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Concept Exploration of an Australian Indigenous Space Launch Capability

Anthony J. Rogers

CONCEPT EXPLORATION OF AN

AUSTRALIAN INDIGENOUS SPACE

LAUNCH CAPABILITY

THESIS

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List of Acronyms

$$	Overall Program Dollars
%I	Percentage Indigenous
%R	Percentage Reusable
ACT	Australian Capital Territory
ASC	Australian Space Council
ASO	Australian Space Office
AUSD	Australian Dollars
CE	Concept Exploration
COSSA	CSIRO Office of Space Science and Applications
CRCSS	Cooperative Research Centre for Satellite Systems
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Dur	Program Duration
ELDO	European Launcher Development Organisation
ETB	Elevated Technology Base
ESA	European Space Agency
FedSat-1	Federation Satellite 1
IEEE	Institute of Electrical and Electronic Engineers
GTO	Geo Transfer Orbit
IC	Initial Condition
I_{SP}	Specific Impulse
IV	Independent Variable
Lat	Latitude
LEO	Low Earth Orbit

Long	Longitude
MF	Mass Fraction
NASA	National Aeronautics and Space Administration
NSP	National Space Program
PA	Political Advancement
PMF	Payload Mass Fraction
R&D	Research and Development
Sec	Security
TM	Launch Vehicle Total Mass
UK	United Kingdom
US	United States
USA	United States of America
USD	United States Dollars
WRESAT	Weapons Research Establishment Satellite

Abstract

Currently there are only nine countries with a space launch capability, relatively few considering the importance and prestige of such an ability. Although Australia has played an important role in the development and exploration of space from the beginning, it has failed to capitalise the potential benefits of having its space program. This thesis endeavours to explore the possibility of establishing an Australian indigenous space launch capability through developing and examining an Australian space launch program model. The model is based around launch site location, vehicle design, program duration, and the percentage Australian indigenous input into the space launch program. This model was optimised in an effort to maximise the benefits of such a capability, namely political prestige, security and in-country technological base, while minimising the program's overall cost. Through this concept exploration, sound judgements can be made on whether or not to proceed to the next systems engineering step – Preliminary system design.

CONCEPT EXPLORATION OF AN AUSTRALIAN INDIGENOUS SPACE LAUNCH CAPABILITY

CHAPTER 1 Introduction

Australia has played an important role in the development and exploration of space right from the earliest days of the space race. It was the fourth country in the world to launch its own sovereign made and launched satellite (WRESAT-1 – 29 Nov 1967) [1]. However, post mid 1970 Australia has failed to capitalise on its early involvement in the development and use of space.

Recently the Australia government enacted the Space Activities Act 1998 to regulate commercial space launch operations in Australia [2]. There are presently five proposals for launch facilities in Australia, and the launch industry is likely to generate up to $900 million in net exports and an average of 2,000 new jobs over the coming decade [3].

None of the five proposals plan to establish in Australian a capability to construct, manage and launch a truly indigenous system. Instead they propose turnkey commercial launch solutions using overseas launch systems and expertise, with Australia purely as the launch site. While there are certainly many benefits of such a plan, it does not provide Australia with a launch capability under sovereign control.

1.1 Purpose of Thesis

The primary goal of this thesis is to explore the possibility of establishing an Australian indigenous space launch capability. This is accomplished by first introducing the reader to the history behind Australia's involvement in space and what its plans are for the future. The systems engineering approach is outlined in Chapter 2 along with a detailed breakdown of the space launch program model. Chapter 3 contains the results of optimising the model and is concluded by an analysis of these results.

1.2 History of Australia's Involvement in Space

Australia first became involved in the space race through the Anglo-Australian Joint Project agreement that resulted in the formation of the Long Range Weapons Establishment at Woomera, South Australia on 1 Apr 1947 [4]. Over the course of thirty years some sixteen missile/rocket systems were launched from Woomera including the "Australian" Sparta launcher (using a modified US Redstone rocket), the British Black Arrow, and the European Europa.

Use of Woomera as a space launch facility can be broken into three main and separate participators, the Australian contingent, the United Kingdom, and the European Launcher Development Organisation.

1.2.1 The Australian Government's Space Launch history

Australia's space heyday in the twentieth century lasted for under two months culminating with the launch of the WRESAT-1 small scientific satellite on 29 Nov 1967, making Australia the fourth nation to send a satellite into space. WRESAT-1, a 45 kg payload constructed by the University of Adelaide in 11 months for a total cost of \$250,000, completed 642 orbits and collected solar radiation and upper atmospheric data for 73 of those orbits [5]. However, two subsequent launch attempts in July 1969 and June 1970 failed to reach orbit and the program was abandoned.

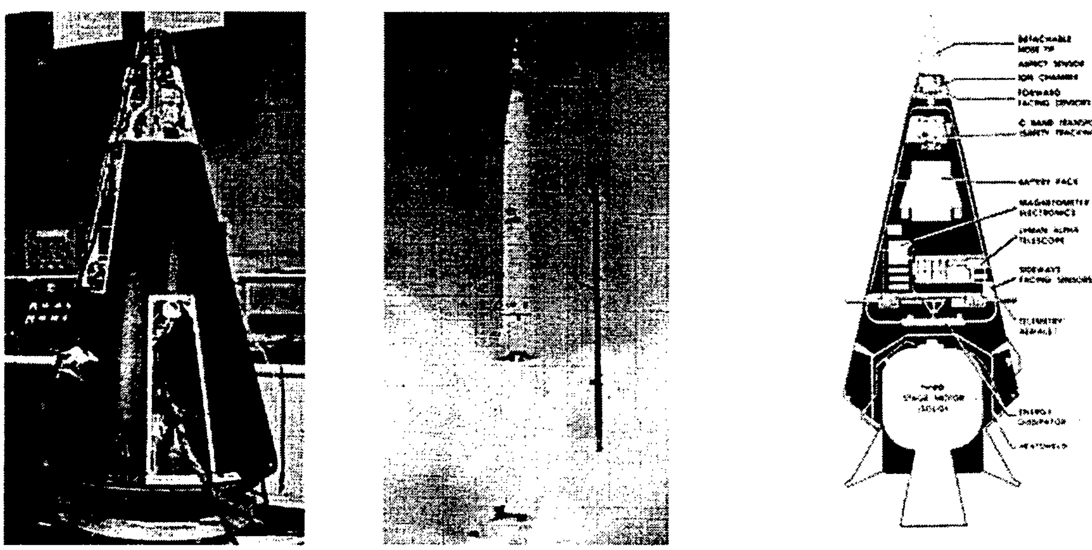


Figure 1-1 WRESAT-1 [6]

The first non-US radio amateur satellite, OSCAR-5, also known as Australis, was built by the University of Melbourne and launched by NASA for free on a Thor-Delta rocket on 23 January 1970. Then followed a lull in Australian indigenous space activities for the next two decades.

In 1996, the Minister for Science and Technology announced the commencement of a small space application demonstration project, which would be funded jointly by the federal government and industry [7]. The aim of the program was to demonstrate national capabilities to both its own people and to the world market. To ensure adequate funding, the program was linked to the Centenary of Federation in 2001 and was given the title Federation Satellite 1 (FedSat-1). FedSat-1 is due for launch from a Japanese H-IIA Launch Vehicle in November 2001.

1.2.2 International Ventures Within Australia

The European Launcher Development Organisation, ELDO, the predecessor of the European Space Agency, ESA, was established to provide Europe with a satellite launch vehicle. At the time Australia was the only non-European member of the alliance providing the launch facilities at the Woomera Prohibited Area. The project was divided into three phases, totalling ten launches.

Phase 1 (1964-65) saw three successful launches of the first stage, launching toward Talgarno in North-western Western Australia. In phase 2 (1966-67) only one of the four two-stage rocket launches was successful, with the launch direction due North into the Simpson Desert. Phase 3 (1967-70) consisted of four planned orbital launches. The first two exploded and the third was successful, however, the satellite failed to orbit. The fourth launch was cancelled. ELDO finally decided to shift launch locations to the French site Kourou, in French Guiana, now home to ESA's Ariane launches [8].

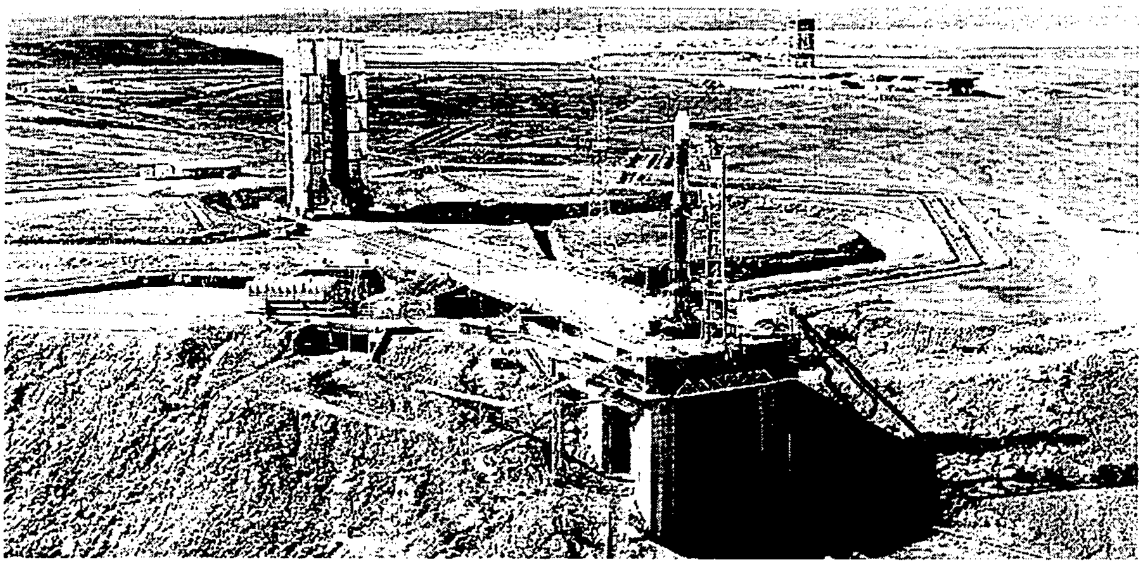


Figure 1-2 ELDO Launch Range at Woomera

The United Kingdom tested its Black Arrow Rocket at the Woomera Prohibited Area between 1969 and 1971. On 28 October 1971, the fourth and last flight of the Black Arrow program, the UK became the sixth country to successful orbit the earth with a satellite.

1.2.3 Satellite and Exploration Tracking Support

Australia has played an important role in support of United States Space exploration programs. Although this capability is completely different from achieving access to space, the history provides an interesting insight into Australia's willingness to get involved.

Australia joined the United States Space program in 1957, with the aim of providing tracking support to US operations. An initial station was established at Woomera to provided coverage to the Explorer and Vanguard programs and In 1960 the Governments of Australia and the US formally agreed to co-operate in space flight programs being conducted by the US and a ten-year agreement was signed.

Another station was established at Muchea, near Perth, in 1960 and the Woomera radar at Red Lake was installed the same year. These two stations were both used to support John Glenn's orbital flight in 1962. A station capable of deep space tracking was next established at Island Lagoon, near Woomera, which supported NASA's Mariner II probe to Venus in 1962. A large station was established at Carnarvon, Western Australia, in 1963, to replace the smaller Muchea station, and it supported NASA's Gemini and Apollo programs. The station was closed in 1975 upon completion of the Apollo program [9].

NASA then notified Australia of the need for four or five stations located on the east of the continent, to support manned and deep space programs. This led to the building of several tracking stations in the Australian Capital Territory, ACT. After extensive surveying by Australian Weapons Research Establishment staff and NASA, several sites in the ACT were chosen with the first station, the Deep Space Instrumentation Facility, completed at Tidbinbilla, to the south west of Canberra. Under the US/Australia agreement the US agreed to meet most of the operation costs, with Australia contributing $140,000 a year, the cost of local support at the time.

A second station in the ACT, at Orroral Valley, was opened in 1965. A 26-metre antenna was erected and operated 24 hours a day, seven days a week, supporting a variety of satellites in orbit. The main requirement of this station, as distinct from the long-range communications functions of Tidbinbilla, was to be able to switch quickly from supporting one satellite to another. Signals received from satellites in Earth orbit are relatively strong but the view period may be extremely short, often lasting only a few minutes. Shortly after completion, additional equipment was installed at Orroral Valley to enable the tracking of four satellites simultaneously. A Minitrack Station from Woomera was moved to Orroral in 1967, enabling the time of meridian crossing to be detected precisely [10].

A third ACT station at Honeysuckle Creek was opened in 1967. A 26-metre antenna was erected and the station was officially opened by the then Prime Minister the honourable Harold Holt. The station's role was to handle communications with astronauts on the Moon and receive their television and radio transmissions. The first mission Honeysuckle Creek supported was the Apollo 4 unmanned test flight in November 1967. The last manned mission supported by the Honeysuckle Creek station was Skylab, the manned space station. In 1979, NASA announced a plan to consolidate the Deep Space Network and the station was closed in November 1981 with the residual tasks transferring to Orroral Valley and Tidbinbilla. Inline with the consolidation plan, NASA relocated the 26-metre antenna from Honeysuckle Creek to Tidbinbilla. The move was completed by August 1984 [11].

Although, at one stage, Australia operated six NASA space tracking and communication stations, the only remaining major station is the Canberra Deep Space Communications Complex at Tidbinbilla. This facility operates an eleven metre dish, two thirty-four metre dishes, and a seventy metre dish forming part the deep space communications network in conjunction with the deep space tracking facilities in Madrid, Spain and Goldstone, USA.

Figure 1-3 Canberra Deep Space Communications Complex, Tidbinbilla [12]

1.2.4 Australian Government Space Agencies

The Australian Federal Government established the Australian Space Office, ASO, in 1985 to coordinate the National Space Program, NSP. This agency operated on a small budget of roughly $4 million Australian per year for a total of $30.2 million between 1985 and 1992 [7]. Operating separately to the ASO was a branch of the Commonwealth Scientific and Industrial Research Organisation, CSIRO, known as the CSIRO Office of Space Science and Applications, COSSA. Formed in 1984, COSSA's focus was on national and international space science activities and earth observation.

Following the 1992 Curtis review of the NSP, the federal government formed the Australian Space Council, ASC, to review and comment on international and national space endeavours. At the start of 1996, an interdepartmental committee recommended that, on an economic basis alone, Australia should enhance its commitment to space endeavours and increase federal expenditure by $20 million Australian per year [7].

The Australian Institute of Engineers took the 1996 report as an opportunity to attack the government saying, *"that a local space industry has failed to flourish because Australian companies had no significant domestic space programs on which to build a critical mass of expertise and support"* [7]. The Institute closed its attack by pointing out that Australia was spending over $600 million Australian per year for overseas space services.

Following a June 1996 full review of the NSP by the incoming Government, all funding was terminated despite six favourable government reports over the previous decade and the existence of both the ASO and ASC. Both the ASO and ASC were disbanded and replaced by a much smaller organisation, the Australian Space Policy Unit, within the Department of Industry, Science and Resources.

On 10 July 1997, the Minister for Science announced the formation of the Cooperative Research Centre for Satellite Systems, a subsidiary of COSSA, whose mission statement is *"To deliver a new, sustainable advantage for Australian industries and government agencies involved in services based on the applications of future generations of small satellites"* [13].

The 1997-98 federal budget allocated $0.7 million Australian to the NSP along with $20 million Australian for the small space application demonstration project, FedSat-1. It is interesting to note that this celebration of Australia's centenary of federation, and Australian science and industry resourcefulness will be launched aboard a Japanese H-II rocket from Japanese soil.

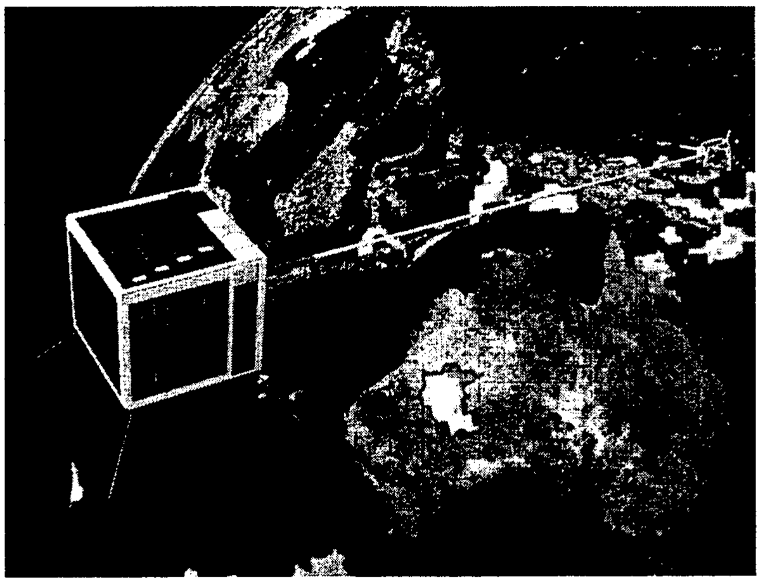


Figure 1-4 Artist Rendition of FedSat-1 in Orbit [14]

CHAPTER 2 Methodology

2.1 The Systems Approach

The Institute of Electrical and Electronic Engineers, IEEE, defines that the fundamental objective of systems engineering is to *"provide high quality products and services, with the correct people, and performance features, at an affordable price, and on time"* [15]. The Institute goes on to say that *"this involves developing, producing, testing, and supporting an integrated set of products (hardware, software, people, data, facilities, and material) and process (services and techniques) that is acceptable to customers, satisfies enterprise and external constraints, and considers and defines the process for developing, producing, testing, handling, operating, and supporting the products and life cycle processes."* [15]. The objective is achieved by concurrent treatment of both the product and the process, focusing project design decisions and resources on the formation of an effective system design. [15]

This product and process amalgamation covers the entire product life cycle. From the moment of the inception of an idea or need to its demise, the idea/need follows a natural course of development. Through the application of systems engineering, the product-process amalgamation and the interdisciplinary tasks required throughout the system life cycle are formalised in an effort to provide the most effective system design.

