COST-BASED LAUNCH OPPORTUNITY SELECTION APPLIED TO RENDEZVOUS WITH 99942 APOPHIS

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Pork chop plots of launch C3 and arrival ΔV are commonly used to select launch opportunities for interplanetary missions. However, the launch dates for minimum launch C3 and minimum arrival ΔV rarely coincide. To link these two metrics, this paper presents a method for creating program-cost-based pork chop plots from standard velocity-based pork chop plots and other mission requirements such as payload mass and engine specific impulse. Furthermore, these results are expanded by assigning probability density functions to mission requirements and determining the probability of meeting various cost caps. The method defined here allows for non-deterministic, robust selection of launch and arrival dates very early in the design process. This method is applied to a simulated robotic mission to the near-Earth asteroid Apophis.

INTRODUCTION

In interplanetary mission design, launch opportunities are often chosen based on pork chop plots of launch C3 or arrival ΔV. However, because the launch and arrival burns are almost always performed by separate vehicles, neither of these parameters by themselves is necessarily sufficient to select a launch opportunity. That is, rarely do the minimum C3 and minimum arrival ΔV occur at the same launch and arrival date combination. Fortunately, even at the first-order sizing level, C3 and arrival ΔV do have a direct influence on system cost, which is taken here to be a suitable objective function. The required C3 directly governs the selection of a launch vehicle, and the arrival ΔV governs vehicle gross mass. This paper presents a method of creating pork-chop plots of cost and cost sensitivity for interplanetary missions as a function of payload mass, target orbit maintenance requirements, and engine specific impulse. The context in which this process is presented is a simulated robotic mission to the near-Earth asteroid Apophis.

PROCESS OVERVIEW

The process of creating cost-based pork chop plots for launch opportunity selection consists of combining data from trajectory requirements, mission requirements, and subsystem components in order to calculate mass estimates which drive the costs of the program.

The first step of this process is the generation of standard velocity-based pork chop plots. Two pork chop plots are needed, the first of which shows the C3 required to insert the spacecraft into its escape trajectory. The second plot shows the ΔV required at target arrival as a function of launch and arrival date. The pork chop plots generated for this example are created using MATLAB to solve the Lambert/Gauss problem via the Universal Variable[1] method and ephemeris data downloaded from the Jet Propulsion Laboratory's online HORIZONS system. Figure 1 shows these pork chop plots for the launch opportunity used in this application.

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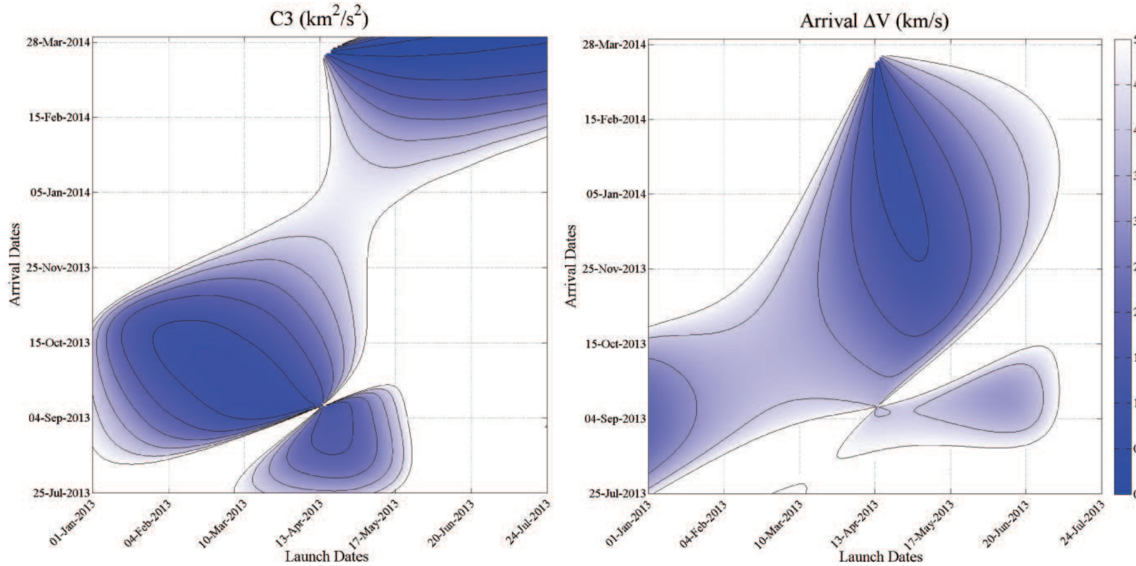

