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Alternative Launch Site Selection

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Abstract. Due to circumstances beyond its control, Lockheed Martin's Athena Small Launch Vehicle Program is being forced to relocate from the current Space Launch Complex (SLC) 6 at Vandenberg AFB, CA, to an alternate location. The objective of this study is to recommend highly favorable launch sites to Lockheed Martin Astronautics management for further development. We develop and use a hierarchical, multiobjective value model, to analyze and evaluate alternative launch sites capable of performing SLC-6 polar orbiting missions, as well as future easterly launches.

Background

The Athena Launch Vehicle, previously known as both the Lockheed Launch Vehicle and the Lockheed Martin Launch Vehicle, uses SLC-6 at Vandenberg AFB, CA for launches requiring polar and retrograde orbits. Through early 1998, two launch operations had been conducted at SLC-6, and two more were scheduled at SLC-6 through the end of the calendar year 1998. SLC-6 was originally built for the Manned Orbiting Laboratory Program, was later converted to support the DYNOSOAR Program, and was modified in the 1980's to launch Space Shuttle missions from the West Coast. After the Challenger accident in 1986, the site was turned over to the Air Force's 30th Space Wing for maintenance. This site was inactive until the creation of the Athena program in early 1994, when SLC-6 was leased from the Air Force for Athena's commercial launch operations. The original lease structure permitted Athena to launch at SLC-6 through the fiscal year 1999. Options to extend beyond the initial term required 30th Space Wing approval. However, after signing the lease, the Air Force made additional commitments to McDonnell Douglas (now Boeing) for the use of SLC-6 should their Evolved Expendable Launch Vehicle (EELV) contender win the contract. In February 1998, the Air Force decided not to downselect to a single EELV launch provider, and therefore awarded EELV contracts to both Lockheed Martin and Boeing. This chain of events led to Athena's impending eviction from SLC-6. To further complicate the situation, the Athena program managers had submitted proposals on up to 15 launch contracts, many of which require orbits similar to that which SLC-6 provides. In order to maintain schedule and technical credibility a replacement launch site had to be selected, prompting the necessity for this study.

Multiobjective Value Analysis

In choosing among the available analysis alternatives, we considered the trade-off between depth of analysis and time. We selected multiobjective value analysis as most appropriate (Kirkwood, 1997; Keeney, 1992; Keeney and Raiffa, 1976). It allowed us to evaluate the alternatives at an appropriate level of detail and within the time available. To use multiobjective value analysis, we had to create a value model to evaluate the qualities of the alternatives. In this analysis, the alternatives were the potential launch sites to replace SLC-6, and the qualities were the evaluation considerations and evaluation measures that collectively constitute the operational effectiveness of the launch sites. For each evaluation measure, we specified a measurement scale and developed the associated single dimensional value function to assess the incremental value of each level on the measurement scale. Finally, weights were specified for each single dimensional value function and an overall multiobjective value function was developed. The form of this function was a weighted sum of functions over each individual evaluation measure.

Program management assembled a four-member project team, with membership having backgrounds in one of the following areas: Logistics, Operations, Systems, and Safety. Prior to conducting site surveys, inputs were received from each of the team members on the evaluation measures and weighting system to be used for the study. The authors then synthesized these inputs and created the study baseline, which was then redistributed to the team for review and comment. After consolidation of the final review comments, group consensus was obtained for the final measures and scales contained in this study.

Objectives and Value Structuring

The basic issues that must be addressed in dealing with objectives for a decision analysis are (i) determining what is important, and (ii) establishing how to measure how well the various decision alternatives perform with respect to the "important things" (Kirkwood, 1997). The qualitative elements of the launch site selection problem took the form of the value hierarchy (Figure 1), which included the primary objective at the top (select the best alternative launch site) and specified five evaluation considerations – the significant criteria to consider when comparing alternatives – at the lower level.

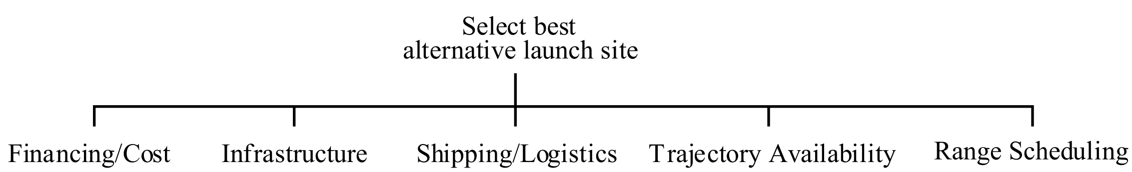

FIGURE 1. Athena launch site selection value hierarchy.