The life cycle can be broken down into six phases:

Concept Exploration, CE, the initial study phase that results in the definition of the systems requirements and components.

System Design, the detailed design phase, resulting in the comprehensive definition of the system components.

Production, commonly referred to as the construction phase. In the case of a physical systems, this phase involves the construction of system hardware and software.

Validation and Verification, system testing, validation and verification before "fielding".

Operations and Support, the day-to-day operation and support of the product/outcome.

Disposal, the final phase of the system life cycle, resulting in the process of closeout or program end.

2.1.1 Concept Exploration

An idea by itself often creates a large number of critical questions that, if left unanswered, can stop the evolution of the idea into a system before the process even starts. CE provides a mechanism through which to explore the idea further, applying addition effort to the definition of the overall system as a whole. A typical concept exploration consists of: [16]

- Consideration of technology,
- Assessment of the advantages and disadvantages of alternative concepts,
- Identification of rough order of magnitude costings, and

- Development of system requirements.

Modelling and simulation of the overall product are important tools of CE and are used to optimise a trade space of requirements and alterables. This thesis takes a fixed mission statement and set of objectives and models a trade space of alterables derived from these fixed components. Any modification of the mission statement and/or objectives would require a strategic revisit on the reasoning and justification behind the original idea. The outputs of this process are a set of optimised requirements that are then fed into the system design phase. This next step is not considered as part of this thesis.

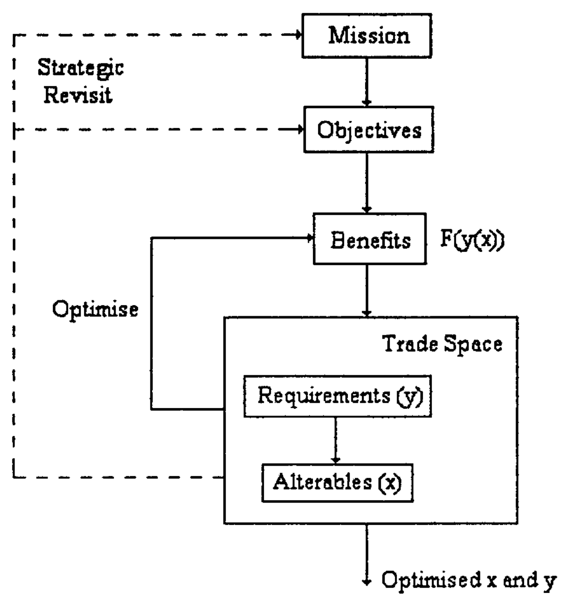


Figure 2-1 Concept Exploration Process Flow Diagram

2.2 System Definition

In order for Australia to establish an indigenous space launch capability the country requires a program whose primary goal is to achieve such a means. Similarly, to assess whether this goal has been met a series of objectives need to be clearly defined. For the purpose of this study the program mission statement and objectives were derived and then fixed for the duration of the concept exploration.

Following detailed discussions between the author and the thesis committee, the following mission statement and objectives were defined:

2.2.1 Mission Statement

Establish an indigenous launch capability for Australia.

2.2.2 Objectives

- Develop an aerospace industry and technology base in-country to provide Australia with an indigenous space launch capability.
    - Provide capital and human resources for manufacturing and operations of a launch system.
    - Nurture and encourage the formulation of scientific learning in the education system through specialised programs to create a workforce with the requisite skills.
    - Institute/Enhance second and third tier support organisations and companies.

- Develop an indigenous space launch system.
  - Develop and manufacture a space launch vehicle(s).
  - Construct a launch and operations facility, and associated infrastructure.
  - Establish an agency to manage the system.
- Provide commercial space launch services.
  - Provide the mechanisms to support commercial launch services
  - Make the enterprise economically viable.

2.2.3 Benefits

By assessing the relative benefits of different program architectures allows us to optimise program components such as duration, launch site location and vehicle configuration. The resulting set of conditions and requirements can then be used to decide whether or not to precede the idea to the next phase. Determination of the benefits was carried out concurrently with the formulation of the program objectives. If the program objectives were met then Australia would experience the following benefits:

- **Political Advancement** – This applies to both domestic and international recognition. A prime example of external recognition is China's attempts at becoming the third nation to have a manned space program. A leading U.S. military space expert, Dwayne A. Day believes that *"China's motivation is prestige, plain and clear. The whole idea is that it makes them one of the big boys, one of the great powers."*[17] Another example is Brazil who has been developing a micro satellite launch capability. Although to date the program has been unsuccessful, it has opened numerous political doors, allowing Brazil to join the elite Missile Technology Control Regime and participate in the International Space Station Program. Through the development of a space launch program Australia would become a "player", being seen as a participator rather than a bystander. The program should provide Australia with:

  - Enhanced status within the Southeast Asian Region,
  - Enhanced status with its Allies, and
  - Enhanced status at the United Nations.

- **Security** – This can be broken down into two main areas, regional stability through deterrents and mission/payload security.

  - A launch capability can equate directly to a ballistic missile capability. In fact a number of today's satellite launch vehicles are based on surplus warhead delivery systems.

- Provides confidentiality when launching sensitive reconnaissance and communications payloads.
- Enables launch on demand, i.e. launch when Australia wants to launch.

- **Economic Prosperity** – As mentioned earlier Australia spends $½ billion annually overseas for access to space assets. Redirection of this money into a country's capabilities and infrastructure while maintaining the same products can only result in growth and prosperity. This growth can result in product enhancement and open economic markets previously unavailable to Australia. The upfront investment would be quite large. However, the long-term gain would be substantial with potential for the program to be self-sustaining. The program would eventually provide commercial launch services and would attempt to establish and cultivate a market niche.

- **Elevation of the in-country technology base** (Technology Infrastructure, Expertise, Education) of Australia would almost be immediate. Demand for technical expertise would establish/enhance an aerospace commercial base within country and could motivate/stimulate new programs/courses at universities. Along with core industries, a space program would attract and enhance second and third tier support organisations and companies. Most importantly of all it would provide incentives to stop the outflow of highly skilled technical people who normally have to go abroad to find technically challenging employment.

2.3 The Model

In its simplest form a model is comprised of independent variables, IVs that interact with each other through relationships to formulate an overall benefit function. This function can then be minimised or maximised by altering the values of the IVs. As the model becomes more complicated, intermediate steps are introduced between the IVs and the function.

2.3.1 Benefit Function

The intention of the thesis is to explain the methodology behind the formulation of an abstract idea into a function that can be quantitatively modelled. The function is derived from a set of IVs whose scope ultimately bounds the idea. For the purposes of this thesis the three benefits discussed above, along with the overall program cost, were combined to form the benefit function to be modelled.

By comparing each benefit independently with the others and calculating the overall importance, a series of weighting ratios for these four components could be determined. For example Political Advancement is three times as important to the program as security, conversely Security is only 1/3 as important as Political Advancement. The rows are then total and then each row sum is divided by the overall table sum giving the calculated weights. The calculated weights are rounded to produce the modified weights. The table below illustrates the process and calculations results used to obtain the ratios.

	Political Advancement	Elevated Technology Base	Security	Overall Program Dollars	Total	Calculated Weight	Modified Weight
Political Advancement	1	3	3	2	9	0.3724	**0.4**
Elevated Technology Base	$\frac{1}{3}$	1	3	$\frac{1}{3}$	$4\frac{2}{3}$	0.1931	**0.2**
Security	$\frac{1}{3}$	$\frac{1}{3}$	1	$\frac{1}{3}$	2	0.0828	**0.1**
Overall Program Dollars	$\frac{1}{2}$	3	4	1	$8\frac{1}{2}$	0.3517	**0.3**
Total	$2\frac{1}{6}$	$7\frac{1}{3}$	11	$3\frac{2}{3}$	$24\frac{1}{6}$	1	1

Table 2-1 Program Benefit Weighting Ratios

The resulting program function is given by:

Function = 0.4 x Political Advancement + 0.3 x Overall Program Dollars

+ 0.2 x Elevated Technology Base + 0.1 x Security

Or

$$\text{FCN} = 0.4 \times \text{PA} + 0.3 \times \$\$ + 0.2 \times \text{ETB} + 0.1 \times \text{Sec} \tag{2-1}$$

These weightings are completely arbitrary and on the surface seem artificial. However, the process of independent comparison ensures that the relationship between each benefit is taken into consideration with respect to relative importance. Some initial sensitivity analysis into the final weightings found the outcome to be robust to small changes in the weights.

2.3.2 Independent Variables

The next step in establishing the model was to determine the IVs and the relationships that associate them to the benefits and the overall program cost. The process of model construction is an evolutionary one punctuated by evaluation and decision points. In terms of modelling a space program, the model can always be refined as changes in government policy, and technology and social evolution shape the way priorities and decisions are made. This model does, however, provide enough latitude to encompass the intent of the CE process, and is logically sound enough to be used as the basis for program progression.

The IVs play an important role in the CE process. They form the foundation upon which the evolution of the idea is built. Ultimately the model outcome is a process of relationships and interactions built from the IVs and so identification and defining the IVs is critical. Key areas of focus for the IVs initially revolved around launch site location, program duration, payload capacity, percentage reusability of the launch system, and the percentage Australian indigenous input into the space launch program. As research into existing space programs deepened and the capabilities of current launch systems became apparent the IVs were adjusted to include launch vehicle design components such as mass fraction, payload mass fraction, specific impulse and the total mass of the vehicle. Figure 2-2 illustrates the relationship between the benefit function and the IVs, where the benefit function is to the left and the IVs are to the right.

- Benefit Function
  - Political Advancement
    - No. of Launches per Year
      - No. of Rainy Days per Year
        - Latitude
        - Longitude
      - % Reusable
    - Mass of Payload
      - Total Mass
      - Mass Fraction
      - Payload Mass Fraction
    - ΔV
      - Rocket Equation
        - ISP
        - Mass Fraction
        - Total Mass
      - Inclination Range
        - Latitude
        - Longitude
      - Latitude
    - Program Duration
    - % Indigenous
    - % Reusable
  - Elevated Tech Base
    - No. of Launches per Year
      - No. of Rainy Days per Year
        - Latitude
        - Longitude
      - % Reusable
    - ISP
    - Mass Fraction
    - Payload Mass Fraction
    - % Indigenous
    - % Reusable
    - Program Duration
  - Security
    - ΔV
      - Rocket Equation
        - ISP
        - Mass Fraction
        - Total Mass
      - Inclination Range
        - Latitude
        - Longitude
      - Latitude
    - Mass of Payload
      - Total Mass
      - Mass Fraction
      - Payload Mass Fraction
    - % Indigenous
  - Overall Program Cost
    - Distance to Transport Infrastructure
      - Latitude
      - Longitude
    - Distance to Industry
      - Latitude
      - Longitude
    - % Site Infrastructure
      - Latitude
      - Longitude
    - Cost of Total No. of Launches
      - No. of Launches per Year
        - No. of Rainy Days per Year
          - Latitude
          - Longitude
        - % Reusable
      - Program Duration
    - Maintenance Costs
      - No. of Launches per Year
        - No. of Rainy Days per Year
          - Latitude
          - Longitude
        - % Reusable
      - % Reusable
    - R&D Costs
      - ISP
      - Total Mass
      - Mass Fraction
      - Payload Mass Fraction
      - Program Duration
      - % Indigenous
      - % Reusable

Figure 2-2 Correlation Between the Benefit Function and IVs

Research into launch site location indicated that selecting fifteen discrete sites would reduce the total number of IVs and make the model more computationally traceable , rather than input the continent as a continuous entity. From the IVs of latitude and longitude six key site considerations were determined, they are:

- Distance to heavy industry;
- Number of rainy days per year;
- Current site infrastructure suitable for establishing a space launch capability;
- Distance to heavy transport infrastructure such as rail or port facilities;
- Range of available launch inclinations (best described as an arc of launch azimuths, usually restricted by population and vital asset distribution and results in a ΔV cost to achieve the popular launch inclinations unavailable from that site).
- Velocity assistance due to the rotation of the earth.

These relationships are all functions of Latitude and/or Longitude and can be modelled to select the most appropriate site. However, from analysis of the continent of Australia, its current and planned infrastructure, weather patterns and population distributions, it was established that the model would most probably end up selecting one of the fifteen discrete sites already determined through a detailed analysis of the above site components. So site location, Latitude and Longitude, were provided as a discrete input into the space program model.

Vehicle design was broken down into five IVs:

- Specific Impulse (I_{SP}) – this parameter compares the thrust derived from a system as a function of the propellant mass flow rate:

$$I_{SP} = \frac{\text{Thrust}}{\text{Mass Flow Rate} \times \text{Gravity}} \tag{2-2}$$

- Mass Fraction (MF), this parameter is a ratio of the mass of the fuel to the total fuelled mass of the launch vehicle:

$$MF = \frac{\text{Mass of Fuel}}{\text{Total Mass of the Launch System}} \tag{2-3}$$

- Payload Mass Fraction (PMF), this parameter provides the fraction by mass of the dry weight of the launch vehicle that is the payload:

$$PMF = \frac{\text{Mass of the Payload}}{\text{Total Dry Mass of the Launch Vehicle}} \tag{2-4}$$

- Launch Vehicle Total Mass (TM), this parameter is the total mass of the launch vehicle fully fuelled.
- Percentage Reusable (%R), how much of the launch system will be recovered and reused.

These five IVs were continuous over the ranges shown in Table 2-2 below:

Independent Variable	**Variable Range**
Specific Impulse	0 to 1,000 seconds
Mass Fraction	0 to 1
Payload Mass Fraction	0 to 0.8
Total Vehicle Mass	10,000 to 700,000 kg
Percentage Reusable	0 to 100 %

Table 2-2 Vehicle Design Independent Variable Ranges

The range for the launch vehicle total mass was established from analysis of 54 launch vehicles currently in service [18]. A summary of the analysis of these launch vehicles is attached in Appendix A. The last two IVs are Program Duration (Dur) and percentage Australian indigenous input into the space launch program (%I). Both these IVs are continuous over the ranges of 0 to 40 years and 0 to 100 % respectively.

2.3.3 Model Relationships

This area of the thesis outlines the role of the model relationships. These interactions between the IVs are fixed; however, they do provide a series of relationships that are definable, explainable and importantly repeatable. Of course as government policy and technology change, and society evolves these relationships can be changed, deleted and/or replaced. The intent was not to focus on the development of these relationships, rather on the methodology behind their development and how the model fits together.

There are two ways that the IVs are related to the Benefits, either indirectly or directly. The indirect association occurs when intermediate relationships are needed to correctly express the IV/Benefit relationship. The direct correlation occurs when the IV/Benefit expression does not require this intermediate step. An example of this illustrated below for ETB. Latitude and Longitude are indirectly related to ETB via the number of rainy days per year, which in turn provides an input into calculating the number of launches per year (more launches require more operation support and infrastructure), which then feeds into ETB. %I, Dur, I_{SP}, MF, and PMF relationships feed directly into ETB. Of note is %R, which is related to ETB both directly and indirectly.

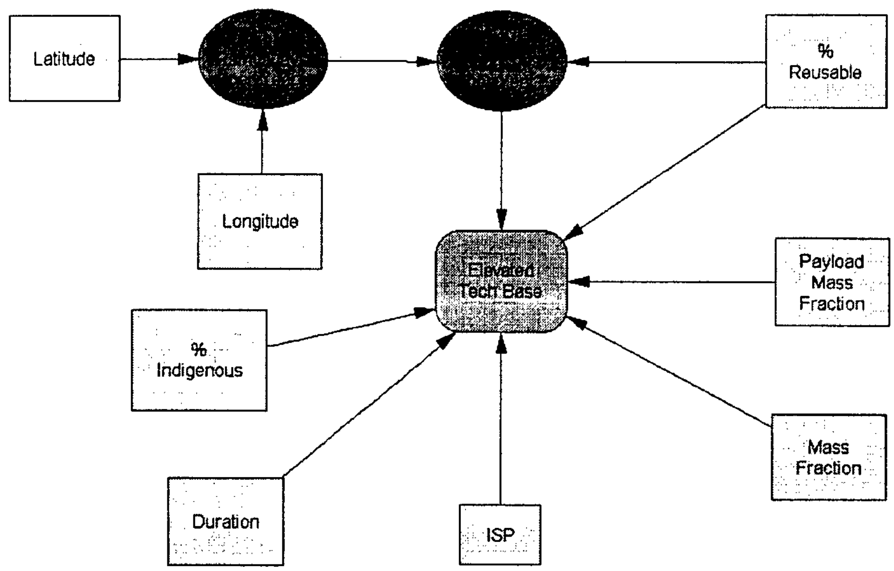


Figure 2-3 Elevated Technology Base Direct and Indirect Correlation to the Independent Variables

Figure 2-4 illustrates what can be considered as the corner stone of the thesis. The figure diagrammatically represents the entire program model. It illustrates the relationships between the IVs and the benefits; capturing both the direct and indirect benefit associations. The IVs are shown as squares, the benefits as squares with rounded edges, and the intermediate relationships as circles. Although launch site location is a discrete input, the influence that latitude and longitude have on the six launch site components is clearly shown.