Figure 1. Standard pork chop plots of launch C3 and hyperbolic arrival velocity. Note that for this asteroid problem, arrival velocity is equivalent to arrival ΔV since the spacecraft is required to come to a complete stop relative to the asteroid.

As can be seen in Figure 1, the launch-arrival date combinations for the lowest-C3 launch and the slowest-approach launch do not coincide. The data responsible for the two plots in the figure above show that the optimum launch and arrival date combination is an early-March 2013 launch with a late-September 2013 arrival for the minimum C3 point, but a mid-April 2013 launch with a mid-March 2014 arrival.

Figure 2 below shows how the traditional pork chop plots and other inputs are processed into vehicle mass estimates and ultimately program cost. Vehicle dry mass and gross mass estimates are derived from target-centric arrival ΔV and additional mission requirements of maintenance ΔV, engine specific impulse (I_{sp}), and payload mass. Combining these mass estimates with standard cost models allows program costs to be estimated for any combination of these variables. Each step of the process is detailed below.

Spacecraft Gross Mass Estimation. Spacecraft gross mass is estimated via application of the rocket equation using the dry mass estimated by a historical curve fit based on similar past missions and the arrival and maintenance ΔV values. For this example, the first step is the dry mass estimation, which is based on a payload mass of 53.2 kg from an analysis and preliminary selection of candidate instruments for the vehicle. This results in a dry mass estimate of 478 kg. Spacecraft gross mass is estimated by applying the rocket equation to this dry mass assuming a maintenance ΔV of 300 m/s in addition to the arrival ΔV, propelled by a hypergolic engine with a specific impulse of 309 s.

Launch Vehicle Selection. The lowest-cost launch vehicle which can lift the spacecraft to the specified C3 is automatically selected from an in-house Georgia Tech Space Systems Design Laboratory (SSDL) American launch vehicle database. All costs are converted to FY07 dollars.

DDT&E Cost Estimation. Design, Development, Test, and Evaluation (DDT&E) cost, including the theoretical first unit cost, is estimated using an Advanced Missions Cost Model[2] which has been calibrated to the actual DDT&E costs for the NEAR-Shoemaker mission to the asteroid Eros. This cost is linked to the dry mass of the vehicle and does not depend on the gross mass.

Ancillary Cost Estimation. Integration, Assembly, and Test (IA&T), program management, ground equipment, operations, and software costs are estimated using methods from Larson and Wertz[3]. These costs are strongly linked to the DDT&E cost estimates for the example in this paper.