Evaluation Considerations

To ensure the evaluation considerations were communicable to program decision-makers, definitions of each criterion were developed and specific, quantifiable evaluation measures were identified. In the process, some evaluation criteria that were initially included in the model were either consolidated or eliminated from the study. For example, Communications was thought to be an important area for consideration; further review revealed that this would be adequately measured under the Infrastructure criterion. In addition, Shipping and Logistics were originally separate evaluation criteria; however, combining the two was a logical choice for the assessment team.

- **Financing/Cost** was defined as the level of investment required by the corporation to make the launch site ready to conduct launch operations.
- **Infrastructure** referred to status of facilities at the launch site (i.e. launch pad, payload processing facilities, hazardous processing areas, etc.), which were deemed compatible with established Athena launch operations requirements.
- **Shipping/Logistics** evolved into the amount of time required to ship rocket motors from their respective production facilities to the launch site; indirectly, this also addressed the method of motor shipment.

- **Trajectory Availability** considered the variety and types of orbits attainable from a launch site.
- **Range Scheduling** addressed the scheduling philosophy of the host launch range, and its associated impacts on a commercial launch vehicle program.

Weights

After much discussion regarding the weights w_i for each evaluation consideration, Financing/Cost, Trajectory Availability, and Range Scheduling were determined to be equally important, and thus received identical weights of 26.67% each. Of lesser importance was Infrastructure and Shipping/Logistics, which were also equally weighted at 10% each.

Measurement Scales and Single-Dimensional Value Functions

Measurement scales for each evaluation measure provided a scoring vehicle to accurately assess the capability and compatibility of each launch site with respect to the evaluation criteria. As each alternative launch site would receive a score X_i on each evaluation measure *i*, descriptive definitions for each level on the scale were developed. The relative importance – or incremental value – of each score was then assessed through a piece-wise linear single dimensional value function, where $V_i(X_i)$ represents the value function for the i^{th} evaluation measure. These single dimensional value functions provided the additional benefit of normalizing all evaluation measure scores to a common 0-1 scale.

The Financing/Cost criterion was determined to have four associated levels: *None, Minimal, Significant,* and *All* (Figure 2). *None* was defined as no money made available from external sources to build and activate the launch site, and received a value of 0 (e.g., $V_F(X_F = None) = 0.0$). A *Minimal* score implied that less than 50% of the total costs for site construction and activation would be borne by other agencies, and was valued at 0.2. *Significant* funding required 50 – 75% of the total costs be provided by sources external to the Athena program; this was perceived to be the most significant increase in value for the Financing/Cost criterion, and as such received a value of 0.8. Finally if other interested parties provided all funding, the site would be assessed with an *All* rating and a value of 1.0.

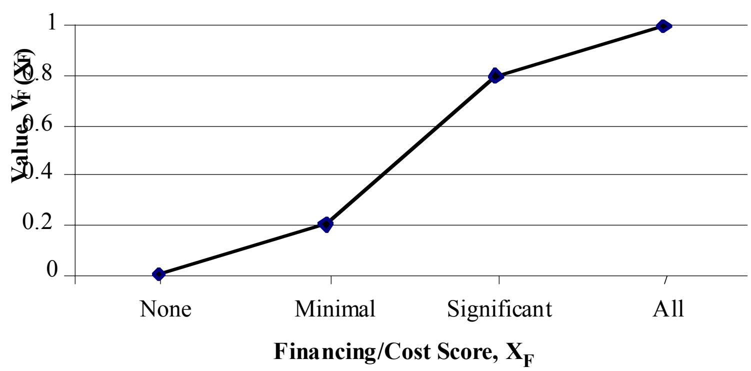

FIGURE 2. Single dimensional value function for the Financing/Cost evaluation criterion.

The measurement scale for Infrastructure was defined similar to Financing/Cost. Four possible levels of X_I were attributed to this criterion*: None, In Construction, Existing,* and *New*. If a site had no Athena-compatible facilities readily available, then a rating of *None* was assessed, with a value of 0. The other levels were given values of 0.3, 0.6, and 1.0, respectively. A *New* rating would only be achieved if the facilities were already complete at the time of this study; future site readiness was beyond the scope of this study.