The figure illustrates thirty-nine distinct relationships, categorised under the four benefits and detailed below.

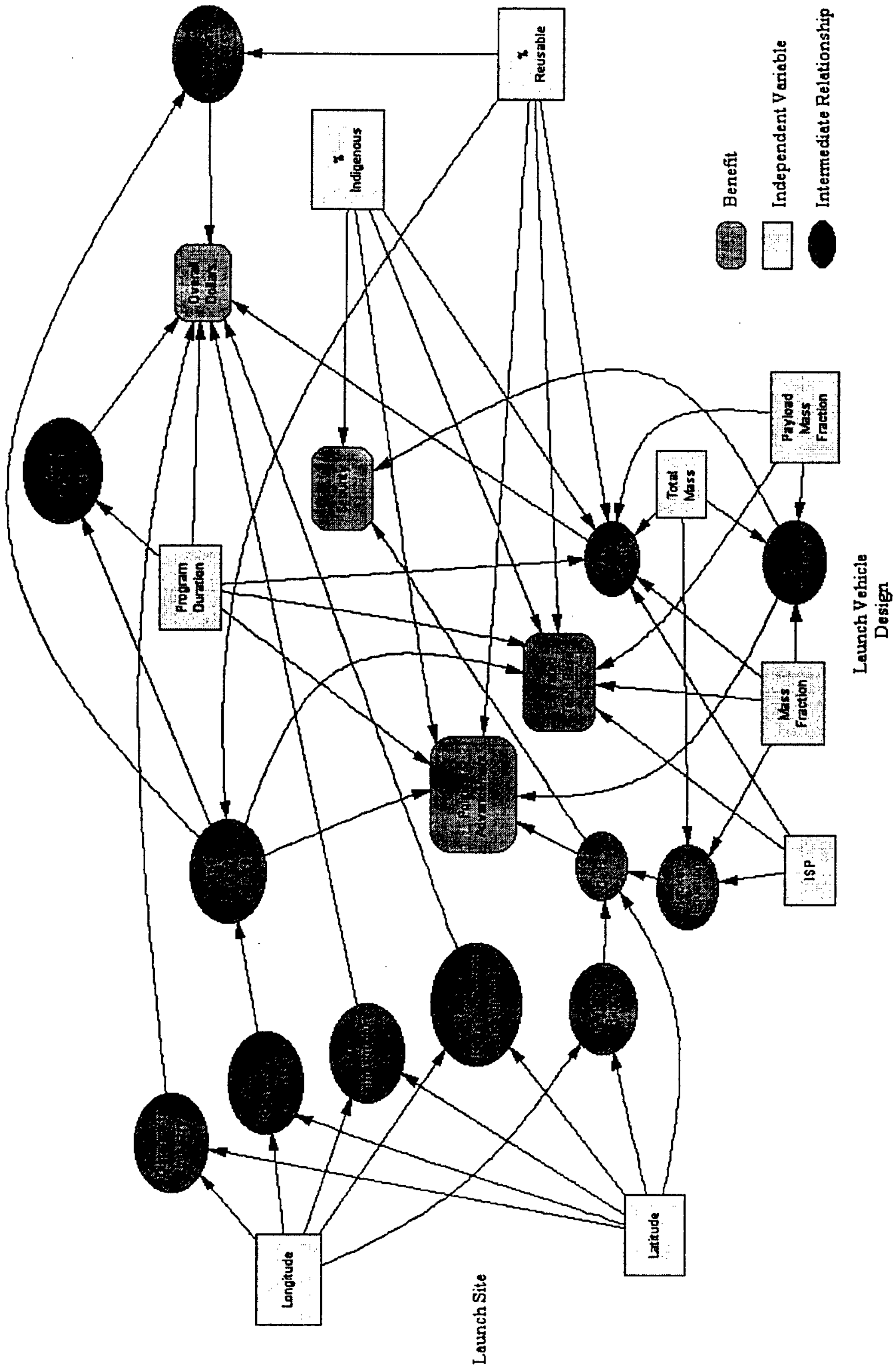


Figure 2-4 Space Launch Program Model

2.3.3.1 Political Advantage

- Political Advancement
  - No. of Launches per Year
    - No. of Rainy Days per Year
      - Latitude
      - Longitude
    - % Reusable
  - Mass of Payload
    - Total Mass
    - Mass Fraction
    - Payload Mass Fraction
  - ΔV
    - Rocket Equation
      - ISP
      - Mass Fraction
      - Total Mass
    - Inclination Range
      - Latitude
      - Longitude
    - Latitude
  - Program Duration
  - % Indigenous
  - % Reusable

The political advancement resulting from an indigenous space launch capability is a combination of five key components factored together and then multiplied by the percentage indigenous content to provide a normalised measurable degree of resulting political advantage.

$$\text{Political Advantage} = \frac{\%I}{100} \times \begin{pmatrix} 0.3 \times PA(\Delta V) + 0.25 \times PA(Dur) + 0.2 \times PA(PM) \\ + 0.15 \times PA(\%R) + 0.1 \times PA(NL) \end{pmatrix} \quad (2\text{-}5)$$

The weighting ratios were calculated in a similar manner to the benefit weighting ratios. The table below illustrates these ratio relationships.

Political Advancement	Delta V	Payload Mass	Percent Reusable	Program Duration	No. Launches per Year	**Total**	**Unmodified Weight**	**Modified Weight**
Delta V	1	1.75	2	1.5	3	9.25	**0.31**	**0.3**
Payload Mass	0.57	1	1.5	0.75	2	5.82	**0.19**	**0.2**
Percent Reusable	0.5	0.67	1	0.5	1.5	4.17	**0.14**	**0.15**
Program Duration	0.67	1.33	2	1	3	8	**0.27**	**0.25**
No. Launches per Year	0.33	0.5	0.7	0.33	1	2.83	**0.09**	**0.1**
Total	3.07	5.25	7.2	4.08	10.5	**30.1**	**1**	**1**

Table 2-3 Political Advantage Weighting Ratios

The political advantage due to the launch system velocity – PA(ΔV), is premised on the fact that the higher the velocity capability of the launch platform the more status obtained by the program. The relationship is an S-curve function and is calculated by:

$$PA\,(\Delta V)=\frac{\mathrm{Tanh}\left(\dfrac{4.2\times\Delta V}{20}-2.1\right)+\mathrm{Tanh}(2.1)}{2\times\mathrm{Tanh}(2.1)} \tag{2-6}$$

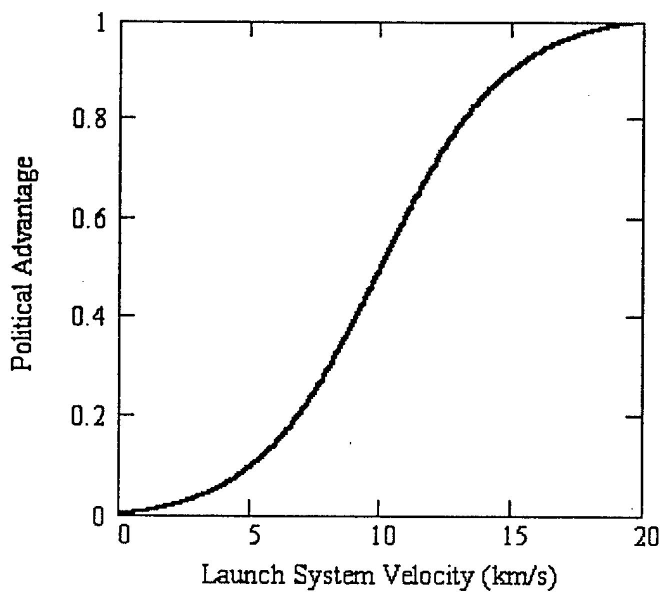


Figure 2-5 Political Advantage as a function of Launch System Velocity

Launch system velocity - ΔV, is the combination of three velocity components; the rocket equation, the velocity assistance provided by the rotation of the earth, and the velocity required to achieve popular orbit inclinations based on the range of inclinations available from each launch site. The equation sub-component ΔVs is calculated as follows:

$$\Delta V = \Delta V_{RE} + \Delta V_{\omega e} - \Delta V_{inc} \tag{2-7}$$

The rocket equation - ΔV_{RE}, is fundamental to the design of the launch vehicle and is used in the model to ensure that the optimum space launch program vehicle has enough velocity to at least reach low earth orbit (LEO). The rocket equation is a combination of three of the vehicle design IVs; Specific Impulse, Mass Fraction, and Total Mass; and is calculated using the natural log function:

$$\Delta V_{RE} = \text{Gravity} \times I_{SP} \times LN\left(\frac{TM}{TM \times (1 - MF)}\right) \tag{2-8}$$

The velocity assistance provided by the rotation of the earth - $\Delta V_{\omega e}$, is a function of latitude, the closer to the equator the more assistance, and is calculated from:

$$\Delta V_{\omega e} = \omega_e \times r_e \times \text{Cos}(\text{Lat}) \tag{2-9}$$

$$\text{where } \omega_e = \frac{360^\circ}{23\text{ Hrs } 54\text{ min } 4.09\text{ s}}$$

$$\text{and} \quad r_e = 6378.135\text{ km}$$

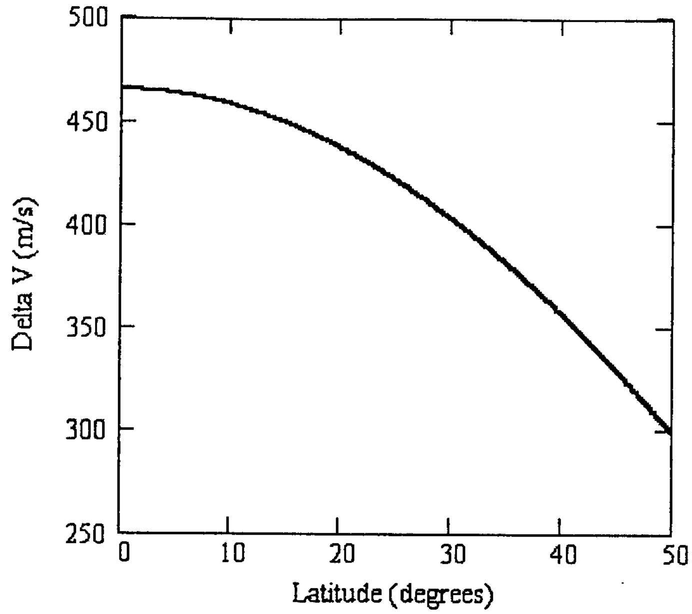


Figure 2-6 Velocity due to the Rotation of the Earth as a Function of Latitude

The velocity required to achieve popular satellite orbit inclinations - ΔV_{inc}, is based on the range of inclinations available from each launch site. The NORAD two-line element set for 948 satellites [19] was entered into an EXCEL spreadsheet and the velocities at apogee were calculated, see Appendix B. From this data, the velocity required to achieve those inclinations outside the launch site's inclination range were calculated. For example, the figure below illustrates the range of inclinations available from Woomera. Those orbit inclinations outside 45° to 102° will require an orbital inclination manoeuvre. For the purpose of the orbital burn it was assumed that the satellite would be launched into the nearest inclination possible from that particular site and then under go an inclination change manoeuvre at apogee according to the relation (2-10).

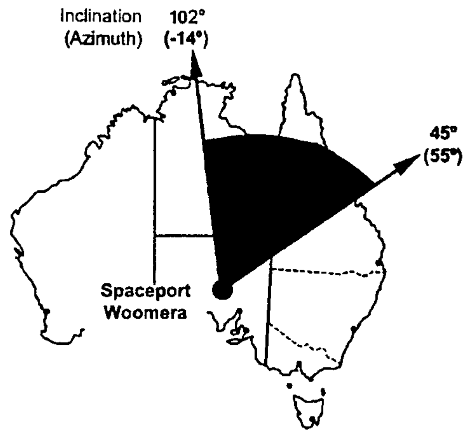


Figure 2-7 Inclination Range Available from Woomera SA

$$\Delta V_{inc} = \frac{\sum_{n}^{948} 2 \times V_{apogee} \times \text{Sin}\left(\frac{\Delta inc_n}{2}\right)}{\text{Number of Satellites in Database}} \tag{2-10}$$

These velocities were than summed and averaged for each site to ascertain the average additional velocity required to achieve popular satellite inclinations from each particular site. The graph below illustrates the popular satellite inclinations through a histogram of 600 bins.

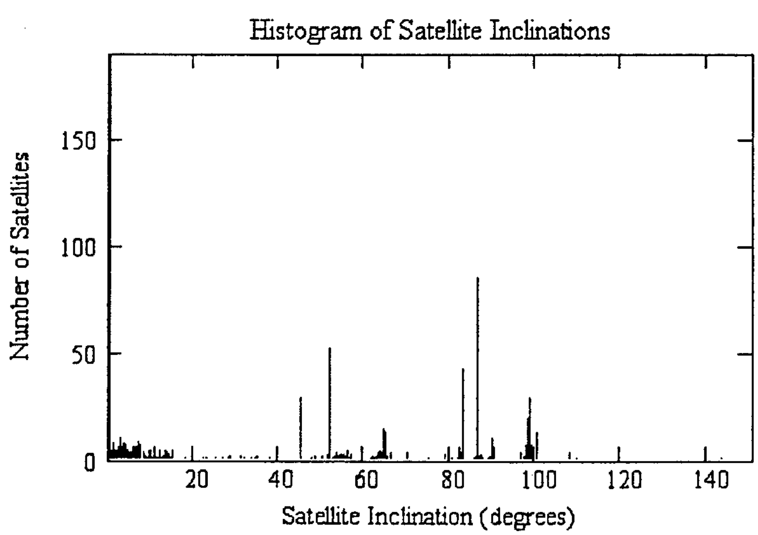


Figure 2-8 Satellite Inclination Histogram

The political advantage due to the program's duration – PA(Dur), is based on the fact that the shorter the program development duration the more political status obtained by the program. The relationship is an S-curve function and is calculated by

$$PA\,(Dur) = \frac{-Dur}{40} + 1 \qquad (2\text{-}11)$$

The political advantage due to the mass of the payload – PA(MP), is premised on the fact that the heavier the payload capability of the launch platform the more status obtained by the program. The asymptote for this function has been set at 5,000 kg. The average payload to LEO is about 7,800 kg, Sun synchronous about 4,020 kg, however, most small communications satellites and future planned reconnaissance satellites are well below this figure. This does not reflect payload design capabilities per say; rather it reflects what is perceived would provide the most political advantage through payload capability. Whether a country can launch 5,000 kg or 10,000 kg does not provide any increase in perceived political status. Status comes from the fact that the country is able to launch a reasonable sized payload and in this case maximum status is achieved at a reasonable 5,000 kg. The relationship is an S-curve function and is calculated by:

$$PA\,(MP) = \frac{\mathrm{Tanh}\left(\frac{4.2 \times MP}{5000} - 2.1\right) + \mathrm{Tanh}(2.1)}{2 \times \mathrm{Tanh}(2.1)} \qquad (2\text{-}12)$$

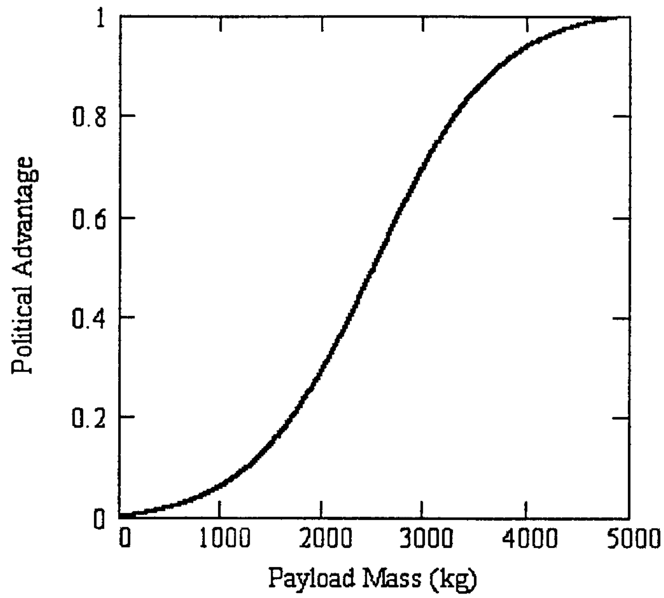


Figure 2-9 Political Advantage as a Function of Payload Mass

Mass of the payload – MP, capability of the launch vehicle is a combination of the payload mass fraction times the total mass of the launch vehicle times the dry mass fraction:

$$MP = PMF \times TM \times (1 - MF) \tag{2-14}$$

The political advantage due to the percent reusability of the launch system is premised on the fact that the more reusability inherent in the system the more political status obtained by the program. This political status is derived from the perception that a highly reusable system is more sophisticated. There are also environment advantages both in terms of space junk and the junk that litters the sea floor. The relationship is an S-curve function and is calculated by:

$$PA\left(\%R\right)=\frac{\mathrm{Tanh}\left(\frac{4.2\times\%R}{100}-2.1\right)+\mathrm{Tanh}\left(2.1\right)}{2\times\mathrm{Tanh}\left(2.1\right)} \tag{2-15}$$

