are unlikely candidates for further study.

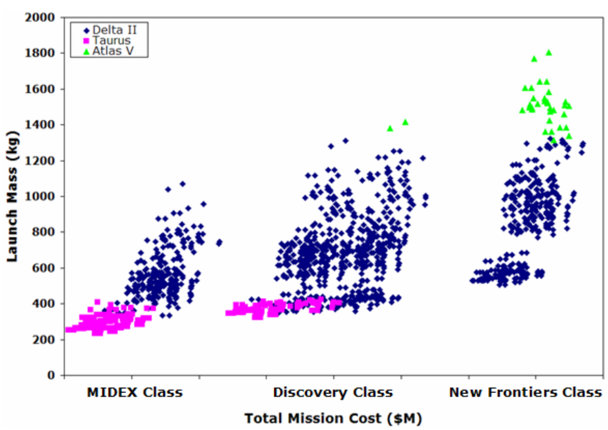

Figure 10 –Launch Vehicle Tradespace

6. EUROPA ORBITER CASE STUDY

Over the past decade, JPL has led several mission studies to examine the various designs for science missions to study the Jovian moon of Europa. Using some of this accumulated work, an effort was undertaken to both exercise the STM tool and study the tradespace envelope of a Europa orbiter [13]. While the conceptual development studies and design effort have continued beyond this work, the following results provide insight on the benefits of tradespace modeling and the characteristics of trade studies for a typical Europa orbiter.

6.1 Key Design Drivers

Similar to the previous case study, the Europa mission is dominated by the type of science payload and the type of trajectory desired. However, this mission contains several technology-related trades as well. For example, the lifetime at Europa is a trade between the science desire for a longer mission and the balance of cost and radiation-hardening technology. The power source is a trade of solar arrays versus the availability of various RTG technologies, and the telecom system is a function of mass, ground system architecture, and onboard mass storage limitations. These trades highlight the competing demands of the science instruments and trajectory desired by the science team, the appropriate technology readiness desired by the engineering team, and minimizing the overall mission cost.

6.2 Model Verification

As part of this Europa tradespace modeling effort, the baseline design entered in STM was verified against the design generated by a flight system team. Additionally, selected trades were reviewed to ensure that the relationships were functioning as intended, such as the mission design trajectory database and the RTG performance algorithms. However, beyond these internal verification exercises, no additional validation effort occurred for this limited duration study.

6.3 Results

In Figure 12, the impact of four payload options is shown. These payload options represent different combinations of cameras, altimeters, radars, and in situ instruments. From this chart, it is clear that the selection of the science payload is a primary cost driver. Additionally, the relative impact can be assessed, as the first three payload options show similar differences, while the fourth option is significantly more costly.

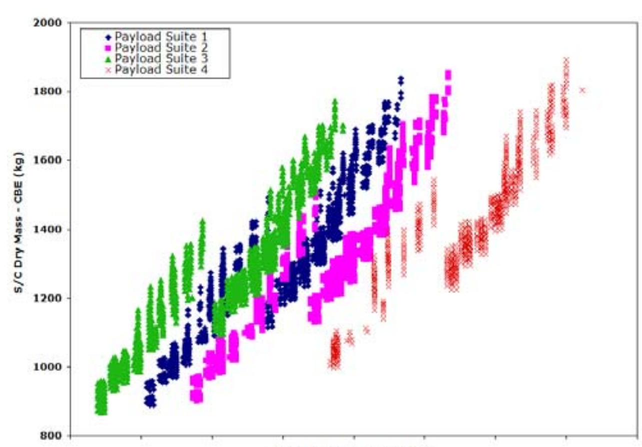

Figure 12 – Impact of Payload Options

The impact of the trajectory selection is shown in Figure 13. The two options shown include a Venus-Earth-Earth – gravity-assist (VEEGA) trajectory and a delta-Vee-Earth-gravity-assist (ΔVEGA) trajectory. From the chart, the ΔVEGA trajectory cost offers the lower cost options. However, implicit in this chart, is that this trade is at the cost of mass margin. The result is that while it would be less costly to select a ΔVEGA trajectory, the importance to mitigate risk and maintain high margins may require a VEEGA trajectory.