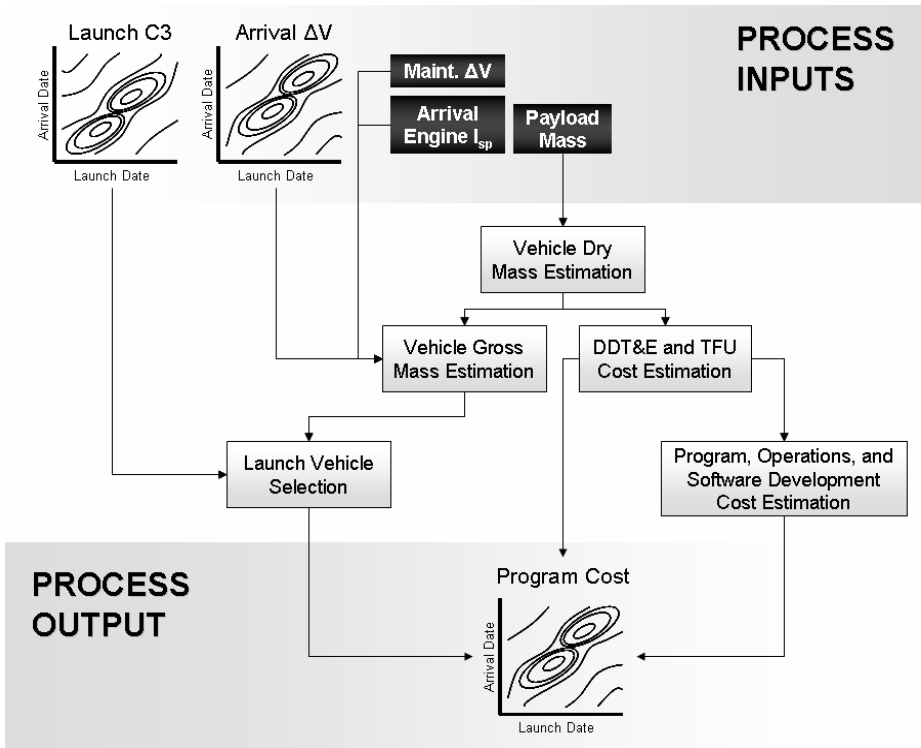

Figure 2. Cost-based pork chop plot development algorithm.

For the example in this paper, the DDT&E and ancillary costs do not change since they are essentially based on the payload mass, which is constant. These figures are $320.3 million and $164.3 million, respectively, and are expressed in FY07 dollars. The total program cost is the sum of the launch vehicle cost, DDT&E cost, and the ancillary costs. Since all costs are constant except for the launch vehicle costs in this example, selection of the launch opportunity becomes the time at which the least expensive launch vehicle may be used.

COST RESULTS

Figure 3 below represents the mission cost as a function of launch and arrival dates subject to the maintenance ΔV, I_{sp}, and payload mass assumptions listed earlier. Note that a clear launch window exists for which the cost is minimized at $388M. This trajectory window covers a launch range of approximately one month and an arrival range of approximately three months. The discrete nature of the lowest-cost trajectory window is due to the ability to launch with the Delta II 7925. The next lowest-cost plateau, which represents a cost of $436M, results from the selection of the Delta IV-M launch vehicle.

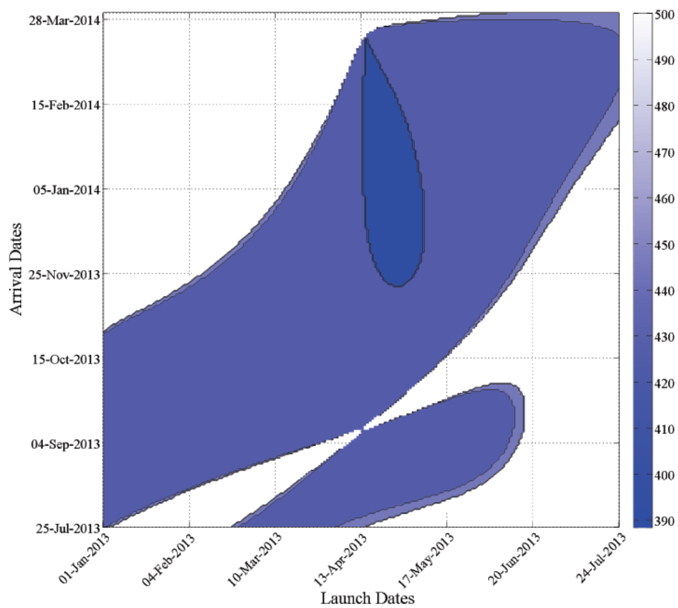

Figure 3. Cost-based pork chop plot of Earth-Apophis transfer in FY07 millions.