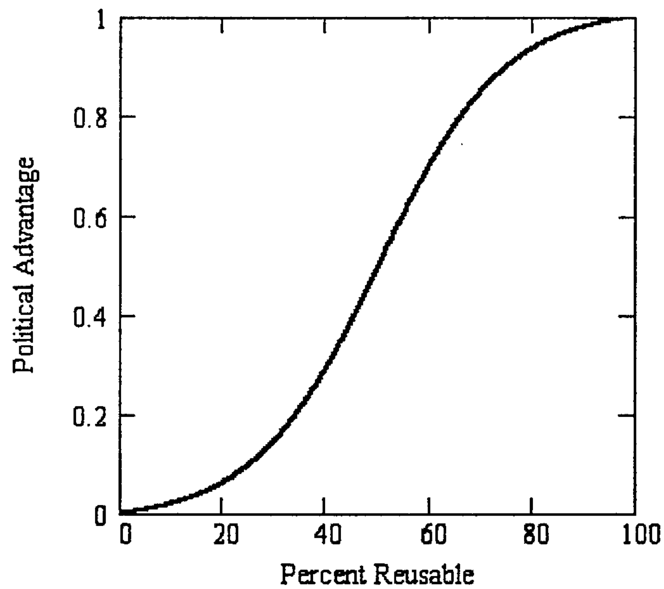


Figure 2-10 Political Advantage as a Function of Percent Reusable

The political advantage due to the number of launches per year – PA(NL), is premised on the fact that the more launches per year the better the reputation acquired by the program. The function is illustrated below.

$$PA\left(NL\right)=\mathrm{Tanh}\left(\frac{NL}{6}\right) \tag{2-15}$$

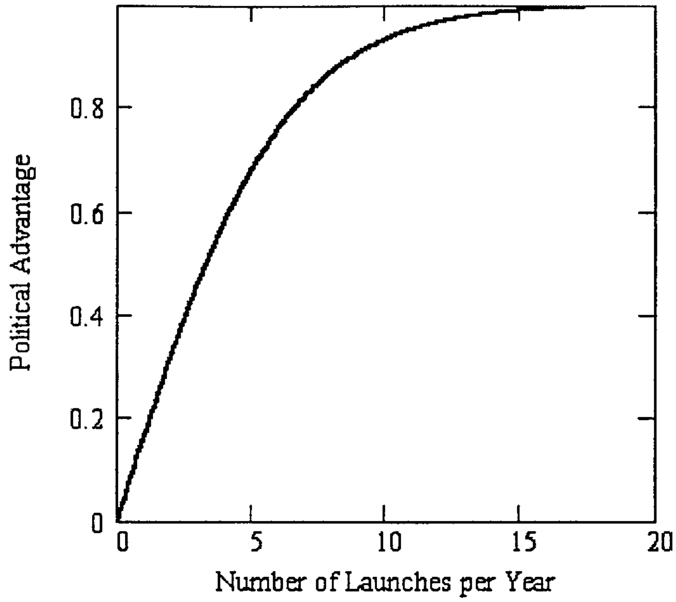


Figure 2-11 Political Advantage as a Function of the Number of Launches per Year

The number of launches per year – NL, is made up of two components, the number of rainy days per year and the percent reusability of the launch system. The number of launches per year as a function of percent reusability is derived from an inverse S-curve and was based on perceived recovery, refurbishment and maintenance requirements. What is not intuitive is that if the system is zero percent reusable then the system can be launched fifteen times a year. The start of this curve was rationalised by assuming only one launch vehicle at a time following a launch - construction, launch – construct process. Obviously if you constructed more vehicles the number of launches goes up. A prime example of this is the US space shuttle program with approximately 12 launches planned in 2001, utilising 4 reusable launch vehicles, corresponding to 3 launches per year per vehicle. The relationship is given by:

$$NL\left(\%R\right)=\frac{5\times\left[\operatorname{Tanh}\left[-\left(\frac{4.2\times\%R}{100}-2.1\right)\right]+\operatorname{Tanh}\left(2.1\right)\right]}{\operatorname{Tanh}\left(2.1\right)}+5 \qquad (2\text{-}16)$$

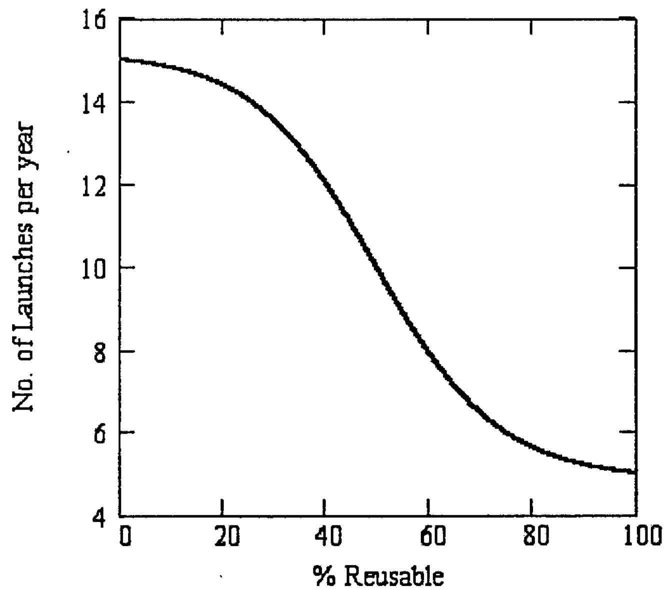


Figure 2-12 Number of Launches per Year as a Function of the Percent Reusability of the System

Then multiplying this number by a ratio of non rainy days per year to total number of days in a year (365), obtained from the Australian Bureau of Meteorology [20], and based on the launch site location. Giving a maximum number of fifteen launches per year and a minimum number of one launch per year. The aim of this process is to take into account not only launch vehicle restrictions, but also environmental constraints.

$$NL=\frac{365-\frac{\text{No. of Rainy Days}}{\text{Year}}}{365}\times NL\left(\%R\right) \qquad (2\text{-}17)$$

2.3.3.2 Elevation of the Technology Base

Elevated Tech Base	No. of Launches per Year	No. of Rainy Days per Year	Latitude
			Longitude
		% Reusable	
	ISP		
	Mass Fraction		
	Payload Mass Fraction		
	% Indigenous		
	% Reusable		
	Program Duration		

The overall benefits achieved by Australia for having an elevated technology base as a direct result of the space launch capability is measured on a normalised scale, between zero and one. Primarily, it is a combination of five key components factored together and then multiplied by the percentage indigenous content, similar to the political advantage calculation. The percentage indigenous content is crucial to elevating the country's technology base. One extreme is to simply use Australia as purely a launching facility with all equipments, expertise and personnel provided from overseas companies. The result is no elevation of technology base. Such turnkey proposals are currently underway with other countries talking about taking advantage of Australia's political stability, vastness and low exchange rate.

$$\mathrm{ETB} = \frac{\%\mathrm{I}}{100} \times \begin{pmatrix} 0.225 \times \mathrm{ETB}\left(\mathrm{I_{SP}}\right) + 0.25 \times \mathrm{ETB}\left(\mathrm{MF}\right) + 0.15 \times \mathrm{ETB}\left(\mathrm{Dur}\right) \\ + 0.15 \times \mathrm{ETB}\left(\mathrm{PMF}\right) + 0.125 \times \mathrm{ETB}\left(\%\mathrm{R}\right) + 0.1 \times \mathrm{ETB}\left(\mathrm{NL}\right) \end{pmatrix} \quad (2\text{-}18)$$

Elevated Technology Base	Specific Impulse	Mass Fraction	Percent Reusable	No. Launches per Year	Payload Mass Fraction	Duration	**Total**	**Unmodified Weight**	**Modified Weight**
Specific Impulse	1	0.8	2	3	1	2	9.75	**0.22**	**0.225**
Mass Fraction	1.3	1	2	3	2	2.5	11.83	**0.27**	**0.25**
Percent Reusable	0.5	0.5	1	2	0.5	0.8	5.3	**0.12**	**0.125**
No. Launches per Year	0.3	0.3	0.5	1	0.5	0.6	3.267	**0.08**	**0.1**
Payload Mass Fraction	1	0.5	2	2	1	1	7.5	**0.17**	**0.15**
Duration	0.5	0.4	1.3	1.7	1	1	5.817	**0.13**	**0.15**
Total	3.2	2.6	5.5	9	4	7.9	**43.5**	**1**	**1**

Table 2-4 Elevated Technology Base Weighting Ratios

Elevation of the Technology Base Level Required to Achieve the Specific Impulse Employed – ETB(I_{SP}), in the launch system is based on the resulting increase in technology required to achieve higher I_{SP}'s. The table below [20] outlines the relationship between different technologies and I_{SP}. For example solid fuel is relatively simple to employ while liquid hydrogen and liquid oxygen engines are far more complicated requiring cryogenic expertise.

Technology	**I_{SP} (s)**
Solid Fuel	170-220
Hydrocarbon Liquid Fuel	200-350
Liquid Hydrogen and Oxygen	455
Nuclear and Hydrogen	300-500
Plasma jet, Arc jet	300-700
Mass Driver	1000-5000+
Ion, MHD thrusters	10,000 - ?

Table 2-5 Representative Propulsion Technologies

The relationship between technology base level and I_{SP} is represented by:

$$\mathrm{ETB}(I_{SP}) = \mathrm{Tanh}\left(\frac{I_{SP}}{600}\right) \qquad (2\text{-}19)$$

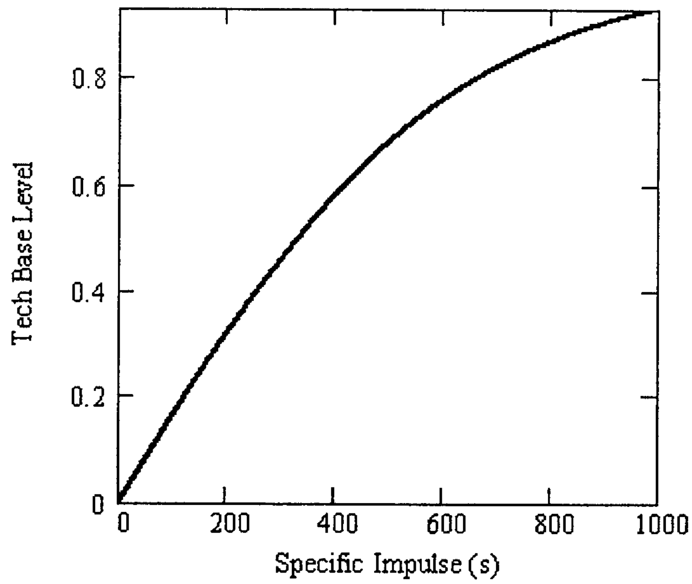


Figure 2-13 Technology Base Level as a Function of I_{SP}

Elevation of the Technology Base Level Required to Achieve the Launch Vehicle's Mass Fraction – ETB(MF), is calculated based on an analysis of current systems, Appendix A, and an extrapolation of the varying mass fraction as a function of complexity, resulting in the following exponential relationship.

$$\mathrm{ETB}(\mathrm{MF}) = \frac{e^{8\times \mathrm{MF}}}{e^{8}} \qquad (2\text{-}20)$$

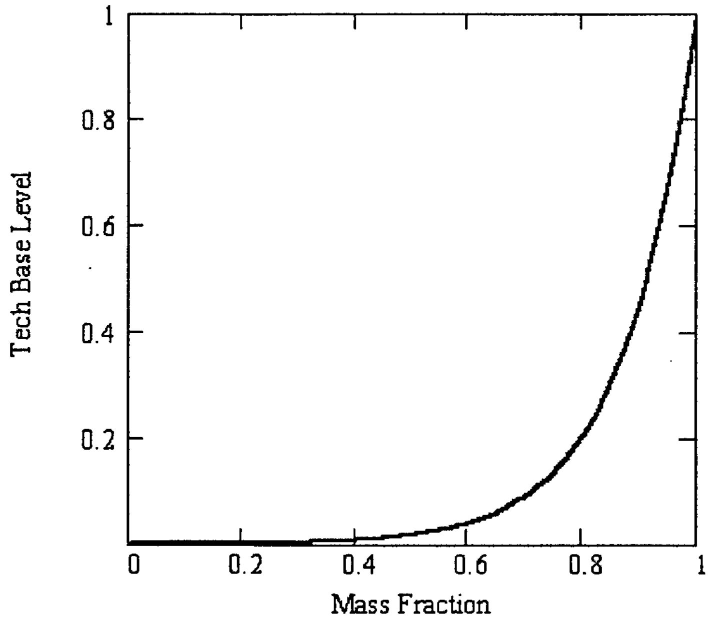


Figure 2-14 Technology Base Level as a Function of Mass Fraction

Elevation of the Technology Base Level Required to Achieve the Launch Vehicle's Payload Mass Fraction – ETB(PMF), is similar in concept to the launch vehicle's mass fraction. Again Appendix A details the results on an analysis of 54 launch vehicles' payload mass fraction for both LEO and Geo Transfer Orbit (GTO) payload mass fractions. The higher the ratio of payload mass to vehicle dry mass the more complicated the system and hence the higher the required level of technology and expertise.

$$\mathrm{ETB}\left(\mathrm{PMF}\right) = \mathrm{Tanh}\left(2 \times \mathrm{PMF}\right) \tag{2-21}$$

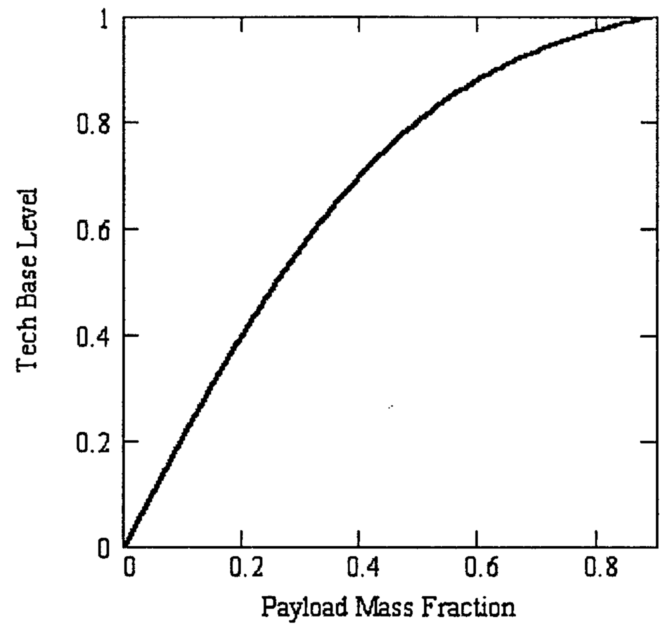


Figure 2-15 Technology Base Level as a Function of Payload Mass Fraction

Elevation of the Technology Base Level Required to Achieve the System Percent Reusability – ETB(%R). Reusability has long been considered a method of launch cost reduction. However, recovery and reuse of space launch components is technically very challenging, and currently the USA is the only national to implement an almost 100% reusable launch system (the external shuttle fuel tank is, at this time, not reused). The level of a country's technology base to achieve increasing system reusability is directly proportional to the level of reusability.

$$\mathrm{ETB}\left(\%\mathrm{R}\right)=\frac{\%\mathrm{R}}{100} \tag{2-22}$$

Elevation of the Technology Base Level Required to Achieve the Number of Launches Per Year – ETB(NL), is represented by an S-curve relationship. More launches per year requires more infrastructure and in-house expertise to cope with the complexities of regular launches.

$$\mathrm{ETB}\,(\mathrm{NL}) = \frac{\mathrm{Tanh}\left(\dfrac{4.2 \times \mathrm{NL}}{20} - 2.1\right) + \mathrm{Tanh}\,(2.1)}{2 \times \mathrm{Tanh}\,(2.1)} \tag{2-23}$$

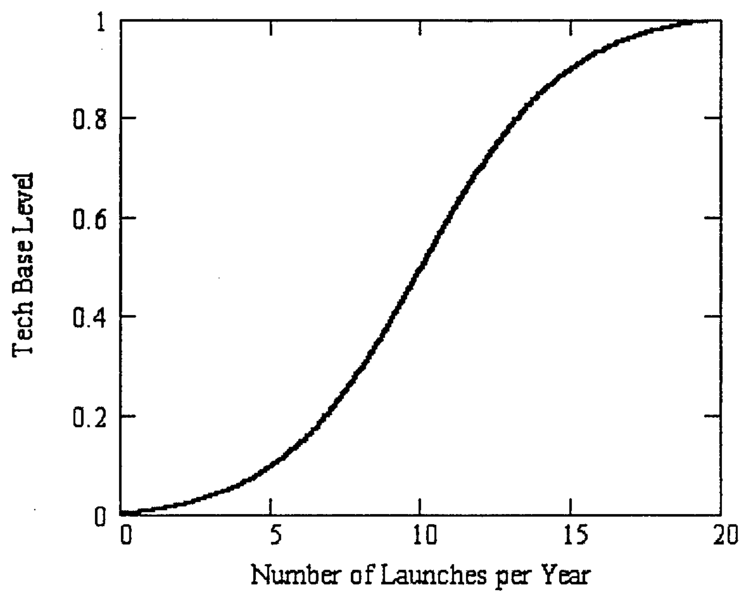


Figure 2-16 Elevated Technology Base as a Function of Number of Launches per Year