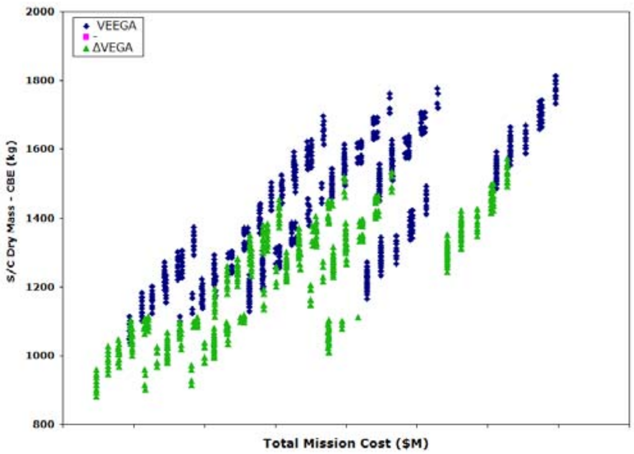

Figure 13 – Impact of Trajectory

For Figure 15, two science acquisition data rates were selected as a comparison (measured in Mb/orbit). The first rate was selected as the science floor, and the second rate was chosen as the expected data return, slightly higher than the allocation of previous studies. The results, as shown in the graph, suggest a relative insensitivity of these two data rates. While this result is due mostly to the modest requests by the science team (already knowledgeable of the inherent challenges), it still suggests that this parameter (at least within these ranges) is not a cost driver. The reason for this, given further analysis, is that other requirements (such as mass storage constraints) preclude any savings from reducing to a lower data rate.

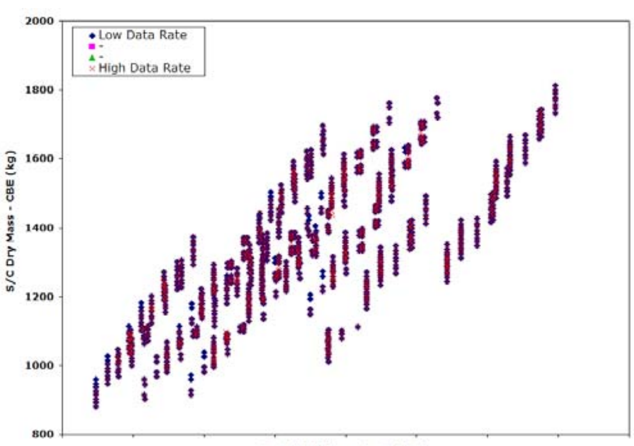

Figure 15 – Impact of Data Rate

A more significant impact can be found in Figure 16, where two types of RTGs are compared. The first type is the MMRTG, which is a new design that is being considered as the standard for future deep space missions. The second type is the GPHS RTG, which is the type of RTG flown on the Cassini mission. As the graph confirms, the latter RTG is both lighter and less expensive. However, it introduces risk, since the availability of these types of RTGs is uncertain, and there may not be enough available RTGs and spare parts to meet the requirements.