Shipping/Logistics addressed directly the length of time required for flight hardware to be transported from the manufacturing facility to the launch site; indirectly, the method of shipment was also addressed. The scores X_S for this criterion were also broken down into four levels: *28+ days using sea lift capability* (value 0), *up to 28 days using sea lift* (value 0.1), *7-10 days using sea lift or rail capability* (value 0.8), and *less than 1 day using airlift* (value 1.0). Since more options were available, the value increment was greatest from the 28-day level to the 7-10 day level for Shipping/Logistics.

The Trajectory Availability criterion analyzed the potential orbits reachable from each launch site. Once again, four levels of X_T were used in the study: *Polar Low(60° i) OR High (120°i) Inclination* (value 0.1), *Polar Both* (value 0.4), *Polar Both plus restricted Easterly* (value 0.7), and *All* (value 1.0). For a site to receive the All rating, no flight paths would be restricted due to overflight of populated areas or land impacts of separated stages.

Finally, the Range Scheduling criterion observed the launch scheduling philosophy of each alternative site. A launch site scheduled through the *Department of Defense* received a value V_R (X_R) = 0, while *a State Spaceport at a DoD site* received a value of 0.2. For launch sites where military/government and commercial launches were given equal status, a *Coexist* rating and value of 0.7 was documented. A value of 1.0 was given for a site *with Complete Commercial* focus in launch and test scheduling.

Value Function

With the single dimensional value functions and weights established, each alternative's final value can be determined by multiplying its evaluation measure value by the appropriate weight and summing over all evaluation measures,

$$v(X_F, X_I, X_S, X_T, X_R) = \sum_i w_i V_i(X_i) \quad . \qquad (1)$$

We assumed that the value model was linear, and our assessments showed that the required additive independence conditions (Keeney and Raiffa, 1976) were approximately met. Therefore, there were no interaction (nonlinear) terms among the evaluation measures.

Alternatives

The Athena program management proposed the alternatives under consideration in this study: Kwajalein Missile Range, Republic of the Marshall Islands; Vandenberg AFB, CA; Kodiak Island Launch Complex, AK; Wallops Flight Facility, VA; Cape Canaveral AS, FL; Kourou, French Guiana; and Alcantara, Brazil. Significant data was gathered on all potential candidate launch sites to ensure that the alternatives received equal attention and study. Prior to discussion on the scoring for each launch site, some additional background information on the alternative sites should be mentioned:

- The **Kwajalein Missile Range** (KMR) is operated by the US Army at Kwajalein Atoll in the Republic of the Marshall Islands. KMR is located approximately 2,500 miles to the west of Hawaii in the Central Pacific Ocean.

- **Vandenberg AFB, CA** has three potential replacement sites for SLC-6: SLC-3W, an old Atlas launch site; SLC-4W, an old Titan launch site; and SLC-7, a new commercial launch site which is still in the early phases of construction. For this analysis, these alternatives have been consolidated into one launch alternative, as all three have similar characteristics for the analysis.

- **Kodiak Launch Complex, AK** located 40 miles southwest of Kodiak, AK, is a commercial launch site being developed by the Alaska Aerospace Development Corporation. Funding for the site is being provided by the Air Force, NASA, and the State of Alaska. Current construction schedules show site completion to occur no later than December 1999, with initial launch capability due by April 2000.

- **Wallops Flight Facility, VA** is an existing NASA launch site located on the Virginia Peninsula approximately 50 miles south of Ocean City, MD. The Virginia Commercial Space Launch Authority, in conjunction with NASA, is developing a new commercial launch complex (Pad 0-B) which will be compatible with Athena I and II requirements. This site is scheduled to be activated by the end of 1999, with initial launch capability in early 2000.

- **Space Launch Complex 46**, **Cape Canaveral Air Station, FL**, is maintained by Spaceport Florida, through agreements with the Air Force and Navy. Spaceport Florida is a state-funded organization which was established to attract new commercial launch business to the Space Coast region. The Athena program has conducted one successful Athena II launch from SLC-46 on 6 Jan 98 (the Lunar Prospector mission for NASA). Two additional launches are currently scheduled from SLC-46, in December 1998 and September 1999.

- The European Space Agency (ESA) conducts Ariane 4 & 5 launch operations from **Kourou, French Guiana** in South America. One of the deactivated Ariane launch pads is under consideration by ESA for renovation and reactivation by an Athena-compatible launch vehicle program. Existing facilities which support Ariane operations could be used for Athena processing and operations, on a non-interference basis.