Elevation of the Technology Base Level as a Function of the Program Duration – ETB(Dur), the relationship is derived from the principle that the shorter the program the stronger the technology base of the country. The function is linear with a negative slope.

$$\mathrm{ETB}\,(\mathrm{Dur}) = \frac{-\,\mathrm{Dur}}{40} + 1 \tag{2-24}$$

2.3.3.3 Security

Security	ΔV	Rocket Equation	ISP Mass Fraction Total Mass
		Inclination Range	Latitude Longitude
	Mass of Payload	Latitude Total Mass Mass Fraction Payload Mass Fraction	
	% Indigenous		

Security – **Sec**, is made up of two key components, the ΔV capability and the payload mass capability of the launch system. These two components are considered equal in the security equation and are weighted equally (50/50). Both ΔV and payload mass equate to ballistic missile capabilities and to sensitive payload capabilities. Again percent indigenous content plays an important role in the establishment of secure launch capabilities.

$$\mathrm{Sec} = \frac{\%I}{100} \times \left[0.5 \times \left(\frac{\mathrm{Tanh}\left(\frac{4.2 \times \Delta V}{20} - 2.1 \right) + \mathrm{Tanh}\,(2.1)}{2 \times \mathrm{Tanh}\,(2.1)} \right) + 0.5 \times \mathrm{Tanh}\left(\frac{MP}{1000} \right) \right] \quad (2\text{-}25)$$

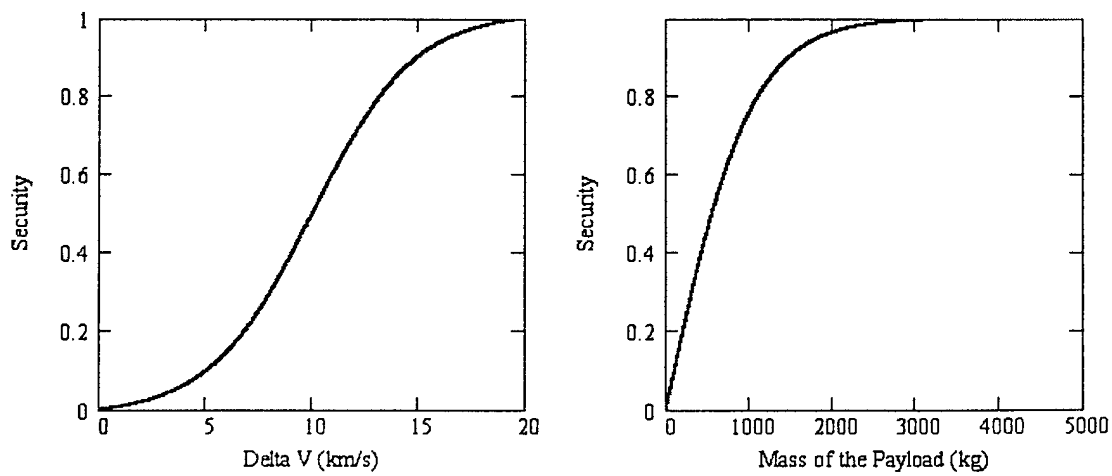


Figure 2-17 Security as a function of ΔV and Payload Mass Capability

2.3.3.4 Cost

- Overall Program Cost
  - Distance to Transport Infrastructure
    - Latitude
    - Longitude
  - Distance to Industry
    - Latitude
    - Longitude
  - % Site Infrastructure
    - Latitude
    - Longitude
  - Cost of Total No. of Launches
    - No. of Launches per Year
      - No. of Rainy Days per Year
        - Latitude
        - Longitude
      - % Reusable
    - Program Duration
  - Maintenance Costs
    - No. of Launches per Year
      - No. of Rainy Days per Year
        - Latitude
        - Longitude
      - % Reusable
    - % Reusable
  - R&D Costs
    - ISP
    - Total Mass
    - Mass Fraction
    - Payload Mass Fraction
    - Program Duration
    - % Indigenous
    - % Reusable

The Cost Factor Benefit – CF, is a combination of two cost features, cost per year (CFPY) and the total cost (CFT$).

Cost Factor as a Function of Cost per Year has linear relationship with a negative gradient. The function has been optimised to a preferred annual cost of no more than $500 million per year.

$$\text{CFPY} = \frac{-\$\$}{500 \times \text{Dur}} + 1 \qquad (2\text{-}26)$$

Cost Factor as a Function of Total Cost has linear relationship with a negative gradient. The function has been optimised to a preferred total program cost of no more than $10 billion.

$$\text{CFT\$} = \frac{-\$\$}{10000} + 1 \qquad (2\text{-}27)$$

The Cost Factor is weighed heavily towards the total program cost while annual cost only make up 30% of the outcome. This was to ensure that the model took into account the fact that a result of prioritising annual costs over the overall costs was an elongation of the program duration. As this is not the intent, by prioritising total costs the model focuses on both total cost and duration reduction. A weighting of 70-30 achieves this intent.

$$CF = 0.7 \times CFT\$ + 0.3 \times CFPY \tag{2-28}$$

**The Overall Program Cost - $$**, is a combination of the costs associated with the total number of launches for the program ($(NL)), human resources ($(Dist Industry)), launch site development ($(% Site)), heavy transport infrastructure development ($(Dist Infra)), research and development ($(R&D)), and maintenance ($(Maint)) of a space launch capability. For the purposes of this thesis all dollars were calculated in US dollars and a conversion factor of 1AUSD = 0.55USD was used to convert Australian dollars to US dollars.

$$\$\$ = \$\,(\text{NL}) + \$\,(\text{Dist Industry}) + \$\,(\%\,\text{Site}) + \$\,(\text{Dist Infra}) + \$\,(\text{R \& D}) + \$\,(\text{Maint}) \tag{2-29}$$

Cost due to the Number of Launches per Year - $(NL), is averaged over the duration of the program by multiplying the equation by a ramping-up factor; in this case a simple ramp factor of ¼ was selected. The cost of $0.000225 million per kg was established by taking the average of the cost per kg of launch vehicle total mass for the 54 launch vehicles at Appendix A. As can be seen in the figure below there is no real trend in the cost as a function of launch vehicle total mass, so an overall average was used.

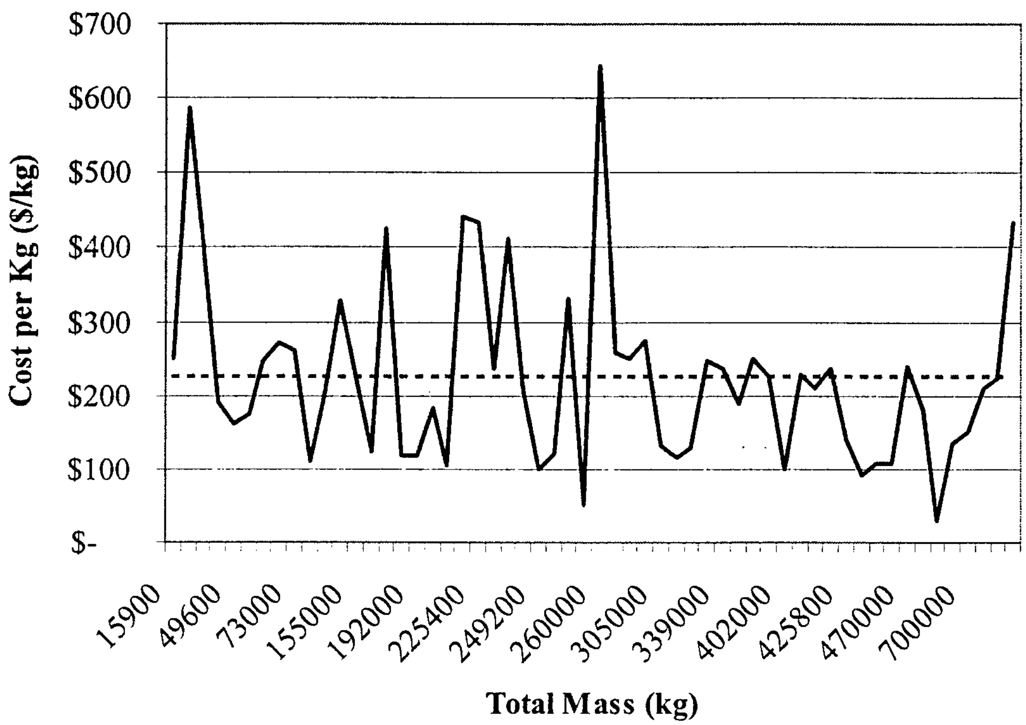


Figure 2-18 Cost per kg as a Function of Launch Vehicle Total Mass

$$\$(\mathrm{NL}) = 0.25 \times \mathrm{Dur} \times \mathrm{NL} \times \mathrm{TM} \times 0.000225 \qquad (2\text{-}30)$$

Costs Incurred as a Result of the Distance to the Nearest Population Centre - \$(Dist Industry), This cost was calculated based on travel and subsidiary expenses of \$500/km/year.

$$\$\,(\text{Dist Industry}) = \text{Dist Industry} \times \text{Dur} \times 0.0005 \qquad \text{(2-31)}$$

Cost due to Constructing the Launch Facility - \$(% Site), This cost is formulated by estimating the amount required to establish a launch facility from scratch and then extrapolating this back based on percentage infrastructure already in place.

$$\$\,(\%\,\text{Site}) = 250 \times \frac{\text{Tanh}\left[-\left(\frac{4.2 \times \%\,\text{Site}}{100} - 2.1\right)\right] + \text{Tanh}(2.1)}{\text{Tanh}(2.1)} \qquad \text{(2-32)}$$

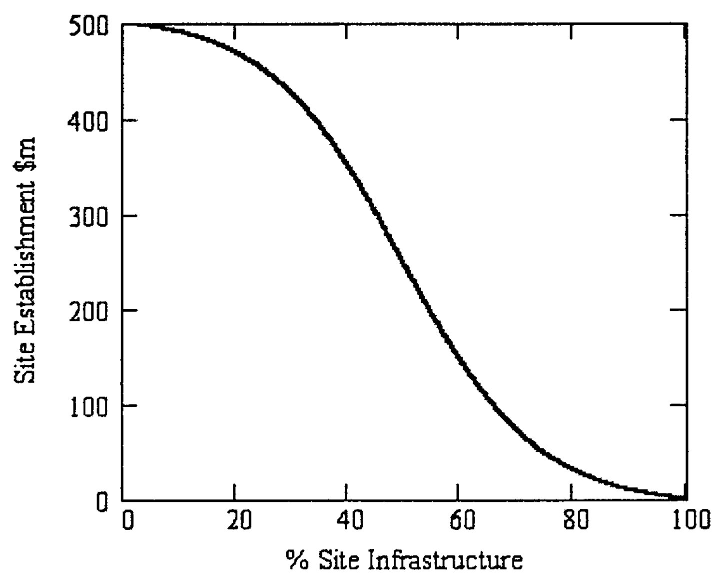


Figure 2-19 Launch Site Establishment Costs as a Function of % Site Infrastructure Already in Place

Costs Incurred as a Result of Connecting the Launch Facility to Heavy Transport Infrastructure - \$(Dist Infra), is calculated by multiplying the distance (in km) to the nearest railway hub or large port facility by \$0.3million. This figure was obtained by averaging major and minor rail construction currently taking place in Australia.

$$\$\left(\text{Dist Infra}\right) = 0.3 \times \text{Dist Infra} \tag{2-33}$$

Cost due to System Maintenance - \$(Maint), was estimated based on the percent reusability of the launch system multiplied by the estimated average number of launches per year over the duration of the program. An additional ramping-up factor is included to, similar to the number of launches per year to account for an increase in maintenance as the program develops, and again a ramp factor of ¼ was selected

$$\$\left(\text{Maint}\right) = \frac{25 \times \text{NL} \times \text{Dur}}{4} \times \frac{\text{Tanh}\left(\dfrac{4.2 \times \%\text{R}}{100} - 2.1\right) + \text{Tanh}\left(2.1\right)}{\text{Tanh}\left(2.1\right)} \tag{2-34}$$

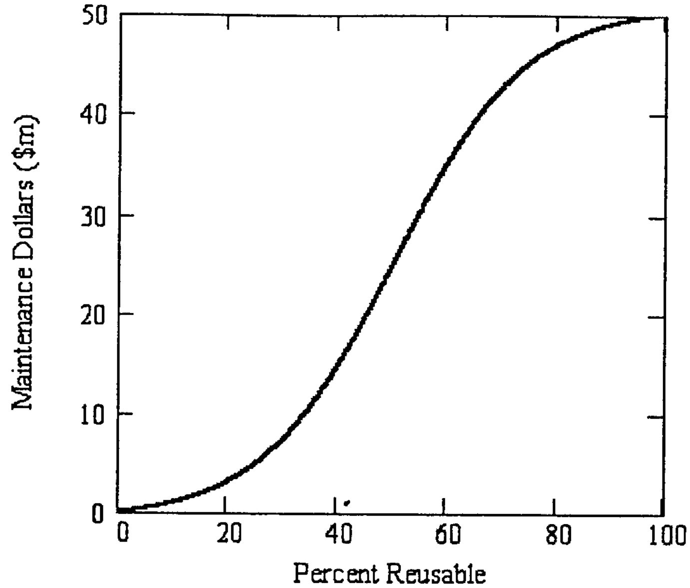


Figure 2-20 Maintenance Costs as a Function of Launch System Percentage Reusability

Total Cost due to Research and Development Costs – $(R&D), is the combination of all the costs associated with the program's areas of R&D as a percentage of how indigenous the program is.

$$\$\left(R\ \&\ D\right)=\frac{\%I}{100}\times\begin{pmatrix}R\ \&\ D\,\$\left(\%R\right)+R\ \&\ D\,\$\left(TM\right)+R\ \&\ D\,\$\left(MF\right)\\ +R\ \&\ D\,\$\left(I_{SP}\right)+R\ \&\ D\,\$\left(PMF\right)\end{pmatrix} \quad (2\text{-}35)$$

Research and Development Costs due to the Launch System Percent Reusability, - R&D$(%R), increases exponentially as the launch system reusability increases. This increase can be attribute, among other things, the complexities of reusable engine technologies, atmospheric re-entry and recovery, and vehicle refurbishment.

$$R\ \&\ D\,\$\left(\%R\right)=\frac{e^{\frac{\%R}{20}}}{0.3}-\frac{10}{3} \quad (2\text{-}36)$$

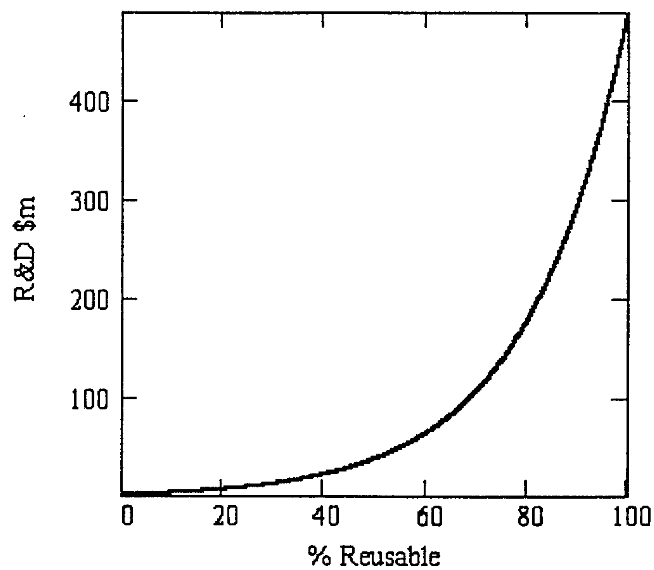


Figure 2-21 R&D Costs as a Function of Launch System Reusability

Research and Development Costs due to the Total Mass of the Launch Vehicle, R&D$(TM), is calculated as a percentage of the overall vehicle mass. These R&D costs are related to development of launch technologies such as material development, avionics and systems integration and are directly proportional to the systems mass.

$$R\,\&\,D\,\$\left(TM\right) = TM \times 0.001 \tag{2-37}$$

Research and Development Costs due to the Mass Fraction of the Launch Vehicle, R&D$(MF), increase rapidly as the vehicle approaches 100% fuel, the theoretical optimum for a space launch vehicle (not entirely practical). Analysis of current systems, Appendix A, reveals that average mass fraction is 0.89 ranging from 0.8 to 0.94. To achieve mass fractions higher than 0.94 requires ground breaking research into new materials, engines and fabrication techniques, an incredibly expensive undertaking. However, to achieve a mass fraction below 0.8 is relatively easy, the only problem is achieving orbit.

$$R\,\&\,D\,\$\left(MF\right)=100\times \mathrm{Tan}\left(\frac{100\times \pi \times MF}{201}\right) \tag{2-38}$$