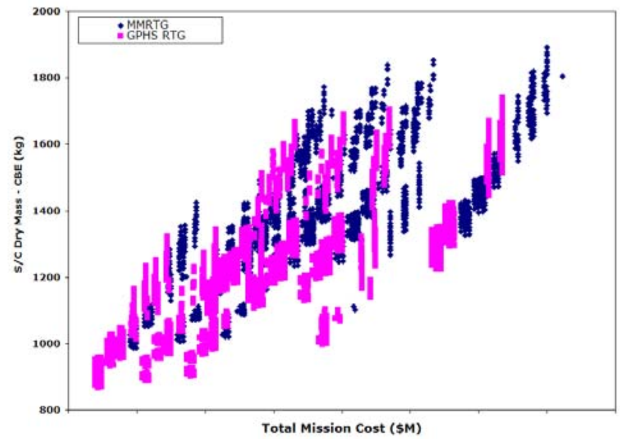

Figure 16 – Impact of Power Source

7. NEA SAMPLE RETURN CASE STUDY

The major science objective of the near-Earth asteroid sample return mission is to collect a regolith sample from a well characterized asteroid and from a known geological context to further the understanding of primitive bodies and solar system formation [14], [15]. The sample collector consists of a passive silicone substrate pad that is touched to the surface of the asteroid for a very short duration using a relatively small amount of force to collect tens of grams of sample [16]. The samples are returned to Earth using an Earth return capsule (ERC) for detailed laboratory analysis.

7.1 Key Design Drivers

A primary driver once again for this study is the trajectory as a function of the electric propulsion engine [17]. The ACS architecture also plays a fundamental role in the design as a mass driver, along with the trade between solar array types. The science instrument payload, however, is less significant driver and is not shown in these charts. Specifically, since the primary objective of this mission is to return a regolith sample there are few options for adjusting the payload.

7.2 Systems Trades Model

The asteroid sample return case study was used to continue development of the STM software to address issues such user-friendliness and worksheet linking architecture. In this context, this type of mission was chosen given the new elements and potential trades that could be introduced, based on previous case studies. In this sense, the flexibility of the tool was tested and adapted where necessary to accommodate the variety of architecture differences such as multiple flight system elements and electric propulsion.

6.2 Verification and Validation

For this case study, two point designs were available for a preliminary validation of the model. Contact with design team members was initiated as data was entered into the STM if necessary for further verification and validation of the data. Both point designs were validated by the design team as well as by an outside peer review team.

7.3 Results

Figure 17 shows the impact of the trade between electric propulsion engines. The propulsion engine trade is a primary cost driver. The Hall engine tends to be the lower cost options. The XIPS engine falls in the middle of the cost range while the NSTAR engine trends toward the most costly option.

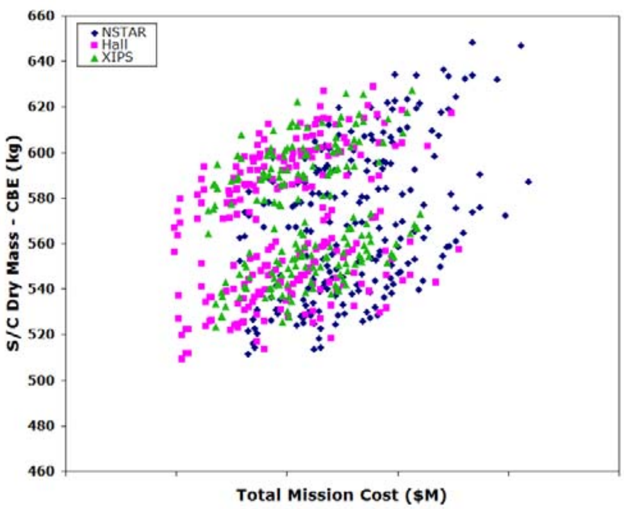

Figure 17 – Impact of Electric Propulsion Engine

In Figure 18, the impact of trading of rigid versus ultra flex solar arrays can clearly be seen. In this case, the solar array option is a distinct mass driver rather than a cost driver. A mass margin hit is taken when a rigid array is chosen over an ultra flex array which in general can drive cost. However, extra space qualification is needed to fly an ultra flex array which can drive up cost. The magnitude of these cost increases has nearly the same impact in both cases. Thus, mass margin is the main driver. The ultra flex array option is the more risky approach.

The impact of the ACS architecture tradespace shows that mission cost is partly driven by the choice between reaction wheels and thrusters (Figure 19). The reaction wheel option is more of a cost driver than the use of only thrusters for the ACS subsystem. However, use of only thrusters is a higher risk option.