One observation to make is that the cost-based pork chop plot resembles (but is not identical to) the arrival ΔV pork chop plot. This indicates the strong dependence on arrival ΔV in this example and a weak dependence on launch C3. The presence of a launch C3 dependence in the cost model affects the shape of the launch window, as does the nonlinear mapping between ΔV and cost inherent in the cost estimation procedure. The disadvantage of this mapping is that the cost function is divided into plateaus due to the discrete nature of launch vehicle selection. Thus, locating plateau borders with certainty is critical to effective cost-based launch opportunity selection.

SENSITIVITY ANALYSIS VIA PROBABILISTIC ASSESSMENT

In order to assess the sensitivity of the cost-based pork chop plot presented thus far, probabilistic assessment is performed assuming that three inputs can be modeled as random variables early in design. The approach used thus far has not captured the uncertainty in the initial assumptions for payload mass, engine and thruster specific impulse, and maintenance ΔV for operations at the asteroid, none of which is well-known in the initial phases of design. The following procedure assigns probability density functions (PDFs) to these assumptions and outputs the probability of meeting a given cost cap for a particular launch and arrival date combination. It should be noted, however, that throughout this process it is assumed that the sizing and cost models are static and deterministic (i.e. uncertainties due to model error are not accounted for; rather, only uncertainties due to assumptions on the inputs to the models are captured).

Selection of Probability Density Functions (PDFs)

Because relatively little is known about the likely values which the input variables may take, simple triangular distributions are used. That is, enough is known to prescribe baseline values and bounds but not much more. Since a most likely value is known, uniform distributions are not considered. Also, since the tails of normal distributions extend to infinity (which could result in nonsensical values for the inputs), these are not considered.

In the case of maintenance ΔV and payload mass, maximum and minimum limits may be prescribed based on engineering judgment. In the case of maintenance ΔV, for this problem it is considered extremely unlikely that this parameter will fall under 200 m/s or over 700 m/s. In the case of payload mass, it is considered extremely unlikely that this will fall under 25 kg or over 75 kg. The modes for the distributions are taken as the baseline values (300 m/s and 53.2 kg, respectively). In the case of engine specific impulse, data on 22 primarily bipropellant hypergolic engines and thrusters in the thrust class for a robotic interplanetary mission are analyzed.[3] The specific impulse distribution of these engines is found to have a mode I_{sp} of 309 s. None of these engines or thrusters is characterized by a steady-state I_{sp} lower than 285 s or higher than 330 s. The distributions utilized are shown in Figure 4.

With the distributions defined, each data point in the launch/arrival date space is evaluated via a 5,000-case Monte Carlo simulation to determine the probability that the cost at that launch/arrival date combination would be less than a specified cost cap. Since the launch/arrival date space in this example consists of 51,250 discrete points, the total number of potential designs evaluated is approximately 256 million.

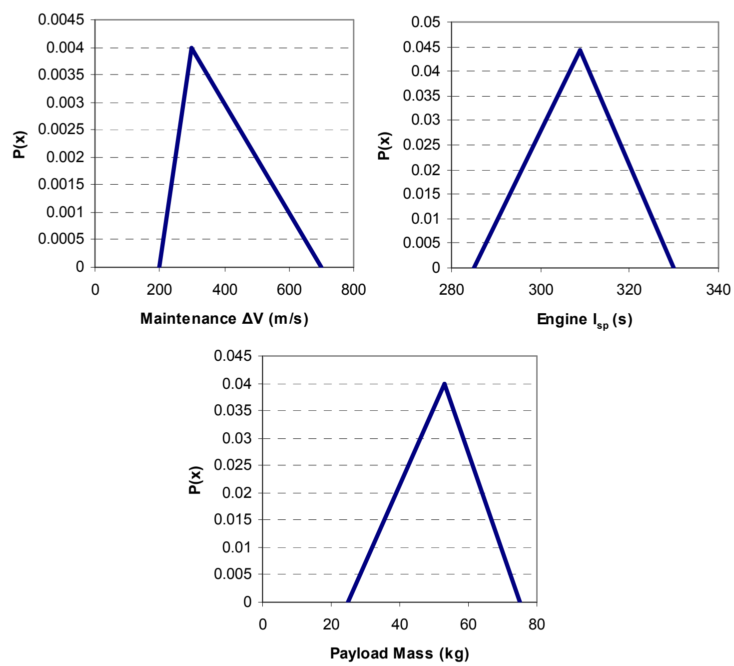

Figure 4. Triangular distributions applied to Maintenance ΔV Required, Payload Mass, and Engine Specific Impulse inputs.