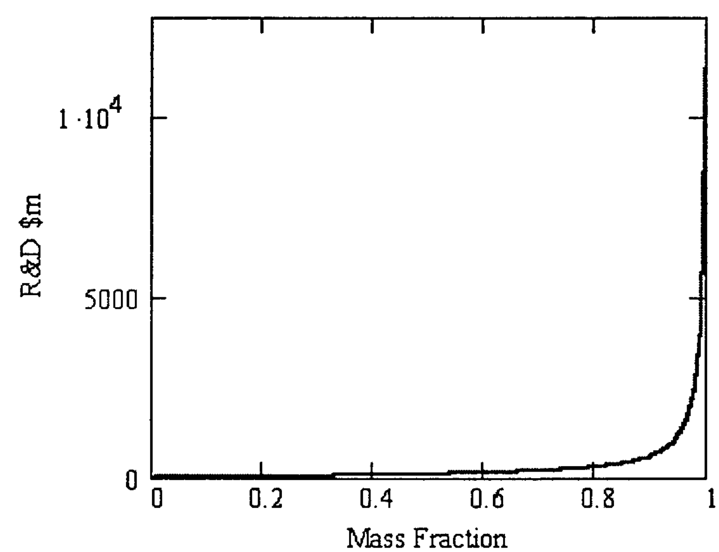


Figure 2-22 R&D Costs as a Function of the Launch Vehicle's Mass Fraction

Research and Development Costs due to the Specific Impulse of the Launch Vehicle – R&D$($I_{SP}$), are exponentially increasing as I_{SP} increases. There is a direct correlation between I_{SP} level and the type of technology employed to develop and implement it. Referring back to Table 2-5 shows that technology and complexity increases as I_{SP} increases. The technologies for the higher I_{SP}'s are incredibly complex and very expensive to develop and implement, hence the exponential relationship.

$$R\&D\$\left(I_{SP}\right)=10\times e^{\frac{I_{SP}}{70}} \qquad (2\text{-}39)$$

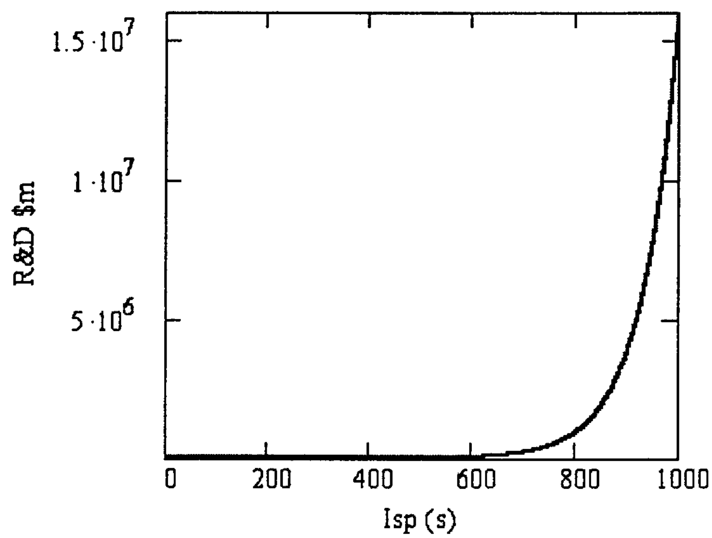


Figure 2-23 R&D Costs as a Function of Launch Vehicle I_{SP}

Research and Development Costs due to the Payload Mass Fraction of the Launch Vehicle – R&D$(PMF), is another example of an exponential increase in cost associated with achieving higher payload mass fractions. Current systems employ a payload mass fraction range of 0.032 to 0.511 for LEO (Appendix A), less for higher orbits. Complexities in reducing the dry mass of the launch vehicle while maintaining the same structural integrity and launch system reliability to allow a corresponding increase in the payload mass (assuming constant vehicle launch characteristics) results in a dramatic increases in R&D costs for higher PMFs.

$$R\,\&\,D\,\$\left(PMF\right) = 200 \times e^{4 \times PMF} - 200 \qquad (2\text{-}40)$$

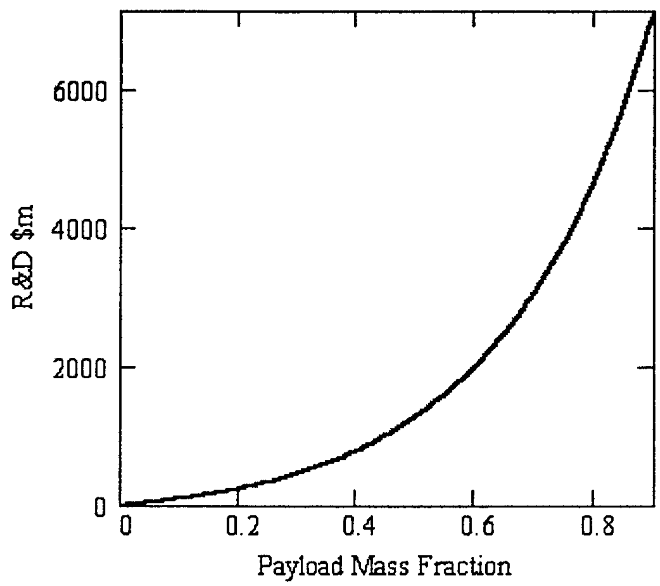


Figure 2-24 R&D Costs as a Function of the Payload Mass Fraction

The previous discussion involved detailed explanations of the model relationships. Although the aim was not to focus to heavily on the development of these relationship curves, it is important to note that there is a degree of logic behind the formulation of each. What is important is that these relationships not only stand up to a degree of scrutiny, they are also repeatable. This repeatability was an essential development consideration ensuring that the model could be run under differing initial conditions.

2.3.4 Simulation

In order to achieve a range of results from what is quintessentially an imperfect model, a number of scenarios were devised. The first and foremost run was to establish the overall model results, against which all other results could be compared.

To achieve this the model algorithms were converted into code. The programming language FORTRAN was selected to optimise the benefit function, initially because it contained a powerful optimisation library. However, a number of difficulties were encountered including one of the nuances of optimising in 6-space and so an initial brute force approach was adopted to localise the optimiser initial conditions (ICs) and obtain some medium resolution results. These results are tabulated in Chapter 3 along with the corresponding analysis.

CHAPTER 3 Results

3.1 Introduction

The aim of this section is to summarise the results of the model in such a way as to provide the reader with an understanding that, although the model is imperfect, it is a valid decision-making tool. Through this tool a systems engineer is able to provide logical substance to assist in the selection of alternative solutions. To achieve this goal, along with the overall model results, a number of alternative results are posed as options. These alternatives may appear inferior when compared with the overall model results, however, this inferiority is within the context of the model and may not accurately reflect the peculiarities and intentions of a particular decision-maker.

3.2 Launch Site Selection

As mentioned above, rather than allow the latitude and longitude of the launch site to vary continuously. A set of possible locations was selected a priori.

Currently in Australia there are five proposals for turnkey commercial launch solutions, utilising three proposed sites. These three sites were the start of the seventeen-site database made up of discrete latitude and longitude coordinates. Twelve of the remaining fourteen sites were selected based on providing what was perceived as superior scores in the majority of the following areas based on the value system design in Figure 2-3.

- Distance to major industrial centre – the closest capital city/major city.
- Average number of rainy days per year.
- Current site infrastructures suitable to support space launch activities, as a fraction of a complete spaceport.
- Distance to the nearest heavy transportation node – railway/heavy seaport.
- Available launch inclination range.
- Velocity assistance due to the rotation of the earth.

The final two sites were selected as test-sites to test the robustness of the model. Following a detailed analysis of Australia and its territories the following 17 sites were selected (Alphabetised by State).

- Christmas Island, proposed under a turnkey commercial solution;
- Borroloola, Northern Territory;
- Gunn Point, Northern Territory;
- Katherine, Northern Territory;
- Nhulunbuy, Northern Territory;
- Broome, Western Australia;
- Port Hedland, Western Australia;
- Wyndham, Western Australia;
- Woomera, South Australia, proposed under a turnkey commercial solution;
- Cape York, Queensland;
- Cooktown, Queensland;

- Hummock Hill, Queensland, proposed under a turnkey commercial solution;
- Mt Isa, Queensland;
- Townsville, Queensland;
- Weipa, Queensland;
- Orange, New South Wales, a test-site; and
- Wilson's Promontory, Victoria, a test-site.

The table below lists each site with its corresponding Latitude and Longitude, and its data points for each of the six areas listed above. All distances are in km.

	IVs		Azimuth		Corresponding		Inclination	Rotation	# Rainy	%	Distance	D
	Lat S	Long E	Az1	Az2	Inc1	Inc2	ΔV (m/s)	ΔV (m/s)	Days/Year	Infra	Transport	I
Christmas Island	10.45	105.69	89	-175	10	95	259	457	173	0	25	
Borroloola	16.07	136.3	65	115	29	29	3166	447	51.5	0	250	
Gunn Point	12.25	131.04	75	120	19	32	3641	455	110.7	0	25	
Katherine	14.44	132.27	58	110	35	24	2826	450	81.6	0	25	
Nhulunbuy	12.2	136.76	78	125	17	37	2662	455	97.9	0	475	
Broome	17.95	122.23	70	110	27	27	3368	436	46.6	0	25	
Port Headland	20.37	118.63	70	100	28	23	3335	436	31	0	25	
Wyndham	15.49	128.1	65	110	29	25	3168	448	64.5	0	450	
Woomera	31.08	136.66	-14	55	102	45	684	398	50	70	75	
Cape York	10.7	142.53	75	140	18	51	1851	457	108.1	0	800	
Cooktown	15.46	145.19	20	130	71	42	1101	448	129.3	0	175	
Hummock Hill	23.83	151.26	24	110	68	31	1402	425	75.1	0	25	
Mt. Isa	20.73	139.49	5	105	85	25	674	435	33.5	0	25	
Townsville	19.25	146.77	5	130	85	44	641	439	91.3	0	25	
Weipa	12.63	141.88	60	130	32	42	2398	454	106.9	0	650	
Orange	33.38	149.12	0	5	90	86	2772	388	124.7	0	25	
Wilson's Promontory	39.13	146.42	65	120	39	48	2692	361	180.1	0	100	

Table 3-1 Launch Site Location Data Set

The figures below illustrate the locations of the 17 launch sites within the continent of Australia and on its territories.

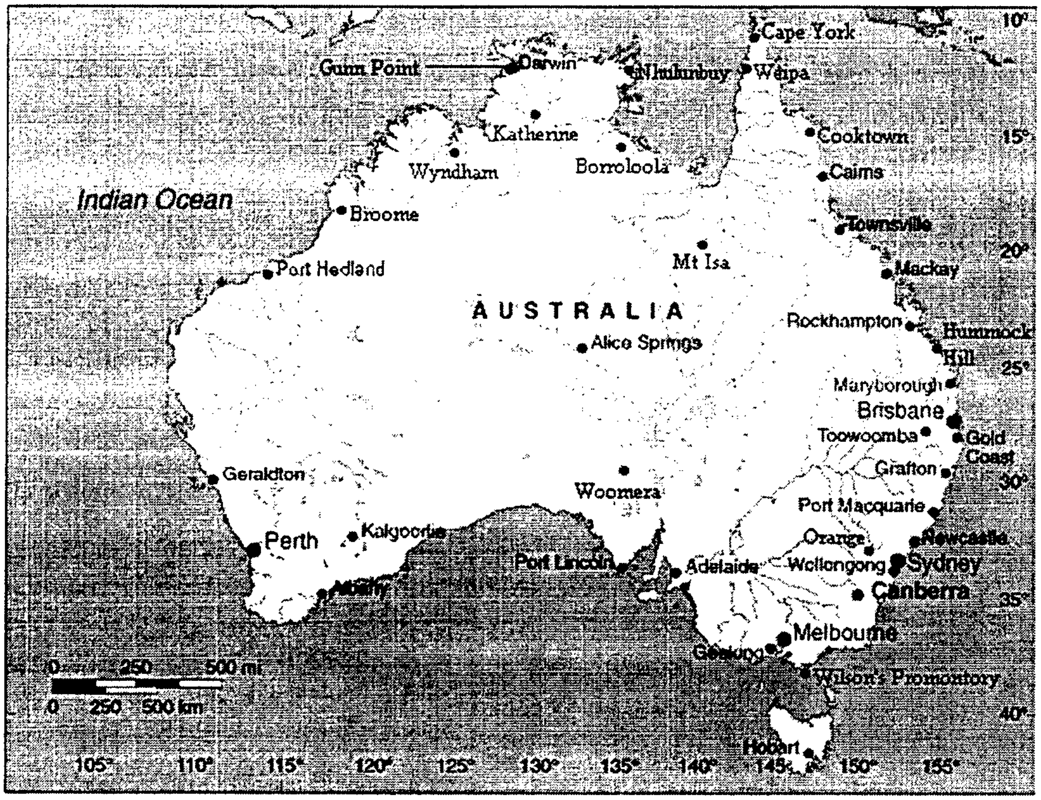


Figure 3-1 Launch Site Locations Within Continental Australia

Figure 3-2 Location of Christmas Island

3.3 Brute Force Approach

The brute force approach evaluated the objective function uniformly across each continuous IV in a grid fashion using a series of nested loops, one for each IV. Initial low-resolution runs were carried out to zero-in on the approximate area of most interest and establish computing speed. Initial runs indicated that a high resolution run could take at least a couple of months and would not provide any significant solution advantages over a medium resolution run.

Before being able to implement a brute force approach a number of characteristics about the function must be known. Firstly the boundaries of the function must be well defined; an idea without scope suggests an infinite grid space. Secondly the resolution of the search must specified, note that a crude resolution results in faster search. And last but not least we need to understand what the expected result should look like. This ensures that the first two characteristics are focused correctly. For the purpose of a concept exploration, significant detail is not required and hence a medium-resolution search is possible. In this particular case 708,750,000 grid points where used for each launch site, a process that took several days to complete on a personal computer.

The table below illustrates the relationships between the IVs, the resolution for each loop and the corresponding range of coverage. Each IV was bounded either by its nature; e.g. percentage 0 to 100, or through research on current systems and programs; e.g. total mass 0 to 500,000 kg. The brute force source code is attached at Appendix C.

Independent Variables	Resolution	Coverage Range
Specific Impulse	21	200 to 600
Mass Fraction	30	0.7 to 0.99
Payload Mass Fraction	30	0 to 0.6
Total Mass	50	10,000 to 500,000 kg
Percentage Reusable	5	80 to 100%
Percentage Indigenous	5	80 to 100%
Program Duration	30	1 to 30 years

Table 3-2 Brute Force Grid Space Breakdown

Table 3-3 summarises the results of this grid space, providing the baseline results for the model. The table lists the results in order of benefit function, from highest to lowest, where the theoretical highest score is a benefit function of 1.

		Benefit Components				Independent Variables						Model Factoids				
Launch Site	Function Benefit	PA	ETB	SEC	CF	ISP	MF	PMF	% Reuse	% Indig	Dur	Total Mass	No. Launch	ΔV (km/s)	Total Cost ($m)	Cost/Yr ($m)
Woomera	**0.734**	0.837	0.544	1	0.631	320	0.93	0.28	88	100	12	250000	0.7	8.1	$ 3,076.7	$ 256.4
Orange	**0.728**	0.833	0.544	1	0.618	280	0.94	0.28	88	100	12	280000	0.6	8.1	$ 3,183.5	$ 265.3
Christmas Island	**0.727**	0.833	0.538	1	0.619	300	0.93	0.28	88	100	12	250000	0.4	8.0	$ 3,171.6	$ 264.3
Townsville	**0.722**	0.829	0.551	1	0.599	300	0.94	0.30	88	100	13	270000	0.6	8.1	$ 3,450.5	$ 265.4
Mt Isa	**0.722**	0.830	0.551	1	0.595	300	0.94	0.30	88	100	13	260000	0.8	8.0	$ 3,485.9	$ 268.1
Cooktown	**0.715**	0.826	0.564	1	0.571	300	0.95	0.30	88	100	13	310000	0.5	8.2	$ 3,693.2	$ 284.1
Hummock Hill	**0.709**	0.828	0.570	1	0.543	320	0.95	0.30	88	100	13	310000	0.7	8.4	$ 3,939.1	$ 303.0
Cape York	**0.701**	0.821	0.566	1	0.530	320	0.95	0.30	88	100	14	310000	0.6	8.0	$ 4,165.6	$ 297.5
Weipa	**0.693**	0.821	0.584	1	0.491	320	0.96	0.32	88	100	14	360000	0.6	8.2	$ 4,509.0	$ 322.1
Wilson's Promontory	**0.691**	0.811	0.586	1	0.495	340	0.96	0.32	88	100	15	360000	0.4	8.4	$ 4,593.6	$ 306.2
Katherine	**0.689**	0.815	0.586	1	0.485	340	0.96	0.32	88	100	15	360000	0.7	8.3	$ 4,683.5	$ 312.2
Borroloola	**0.686**	0.816	0.586	1	0.473	340	0.96	0.32	88	100	15	360000	0.7	8.0	$ 4,787.6	$ 319.2
Nhulunbuy	**0.685**	0.813	0.594	1	0.468	300	0.97	0.34	88	100	15	440000	0.6	8.1	$ 4,833.1	$ 322.2
Wyndham	**0.685**	0.816	0.590	1	0.468	340	0.96	0.32	88	100	15	360000	0.7	8.0	$ 4,834.4	$ 322.3
Broome	**0.682**	0.814	0.600	1	0.451	320	0.97	0.34	88	100	15	430000	0.7	8.1	$ 4,989.7	$ 332.6
Port Hedland	**0.681**	0.815	0.600	1	0.449	320	0.97	0.34	88	100	15	430000	0.8	8.1	$ 5,010.5	$ 334.0
Gunn Point	**0.677**	0.814	0.591	1	0.442	360	0.96	0.32	88	100	15	360000	0.6	8.2	$ 5,074.2	$ 338.3
Averages	**0.702**	0.822	0.573	1	0.525	319	0.95	0.311	88	100	14	335294	0.6	8.1	$ 4,204.8	$ 300.8

Table 3-3 Results of Space Launch Program Model (Baseline Results)

An interesting occurrence in these baseline results is the similarity in vehicle design, program duration and percentage indigenous content, regardless of launch site location. Minor differences do occur in some IVs such as duration, mass fraction, and payload mass fraction. However, in the context of a concept exploration these differences are negligible. Overall the model is proposing, independent of launch site location, a liquid fuelled, mostly reusable launch vehicle. While the program development is to be 100% indigenous over approximately 15 years. It comes as no surprise that the top result was Woomera with a benefit score of 73.4%. This site has been proposed by three of the five turnkey solutions and is the historical home to Australia's space endeavours.