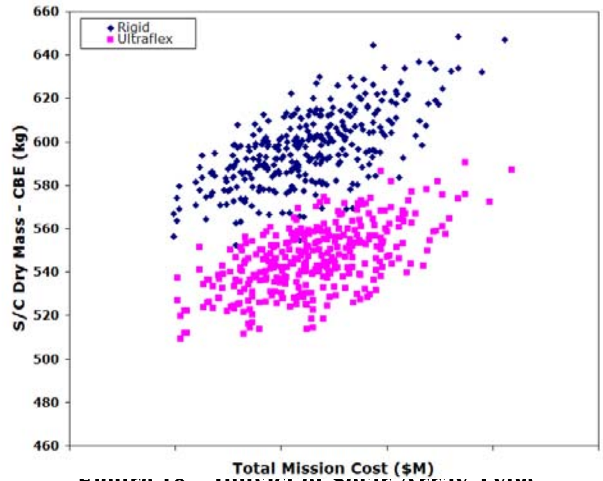

Figure 18 – Impact of Solar Array Type

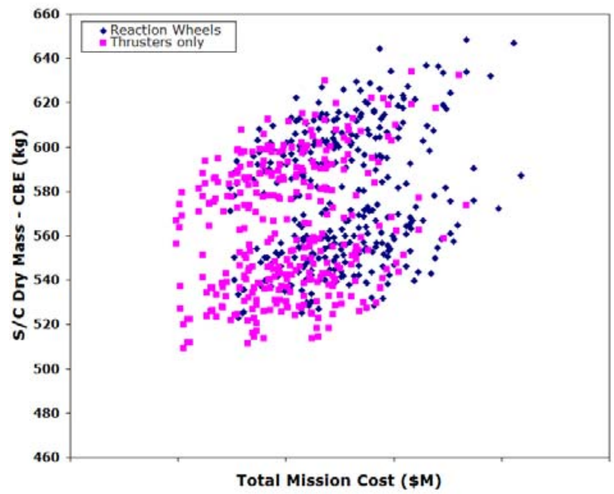

Figure 19 – Impact of ACS Architecture

The key to all of these trades is to balance cost and risk. In this case study, options that involve using thrusters only for the ACS architecture over reaction wheels, ultra flex arrays over rigid arrays, or options that decrease mass margin versus increasing mass margin all increase risk in the mission. All of these items are tightly coupled and have nearly the same magnitude of impact on the overall system. Therefore, it is very difficult to choose the options that best balance the cost and risk without careful analysis and detailed technical understanding of the tradespace. It is for this reason that the use of tradespace modeling tools become important, both as a means to compare a complex series of trades and as a design management tool that, once updated with new technical parameters, may show that a previous trade should now be reconsidered.

8. CONCLUSIONS

As the complexity for deep space missions increases, the importance of establishing the *right* architecture at the earliest point in the process is critical. Yet, given the larger diversity and evolving technology, it has proven difficult to develop a single analysis tool for modeling these missions. Instead, a different approach must be taken, one that integrates a standard structure to capture a mission concept created by a design team and also complements this data with algorithms for modifying and scaling the design. The result is a powerful modeling tool that can be used for a variety of missions, albeit it is dependent on an underlying spacecraft design team to determine the baseline concept and the necessary trade studies.

In this context, STM was developed to both capture the design information generated in a traditional conceptual design study and supplant this information for relationships to greatly expand the number of spacecraft options considered. This tool was then used on three initial studies, including a solar orbiter mission, a Europa orbiter mission, and an asteroid sample return mission.

The results from these three studies were presented here. In general, the results confirmed existing beliefs, such as the importance of the payload and trajectory and the secondary benefit of individual subsystem or technology trades. Additionally, modeling with STM showed how a design may be better understood and optimized. Or, how given new design information, old trades may be easily re-run. The conclusion is this modeling process is a critical step in the formulation process, and its continued and increasing use should be used to mitigate the risk of increased design complexity.

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