Probabilistic Results

The cost probability plots produced via the above procedure are shown in Figure 5. The contours on the plots are the probability of achieving a given program cost goal ($400M, $450M, and $500M are shown) and are plotted against launch and arrival date in the familiar pork-chop-plot format.

A wealth of information is available from the plots in Figure 5. First, note that only a small region of the launch/arrival date space has a greater than 50% likelihood of success in achieving a \$400M cost target, but that this small region grows many times its size when a \$450M target is imposed. When the \$500M plot is shown, a large swath of launch/arrival date combinations has a 100% likelihood of meeting the cost target. Under a \$500M constraint, one might therefore conclude that any point within this 100% probability space is a reasonable design. However, all else being equal, the more intelligent launch and arrival date selection would be one which also has a substantial probability of coming in under-budget. The more robust mission design would be a late-April 2013 launch with a late-January 2014 arrival since this date combination has the highest probability of success in every cost target plot. The information presented in these probability plots complements the fixed-assumption cost contour plot shown earlier.

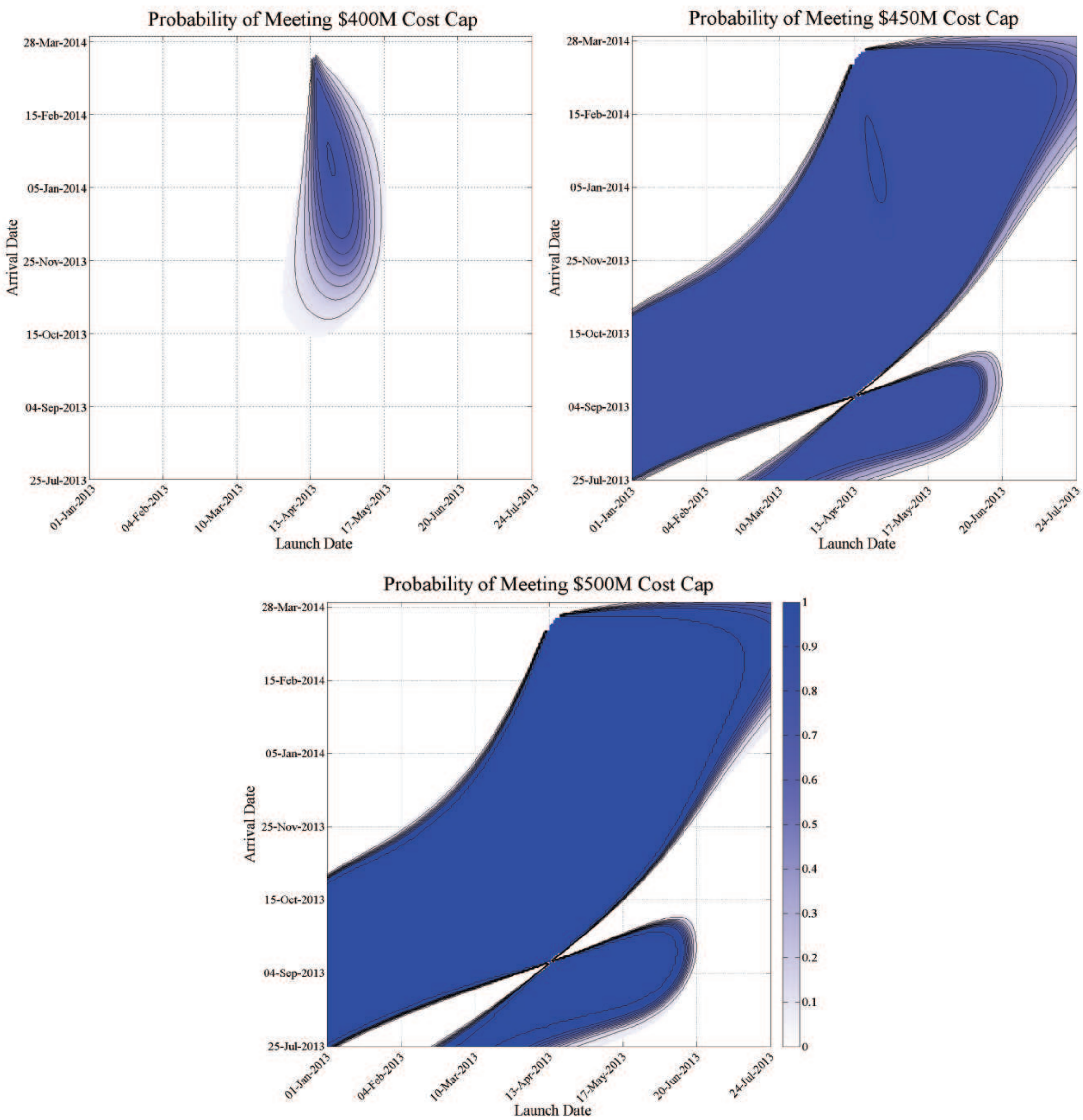

Figure 5. Probability of achieving total program cost goals for \$400M, \$450M, and \$500M cost levels. All costs are in FY07 millions.

One additional note to make is that the shapes of these probability plots resemble the Apophis arrival ΔV plots far more than they resemble the launch C3 plots. However, arrival ΔV plots alone do not allow a designer to approximate program cost, nor can they convey the sensitivity of program cost to launch/arrival date as well as design variables. The use of probabilistic analysis allows rapid assessment of the robustness of a given launch/arrival date range very early in the design process with fairly simple models. In the case at hand, analysis of the probabilistic data shows that the most robust design does not coincide with the optimum slowest approach launch. The most robust design is one with a late-April launch and a late-January arrival while the minimum arrival ΔV launch has a mid-April 2013 launch and a mid-March 2014 arrival. Confidence in the robustness of a given solution is gained with the sizing and costing of millions of (in this case, 256 million) potential designs. Furthermore, since cost data can be regenerated fairly quickly (in this example, 256 million cases were assessed by a single PC over a period of only six to eight hours), changing assumptions can be rapidly incorporated into the decision-making process.