- The final launch site under consideration in this study is the **Alcantara, Brazil** site being developed by the Brazilian government. One indigenous launch has been performed at Alcantara. However, the existing launch facility is not presently compatible with the Athena vehicle and would require modifications.

Two additional launch sites – Andoyo, Norway and Christmas Island, Kiribati – were considered at the beginning of the study but were deleted from the analysis, primarily due to a lack of data and management interest. These sites would also require significant financial commitment from the Athena program without potential for profit through 2001, making these alternatives unattractive.

Analysis

Each alternative was scored against the evaluation measurement scales, and an overall score was obtained according to the multiobjective value analysis methodology of Equation (1). The scores for each alternative on the five evaluation measures are in Table 1, and the weighted single dimensional values and overall multiobjective value for each alternative launch site are shown in Table 2. The overall multiobjective values of the Kodiak and Wallops launch sites are far above those of the other alternative sites. The results for the existing SLC-6 launch site were added at the request of Athena program management, and are useful for reference to the current environment.

TABLE 1. Alternative Launch Site Scores

Launch Site	Financing/ Cost	Infrastructure	Shipping/ Logistics	Trajectory Availability	Range Scheduling
Kwajalein	None	None	28+	Polar Both + East	DoD

Kodiak	Significant	In Construction	7-10	Polar Both	Commercial
Vandenberg	None	Existing	7-10	Polar Both	DoD
Wallops	Significant	Existing	7-10	Polar Both	Coexist
Brazil	Minimal	In Construction	Up to 28	Polar Both + East	State
Kourou	None	Existing	Up to 28	Polar Both + East	State
Cape Canaveral	Minimal	Existing	7-10	Polar Both	DoD
SLC-6	Significant	Existing	7-10	Polar L or H	DoD

TABLE 2. Alternative Launch Site Weighted Single Dimensional Values and Overall Value (sorted by overall value)

Launch Site	Financing/ Cost	Infrastructure	Shipping/ Logistics	Trajectory Availability	Range Scheduling	Overall Value
Kodiak	0.213	0.03	0.08	0.107	0.267	**0.697**
Wallops	0.213	0.06	0.08	0.107	0.187	**0.647**
SLC-6	0.213	0.06	0.08	0.027	0	**0.380**
Brazil	0.053	0.03	0.01	0.187	0.053	**0.333**
Kourou	0	0.06	0.01	0.187	0.053	**0.310**
Cape Canaveral	0.053	0.06	0.08	0.107	0	**0.300**
Vandenberg	0	0.06	0.08	0.107	0	**0.247**
Kwajalein	0	0	0	0.187	0	**0.187**

The Kwajalein site would require Athena to provide all funding for launch pad construction. No current facilities exist which would rapidly be converted for launch operations. Present shipping methods for rocket motors would require ocean-faring barges to sail at least one month from the West Coast to the Marshall Islands. Available trajectories from Kwajalein include all polar and some easterly launches. Finally, DoD missions would maintain scheduling priority over commercial missions. These assessments lead to the overall value of 0.187 for Kwajalein.

The Kodiak Island Launch Complex has received $30 million in funding from the aforementioned sources to build launch-processing facilities; minimalprogram investment would be required. The site is in construction, and barges can deliver motors to the site within 10 days from Seattle to Kodiak. Polar launches can be conducted to a wide variety of trajectories from the commercial range at KLC, leading to an overall value of 0.697 for this alternative.

Vandenberg AFB is an Air Force Space Commandoperated launch site; DoD exercises and missions are given significant scheduling preference over commercial launches. Moving from SLC-6 to an existing launch site with built-in infrastructure would require all modifications to be funded by Athena. Presently, motors are shipped by trailer to Vandenberg within 7 days from the manufacturing plant. Polar launches are typically conducted from Vandenberg. In sum, this launch alternative is valued at 0.247.

Pad 0-B at Wallops is currently being funded through grants from NASA. Minimal non-recurring investment would be required by Athena, and existing facilities can be utilized for processing activities. Motors can be shipped by rail to the launch site within 10 days. A limited amount of easterly and highly inclined launch trajectories can be obtained through operations from Wallops, which operates as a commercial launch site. These factors lead to the overall site value of 0.647.