A number of scenarios were then devised that would provide the decision-maker with a series of alternative configurations against which to compare the baseline. These scenarios where derived from within the feasible solution space and based on complementary configurations of the baseline results. Because the baseline indicates that a liquid, highly reusable launch vehicle provides the most feasible arrangement, a number of alternative configurations based around varying these two IVs were developed.

The first alternative solution examined was a launch vehicle with a solid propulsion system, 200s I_{SP}. Table 3-4 summarises these results, separately for each of the seventeen launch sites. The most obvious difference is the lack of results for more than half the sites. A constraint of a $\Delta V \geq 8$ km/s was embedded in the nested loop source code to ensure that the resulting systems were able to reach LEO. Consequently the model determined that nine out of the seventeen sites were not able to meet this critical constraint and no results were provided. For the remaining sites mass fraction, payload mass fraction and total mass were all pushing against the upper bounds, corresponding to large program costs. Again Woomera and Christmas Island featured in the top three results.

As shown in Table 3-4, the test site Orange has scored the highest providing a benefit of 67.1%. The intent of the test sites was to establish the lower bounds of the model. However, both sites failed to do this in all runs, with Orange always in the top three results. Upon closer examination of both sites' characteristics, it was determined that, although intuitively inferior (due to high annual rainfall and poor launch inclination range because of their proximity to population centres), the six site relationships, from figure 2-3, did not reflect this. A discussion on remedies to better capture the intent of the launch site location IVs is discussed in Chapter 4.

		Benefit Components				Independent Variables						Model Factoids				
Launch Site	Function Benefit	PA	ETB	SEC	CF	ISP	MF	PMF	% Reuse	% Indig	Dur	Total Mass	No. Launch	ΔV (km/s)	Total Cost ($m)	Cost/Yr ($m)
Orange	**0.671**	0.804	0.589	1	0.435	200	0.98	0.40	88	100	15	500000	0.6	8.1	$ 5,136.9	$ 342.5
Woomera	**0.582**	0.709	0.613	1	0.252	200	0.99	0.52	88	100	18	500000	0.7	8.7	$ 7,239.4	$ 402.2
Christmas Island	**0.573**	0.698	0.609	1	0.240	200	0.99	0.52	88	100	19	500000	0.4	9.2	$ 7,483.4	$ 393.9
Cooktown	**0.571**	0.700	0.609	1	0.230	200	0.99	0.52	88	100	19	500000	0.5	8.4	$ 7,580.7	$ 399.0
Townsville	**0.571**	0.707	0.613	1	0.216	200	0.99	0.52	88	100	18	500000	0.6	8.8	$ 7,586.4	$ 421.5
Hummock Hill	**0.570**	0.708	0.613	1	0.214	200	0.99	0.52	88	100	18	500000	0.7	8.0	$ 7,607.9	$ 422.7
Mt Isa	**0.568**	0.710	0.613	1	0.206	200	0.99	0.52	88	100	18	500000	0.8	8.8	$ 7,688.3	$ 427.1
Borroloola	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Gunn Point	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Katherine	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Nhulunbuy	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Broome	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Port Hedland	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Wyndham	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Cape York	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Weipa	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Wilson's Promontory	-	-	-	-	-	200	-	-	-	-	-	-	-	-	-	-
Averages	**0.587**	0.719	0.608	1	0.256	200	0.99	0.50	88	100	18	500000	0.6	8.6	$ 7,189.0	$ 401.3

Table 3-4 Solid Propulsion Alternative Solution

The second alternative solution space was developed around a fully expendable launch vehicle and its results are provided in Table 3-5. Intuitively, this program should be significantly cheaper in terms of research and development costs and overall program running costs. This was indeed the result, with this program approximately $½ billion cheaper on average than the baseline. However, a bigger difference was expected, indicating a weakness in the models generation of the ROM cost figures. This does not detract from the top-level approximation generated by the model, only that it is an area that needs to be strengthened if progressing to preliminary design.

Again Woomera and Christmas Island are in the top three results with favourable benefit functions 66.7% and 65.9% respectively. The program proposed by the model is based around a liquid propulsion, expendable LEO vehicle; a plausible alternative to the baseline. The table below summarises the results from this run.

Launch Site	Function Benefit	Benefit Components				Independent Variables						Model Factoids				
		PA	ETB	SEC	CF	ISP	MF	PMF	% Reuse	% Indig	Dur	Total Mass	No. Launch	ΔV (km/s)	Total Cost ($m)	Cost/Yr ($m)
Woomera	**0.667**	0.698	0.438	1	0.664	320	0.93	0.28	0	100	11	240000	0.9	8.1	$ 2,696.0	$ 245.1
Orange	**0.660**	0.690	0.439	1	0.653	300	0.94	0.30	0	100	12	270000	0.7	8.1	$ 2,889.3	$ 240.8
Christmas Island	**0.659**	0.688	0.428	1	0.658	300	0.93	0.28	0	100	12	250000	0.5	8.0	$ 2,851.7	$ 237.6
Townsville	**0.655**	0.690	0.445	1	0.631	300	0.94	0.30	0	100	12	260000	0.7	8.1	$ 3,077.2	$ 256.4
Mt Isa	**0.655**	0.693	0.445	1	0.627	300	0.94	0.30	0	100	12	260000	0.9	8.0	$ 3,108.0	$ 259.0
Cooktown	**0.647**	0.682	0.454	1	0.610	300	0.95	0.30	0	100	13	310000	0.6	8.2	$ 3,360.6	$ 258.5
Hummock Hill	**0.641**	0.684	0.460	1	0.583	320	0.95	0.30	0	100	13	310000	0.8	8.4	$ 3,591.7	$ 276.3
Cape York	**0.633**	0.676	0.456	1	0.569	320	0.95	0.30	0	100	14	310000	0.7	8.0	$ 3,821.8	$ 273.0
Weipa	**0.625**	0.676	0.462	1	0.538	340	0.95	0.30	0	100	14	310000	0.7	8.0	$ 4,096.7	$ 292.6
Wilson's Promontory	**0.622**	0.667	0.476	1	0.530	340	0.96	0.32	0	100	15	360000	0.5	8.4	$ 4,270.3	$ 284.7
Katherine	**0.621**	0.676	0.480	1	0.515	340	0.96	0.32	0	100	14	350000	0.8	8.3	$ 4,298.9	$ 307.1
Borroloola	**0.619**	0.677	0.480	1	0.504	340	0.96	0.32	0	100	14	350000	0.9	8.0	$ 4,391.6	$ 313.7
Nhulunbuy	**0.617**	0.670	0.476	1	0.510	340	0.96	0.32	0	100	15	360000	0.7	8.5	$ 4,456.9	$ 297.1
Wyndham	**0.617**	0.670	0.476	1	0.509	340	0.96	0.32	0	100	15	350000	0.8	8.0	$ 4,459.8	$ 297.3
Broome	**0.614**	0.676	0.493	1	0.479	320	0.97	0.34	0	100	14	430000	0.9	8.1	$ 4,612.8	$ 329.5
Port Hedland	**0.613**	0.677	0.493	1	0.478	320	0.97	0.34	0	100	14	430000	0.9	8.1	$ 4,628.4	$ 330.6
Gunn Point	**0.609**	0.670	0.481	1	0.480	360	0.96	0.32	0	100	15	360000	0.7	8.2	$ 4,730.3	$ 315.4
Averages	**0.634**	0.680	0.464	1	0.561	324	0.95	0.31	0	100	13	324118	0.7	8.1	$ 3,843.6	$ 283.2

Table 3-5 Zero Percent Reusable Alternative Solution

The final alternative combines the two previous runs fixing both the method of propulsion (to solid) and the percentage reusability (0%). Intuitively this system, although not scoring anywhere near as high as previous results, should provide the cheapest alternative. It is, in fact, the starting point of many nations space programs, including Australia's. However, it provides an inefficient launch system when compared to others currently in use. Unfortunately, due to the models attempts to maximise political gain and elevation of in-country technology base, those sites that were able to register a result were again pushing the upper bounds of the model, resulting in a very expensive program.

These characteristics could be constrained by lowering the upper bounds, however, this defeats the purpose of the model by artificially constraining the program. The model could easily be manipulated in this way to produce wanted results, however, it would be far easy just to write the "answer" down without going developing the model in the first place. Of course this type of results fails to stand up to even the smallest degree of scrutiny.

Launch Site	Function Benefit	Benefit Components: PA	ETB	SEC	CF	Independent Variables: ISP	MF	PMF	% Reuse	% Indig	Dur	Model Factoids: Total Mass	No. Launch	ΔV (km/s)	Total Cost ($m)	Cost/Yr ($m)
Orange	**0.602**	0.659	0.479	1	0.471	200	0.98	0.40	0	100	15	500000	0.7	8.1	$ 4,809.0	$ 320.6
Woomera	**0.524**	0.565	0.503	1	0.289	200	0.99	0.52	0	100	18	500000	0.9	8.7	$ 6,877.3	$ 382.1
Christmas Island	**0.503**	0.553	0.499	1	0.273	200	0.99	0.52	0	100	19	500000	0.5	9.2	$ 7,154.8	$ 376.6
Townsville	**0.502**	0.563	0.503	1	0.252	200	0.99	0.52	0	100	18	500000	0.7	8.8	$ 7,236.6	$ 402.0
Cooktown	**0.502**	0.561	0.503	1	0.254	200	0.99	0.52	0	100	18	500000	0.6	8.4	$ 7,220.1	$ 401.1
Hummock Hill	**0.501**	0.564	0.503	1	0.251	200	0.99	0.52	0	100	18	500000	0.8	8.0	$ 7,253.2	$ 403.0
Mt Isa	**0.500**	0.566	0.503	1	0.244	200	0.99	0.52	0	100	18	500000	0.9	8.8	$ 7,321.2	$ 406.7
Borroloola	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Gunn Point	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Katherine	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Nhulunbuy	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Broome	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Port Hedland	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Wyndham	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Cape York	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Weipa	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Wilson's Promontory	-	-	-	-	-	200	-	-	0	-	-	-	-	-	-	-
Averages	**0.519**	0.576	0.499	1	0.291	200	0.99	0.50	0	100	18	500000	0.7	8.6	$ 6,838.9	$ 384.6

Table 3-6 Solid Propulsion, Zero Percent Reusable Alternative Solution

Common to all results is a score of 1 in the security benefit. This was not an expected result, however, becomes quite apparent upon investigation of the makeup of this benefit. The curves for both ΔV and payload mass are maximised for relatively low velocities and masses making it relatively easy to maximise this benefit. As a consequence when further investigating dominance in the results, the security component was not part of this analysis.

3.4 Non-Linear Programming

A non-linear approach was investigated in an effort to attain a higher resolution result than was achievable with the brute force approach within the time available. An algorithm was selected from the IMSL library, a collection of Fortran and C subroutines and functions useful in statistical and mathematical analysis, and applied to the benefit function in an attempt to maximise it further. This subroutine, NCONF solves a general non-linear programming problem using the successive quadratic programming algorithm and a finite difference gradient. Not only does NCONF allow the problem to be bounded, it also has the added flexibility of supporting constraints. A listing of the subroutine is attached at Appendix D.

Similar to the brute force approach, the problem was controlled with a ΔV constraint to ensure the solutions where able to achieve orbit. A number of other constraints were also tested prior to running the brute force approach in an attempt to overcoming a significant problem of non-linear optimising in n-space. This problem revolves around the development of local maxima within, in this case, 6-space. As a result the non-linear optimiser would get caught in the vicinity of a local maxima.

To alleviate this problem a low resolution brute force approach was initiated to provide initial conditions that would place the non-linear optimiser in the vicinity of the grid space maximum. During the development of the brute force approach, discussed above, the initial results indicated that this approach would actually provide sufficient resolution for the context of a concept exploration. However, the non-linear was still run to provide a comparison. The source code for the non-linear optimiser program can be found at Appendix E.

The table below illustrates the comparison between the brute force baseline results and the non-linear optimised results, using the brute force baseline as the ICs. The non-linear optimiser was not able to provide results for four of the seventeen launch sites due a characteristic of the optimiser. The optimiser has a built in limit on the number of function calls it is able to make for the line search. The runs for the launch sites Broome, Port Hedland, Weipa and Wilson's Promontory all exceeded this value and the program terminated prior to convergence.

Launch Site	Method	Function Benefit	Benefit Components PA	ETB	SEC	CF	Independent Variables ISP	MF	PMF	% Reuse	% Indig	Dur	Model Factoids Total Mass	No. Launch	ΔV (km/s)	Total Cost ($m)	Cost/Yr ($m)
Woomera	BF	**0.734**	0.837	0.544	1	0.631	320	0.93	0.28	88	100	12	250000	0.7	8.1	$ 3,076.7	$ 256.4
	NL	**0.661**	0.661	0.435	1	0.697	319	0.929	0.279	85.8	100	40	250000	0.7	8.0	$ 3,567.4	$ 89.2
Orange	BF	**0.728**	0.833	0.544	1	0.618	280	0.94	0.28	88	100	12	280000	0.6	8.1	$ 3,183.5	$ 265.3
	NL	**0.660**	0.685	0.432	1	0.699	281	0.937	0.277	85.6	100	40	280000	0.6	8.0	$ 3,545.6	$ 88.6
Christmas Island	BF	**0.727**	0.833	0.538	1	0.619	300	0.93	0.28	88	100	12	250000	0.4	8.0	$ 3,171.6	$ 264.3
	NL	**0.660**	0.657	0.430	1	0.702	300	0.93	0.282	85.6	100	40	250000	0.4	8.0	$ 3,504.1	$ 87.6
Townsville	BF	**0.722**	0.829	0.551	1	0.599	300	0.94	0.30	88	100	13	270000	0.6	8.1	$ 3,450.5	$ 265.4
	NL	**0.655**	0.659	0.444	1	0.671	300	0.938	0.294	85.7	100	40	270000	0.6	8.0	$ 3,866.2	$ 96.7
Mt Isa	BF	**0.722**	0.830	0.551	1	0.595	300	0.94	0.30	88	100	13	260000	0.8	8.0	$ 3,485.9	$ 268.1
	NL	**0.652**	0.661	0.447	1	0.657	300	0.939	0.304	85.7	100	40	260000	0.8	8.0	$ 4,034.7	$ 100.9
Cooktown	BF	**0.715**	0.826	0.564	1	0.571	300	0.95	0.30	88	100	13	310000	0.5	8.2	$ 3,693.2	$ 284.1
	NL	**0.652**	0.658	0.456	1	0.656	301	0.947	0.298	86	100	40	310000	0.5	8.0	$ 4,044.1	$ 101.1
Hummock Hill	BF	**0.709**	0.828	0.570	1	0.543	320	0.95	0.30	88	100	13	310000	0.7	8.4	$ 3,939.1	$ 303.0
	NL	**0.647**	0.660	0.452	1	0.637	319	0.943	0.279	86	100	40	310000	0.7	8.0	$ 4,266.0	$ 106.7
Cape York	BF	**0.701**	0.821	0.566	1	0.530	320	0.95	0.30	88	100	14	310000	0.6	8.0	$ 4,165.6	$ 297.5
	NL	**0.639**	0.659	0.469	1	0.605	320	0.95	0.313	86.2	100	40	31000	0.6	8.0	$ 4,652.2	$ 116.3
Weipa	BF	**0.693**	0.821	0.584	1	0.491	320	0.96	0.32	88	100	14	360000	0.6	8.2	$ 4,509.0	$ 322.1
	NL	**No**	**Result**														
Wilson's Promontory	BF	**0.691**	0.811	0.586	1	0.495	340	0.96	0.32	88	100	15	360000	0.4	8.4	$ 4,593.6	$ 306.2
	NL	**No**	**Result**														
Katherine	BF	**0.689**	0.815	0.586	1	0.485	340	0.96	0.32	88	100	15	360000	0.7	8.3	$ 4,683.5	$ 312.2
	NL	**0.430**	0.808	0.555	1	-0.348	353	0.95	0.228	88	100	15	360000	0.7	8.0	$ 12,271.7	$ 815.5
Borroloola	BF	**0.686**	0.816	0.586	1	0.473	340	0.96	0.32	88	100	15	360000	0.7	8.0	$ 4,787.6	$ 319.2
	NL	**0.619**	0.663	0.476	1	0.527	365	0.95	0.285	86.6	100	40	360000	0.7	8.0	$ 5,569.6	$ 139.2
Nhulunbuy	BF	**0.685**	0.813	0.594	1	0.468	300	0.97	0.34	88	100	15	440000	0.6	8.1	$ 4,833.1	$ 322.2
	NL	**0.625**	0.661	0.460	1	0.560	348	0.95	0.239	86.4	100	40	440000	0.6	8.0	$ 5,179.1	$ 129.5
Wyndham	BF	**0.685**	0.816	0.590	1	0.468	340	0.96	0.32	88	100	15	360000	0.7	8.0	$ 4,834.4	$ 322.3
	NL	**0.618**	0.661	0.474	1	0.527	365	0.95	0.275	87	100	40	360000	0.7	8.0	$ 5,569.2	$ 139.2
Broome	BF	**0.682**	0.814	0.600	1	0.451	320	0.97	0.34	88	100	15	430000	0.7	8.1	$ 4,989.7	$ 332.6
	NL	**No**	**Result**														
Port Hedland	BF	**0.681**	0.815	0.600	1	0.449	320	0.97	0.34	88	100	15	430000	0.8	8.1	$ 5,010.5	$ 334.0
	NL	**No**	**Result**														
Gunn Point	BF	**0.677**	0.814	0.591	1	0.442	360	0.96	0.32	88	100	15	360000	0.6	8.2	$ 5,074.2	$ 338.3
	NL	**0.613**	0.658	0.475	1	0.5133	381	0.95	0.261	86.8	100	40	360000	0.6	8	$ 5,725.8	$ 143.1
Averages	BF	**0.702**	0.822	0.573	1	0.525	319	0.95	0.31	88	100	14	335294	0.6	8.1	$ 4,204.8	$ 300.8
	NL	**0.625**	0.673	0.462	1	0.546	327	0.943	0.278	86.2	100	38	295462	0.6	8.0	$ 5,061.2	$ 165.7

BF – Brute Force Optimisation
NL – Non-linear Optimisation

Table 3-7 Comparison Between Brute Force Baseline and Non-Linear Optimisation Results

This table serves two purposes; firstly it shows a major discrepancy between the brute force and non-linear optimisation results. By using the brute force results as the ICs for the non-linear runs this result should not have occurred. Following a review of the source code no apparent errors were recognised and no obvious reason behind this result could be determined. It also shows the value of the brute force approach, although computationally cumbersome, is a valid optimisation technique under the appropriate circumstances. Due to the non-linear optimiser's inability to provide results for four of the sites and the fact that it did not improve the brute force results, these results were not implemented as the new baseline.