CONCLUSIONS

One of the most important metrics in assessing the viability of an interplanetary robotic mission is total program cost. During the early phases of the design process, standard velocity-based pork chop plots are easily created while cost can be difficult to estimate. The process presented in this paper combines standard velocity-based pork chop plots with mission requirements to generate cost-based pork chop plots. This leads to pork chop plots with discrete cost plateaus due to varying costs of launch vehicles. These pork chop plots provide a quick method of determining the most viable launch/arrival window for a given mission. Sensitivity analysis via probabilistic assessment then allows the engineer to determine the region within each cost plateau which will result in the highest probability of meeting a given cost cap. A major advantage of this method is that it allows the engineer to choose a launch window with a high probability of meeting a cost cap earlier in the mission design phase. Another important advantage of using this method is the quick runtime and the speed with which changes in assumptions can be implemented.

The method presented can be improved upon by eliminating the assumption of a single-point launch (i.e. a launch on a single date and arrival on a single date with no schedule margin). If a minimum launch window length is imposed, the mission must be sized to accommodate the maximum ΔV and C3 during the given window length. Including this in the modeling process would create a more realistic method of locating cost plateaus and, ultimately, regions within the plateaus with the highest probability of meeting a given cost cap. Additionally, while this method accounts for uncertainties in mission requirement inputs, it neglects model error. In reality, model error is a factor that must be accounted for. As such, it is important to verify model accuracy for a given application or to modify models to include probabilistic uncertainties. Modifications such as these could further improve this method as a valuable addition to the mission designer's toolbox, allowing for selection of robust, low-cost launch/arrival opportunities during the earliest stages of interplanetary mission design.

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