Brazil and Kourou are essentially similar launch sites, with minor differences in Financing/Cost and existing Infrastructure. Both sites would require barges to traverse the Panama Canal for motor shipment, a trip of longer than 30 days. In addition, both sites provide access to a mix of polar and easterly launches. However, both sites would give preferential treatment to the indigenous programs for test and launch scheduling. Thus, the overall values for Brazil and Kourou are 0.333 and 0.31, respectively.

Finally, SLC-46 at Cape Canaveral is located on a Space Command launch range, providing DoD launches with higher scheduling priority for launches and tests. The launch site already exists, and motor shipment can be effected through rail transport within 7 days. Only limited easterly launches are available at the Cape. Summarily, the overall value for the Spaceport Florida launch site is 0.3.

Based on the established criteria and weighting system, Kodiak and Wallops would appear to be at least twice as beneficial to the Athena program as any other alternative, including the presently used launch sites. The existing launch pad at SLC-6 would be the third most preferred site in the analysis; however, this option has been eliminated as previously addressed. In order to ensure that the analysis is not weighted incorrectly, a sensitivity analysis must be performed on each criterion.

SensitivityAnalysis

Sensitivity analysis, conducted by varying each criterion's weight between 0 and 1, revealed the robustness of the initial results. For example, Figure 3 shows the results of the sensitivity analysis for the weight on the Financing/Cost evaluation criterion. Kodiak and Wallops are far and away the outstanding alternatives, regardless of the weight assessed for this criterion.

In similar analysis of the sensitivity to changes in the Infrastructure weight, Wallops was the favored launch site across the entire range of weights, while Kodiak remained near the top of the alternative list for weights less than or equal to 0.6. Vandenberg, Cape Canaveral, and Kourou became more preferable than Kodiak once the importance of Infrastructure exceeded 0.6. Similarly, Kodiak and Wallops were also preferred for any weight on Shipping/ Logistics; Vandenberg and the Cape were equal with Kodiak and Wallops only when the importance of Shipping rose to 100% of the overall score for the study. Further, for Trajectory Availability weights less than or equal to 0.6, Kodiak and Wallops were once again the front-runners; Kwajalein and Kourou became the preferable alternatives for weights of 0.6 or higher in this category. Finally, for all weights of Range Scheduling, Kodiak and Wallops were significantly rated higher than the other alternatives.

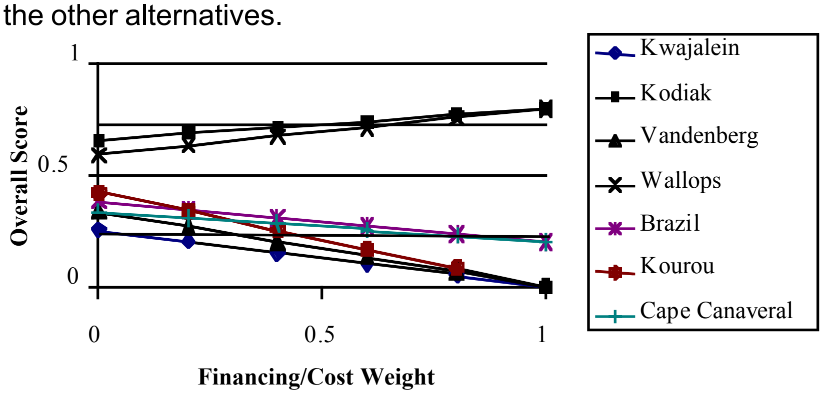

FIGURE 3. Sensitivity analysis on Financing/Cost weight, (w_F)

Therefore, assuming that neither the Infrastructure nor Trajectory Availability weights approach 0.6 or higher, the sensitivity analysis reveals two conclusions: 1) corroboration of the robustness of the initial value analysis conclusions; and 2) Kodiak and Wallops are significantly more advantageous than the other alternatives.

Conclusions

Without question, the analysis indicates that the most favorable alternatives for consideration by Athena program decision-makers are Kodiak and Wallops. The Kodiak Launch Complex is the recommended replacement for the SLC-6 launch site, as the polar launch capability needs to be replaced as soon as possible. However, in a new development that arose shortly after the completion of this analysis, the Athena program was being considered as the launch service provider for a commercial communications satellite company. Award of this launch service contract would require nine launches from Wallops Flight Facility starting in early 2000. The results of this analysis gave program management increased confidence in the suitability of Wallops as a future base of launch operations to meet the continuing and new launch contract obligations.

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