3.5 Analysis and Interpretation

The first step in analysing these results is to convert them into a manageable form that is relevant to the context in which the decision is to be made. Each result is converted from numbers generated by the model into concepts that are then presented to the decision maker. Table 3-8 below takes the top six non-test site answers from the baseline results as well as the top two non-test site results from the alternatives and converts them into this format.

Launch Site	Benefit	Propulsion	Mass Fraction	Payload Mass Fraction	Reusability	Indigenous	Duration	Vehicle size	Orbit Capability	Total Cost ($m)
Baseline										
Woomera	73.4%	Liquid	High	Average	Highly	Fully	12	Medium	LEO	$ 3,076.7
Christmas Island	72.7%	Liquid	High	Average	Highly	Fully	12	Medium	LEO	$ 3,171.6
Townsville	72.2%	Liquid	High	Average	Highly	Fully	13	Medium	LEO	$ 3,450.5
Mt Isa	72.2%	Liquid	High	Average	Highly	Fully	13	Medium	LEO	$ 3,485.9
Cooktown	71.5%	Liquid	Very High	Average	Highly	Fully	13	Medium	LEO	$ 3,693.2
Hummock Hill	70.9%	Liquid	Very High	Average	Highly	Fully	13	Medium	LEO	$ 3,939.1
0% Reusable										
Woomera	66.7%	Liquid	High	Average	None	Fully	11	Medium	LEO	$ 2,696.0
Christmas Island	65.9%	Liquid	High	Average	None	Fully	12	Medium	LEO	$ 2,851.7
Solid										
Woomera	58.2%	Solid	Extreme	Extreme	Highly	Fully	18	Large	LEO	$ 7,239.4
Christmas Island	57.3%	Solid	Extreme	Extreme	Highly	Fully	19	Large	LEO	$ 7,483.4
Solid 0% Reusable										
Woomera	52.4%	Solid	Extreme	Extreme	None	Fully	18	Large	LEO	$ 6,877.3
Christmas Island	50.3%	Solid	Extreme	Extreme	None	Fully	19	Large	LEO	$ 7,154.8

Table 3-8 Summary of the Model's Results

The next step is to demonstrate dominance of this results set over other possible solutions. One method is to plot the results in a Pareto diagram. This diagram illustrates the dominance of a set of results over others through the formation of what is known as a Pareto front. The figure below illustrates two examples of a two-dimensional Pareto diagram. The first has a convex Pareto front, while the second has a concave Pareto front. A result that is high (increasing Y-axis) and to the right (increasing X-axis) of another is said to dominate that result. In Figure 3-3 dominated results are marked with a cross, while Pareto optimal results are marked with a right angle to indicate that there are no other results above or to the right of them. If you were to connect the dominating results with a line, the line would form a front and hence the term Pareto front.

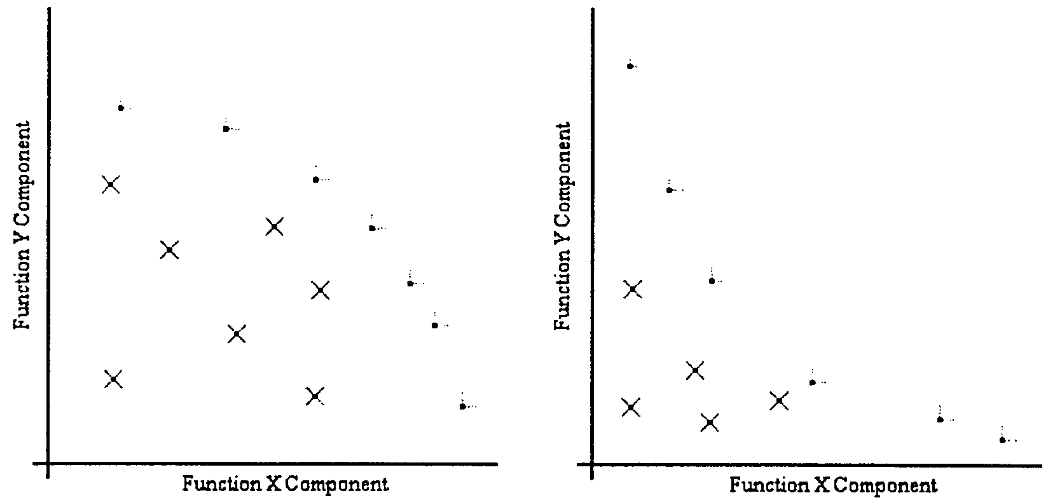


Figure 3-3 Examples of Convex and Concave Pareto Fronts

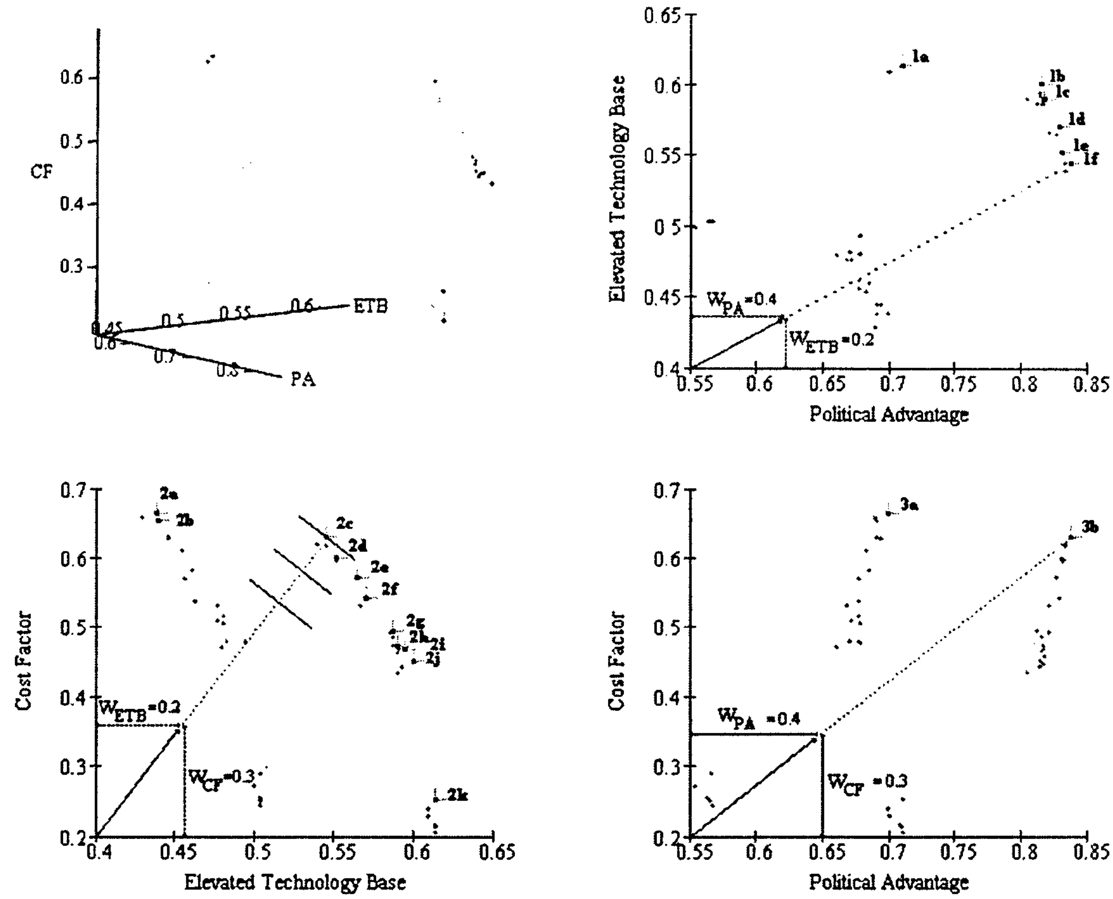
The Pareto optimal solutions are non-dominating with respect to each other and any solution on the front could logically be chosen as the "optimal" solution dependant on the decision maker's priorities. An objective function unit "vector" based on the selected benefit component weights can be add to the diagram to select the "optimal" solution based on the weightings selected. In this case the weightings used were 0.4 PA, 0.3 $$, 0.2 ETB, and 0.1 Sec.

Although the modelled function is made up of the above four benefits, one of them, security, is completely uninteresting. This is convenient as it enables the development of a three dimension Pareto diagram using the remaining three function benefits, political advancement, elevation of technology base and cost factor. In a three-dimensional Pareto diagram sub fronts are formed in each of the three two-dimensional projections.

Figure 3-4 below allows the decision-maker to ascertain if and in what areas other decisions may be considered optimal. It also illustrates the benefit component levels for each solution. This enables logical selection of an optimal solution that scores appropriately in the areas prioritised by the decision maker. Unfortunately the model may not have reflected the decision maker's priorities as accurately as first thought.

By introducing the objective function unit "vector" to each two-dimensional Pareto diagram the optimal solution based on the weighting scheme employed stands out. Another interesting feature is the ability to gauge result robustness through the variation in the objective function required to obtain another "optimal" solution. In the figure below, the objective function clearly points to the Woomera baseline result in all three of the two-dimensional Pareto diagrams.

Added to the Cost Factor – Elevated Technology Base two-dimensional Pareto diagram are three lines perpendicular to the objective function unit "vector". The purpose of these lines is to demonstrate that the "best" result for a weighting scheme of 0.4 PA, 0.3 $$, 0.2 ETB, and 0.1 Sec, is the solution that lies the furthest out in the direction of the objective function along a line perpendicular to that objective function in this case Woomera Baseline. Similar lines on the remaining two two-dimensional Pareto diagrams would also indicate that Woomera Baseline is indeed the most optimal solution for this weighting scheme.



	Site	Benefit	PA	ETB	CF
1a	Mt Isa Solid	0.568	0.710	0.613	0.206
1b	Port Hedland Baseline	0.681	0.815	0.600	0.449
1c	Wyndham Baseline	0.685	0.816	0.590	0.468
1d	Hummock Hill Baseline	0.709	0.828	0.570	0.543
1e	Mt Isa Baseline	0.722	0.830	0.551	0.595
1f	Woomera Baseline	0.734	0.837	0.544	0.631
2a	Woomera 0%	0.667	0.698	0.438	0.664
2b	Orange 0%	0.660	0.690	0.439	0.653
2c	Woomera Baseline	0.734	0.837	0.544	0.631
2d	Townsville Baseline	0.722	0.829	0.551	0.599
2e	Cooktown Baseline	0.715	0.826	0.564	0.571
2f	Hummock Hill Baseline	0.709	0.828	0.570	0.543
2g	Wilson's Promontory Baseline	0.691	0.811	0.586	0.495
2h	Katherine Baseline	0.689	0.815	0.586	0.485
2i	Borroloola Baseline	0.686	0.816	0.586	0.473
2j	Nhulunbuy Baseline	0.685	0.813	0.594	0.468
2k	Woomera Solid	0.582	0.709	0.613	0.252
3a	Woomera 0%	0.667	0.698	0.438	0.664
3b	Woomera Baseline	0.734	0.837	0.544	0.631

Figure 3-4 Benefit Function Pareto Diagram

The next area of interest is cost. The constructs of the cost model were developed from research into each sub component of the whole model. These sub components were then combined to form the overall ROM costings. This bottom up approach is a valid technique and as can be seen by similar programs in other countries, illustrated in the table below, the ROM costings are suitably comparative. The model is indicating a ROM costing of around $250 million per year with a total program cost of around $4 billon. The table below shows the annual costings for other nations' space launch programs, all figures are in USD billions. They range from approximately $50 million per year for Israel to $13.6 billion per year for the US.

Country	**Total Budget Expenditure**	**Space Program Expenditure**	**% of Total Budget**	**Equivalent Australian Expenditure**
Australia[1]	85.386	N/A	N/A	N/A
Brazil[2]	160.747	0.3	0.19	0.159
Canada[3]	109.423	0.1925	0.18	0.150
France[4]	222.202	1.53	0.69	0.588
India[5]	?	0.300	-	-
Israel[6]	?	Approx 0.050	-	-
USA[7]	591.5	13.6	2.3	1.963

1 Australian Commonwealth Budget Outcome 2000
2 Brazilian National Institute of Space Research
3 Canadian Budgetary Expenditures 1999-2000
4 French Budgetary Expenditures 1999-2000
5 World Space Budgets 1996
6 World Space Budgets 1996
7 Discretionary Budget Authority by Agency Fiscal Year 2001

Table 3-9 Space Program Expenditure by Country

CHAPTER 4 Conclusions and Recommendation

4.1 Conclusion

Systems engineering provides a framework within which to tackle complex problems through a logical process of problem definition and breakdown. The first stage in this process, commonly referred to as concept exploration, provides the processes required to examine an idea at a elementary-level. This procedure enables decision-makers to resolve whether to proceed into a more detailed (and costly) examination of an idea without the liability of a large commitment of resources.

This thesis has demonstrated the utility of the CE process in evaluating an abstract concept, the development of an Australian indigenous space launch capability. It has also demonstrated the usefulness of the optimisation technique known as the brute force approach. By clearly defining the boundaries of the grid space and having an understanding of the level of resolution required in the results, this process, is able to repeatedly produce a series of logical alternative solutions that provide a decision maker with set of rational options.

4.2 Thesis Recommendations

The first and most important observation is that an indigenous space launch capability is indeed something within the abilities of Australia to pursue. Not only within the context of economics, but more importantly, within the context of Australia's political and technological interests. Unfortunately Australia has, in the past, let such opportunities go by, failing to build on previous endeavours. Fortunately it is not to late for Australia too rejoin the game.

Based on the results of the model, this thesis recommends that Woomera offers the best launch site location out of the seventeen investigated. It is the highest scoring launch site for the objective function weights chosen and is part of the optimal solution set within the Pareto diagrams. In support of this recommendation, three of the five turnkey commercial launch solutions currently before the Australian parliament are proposing to utilise Woomera as their preferred launch site.

In terms of launch vehicle design the model points towards a liquid, reusable LEO system. This is in line with the current trend of a number of countries that are undertaking research into space launch vehicles. Whether the system is to be automated or man-rated was not investigated as part of this thesis.

The model points to a program duration of between 12 to 15 years, 12 for Woomera, with a total ROM budget of $3,077 million ($256 million per year). This is within the reasonable expenditure range determined by studying the Australian budget and other countries' annual expenditures on space. Obviously this figure is nowhere near what the US spends; however, it is similar to India's and Brazil's annual expenditure. Total number of launches during the development program would be around 8-10 with a ramp up of operations over the duration of the program. The intent would then be to cultivate a market niche in an effort to make the program self sufficient, maybe even profitable.

4.3 Further work

There are a number of ways to improve the model in order to develop it for the preliminary design phase. Currently the costing model provides very rough estimates on overall program costings based on a bottom up approach. Although sufficient to make a decision on whether to proceed or not at a concept exploration level, appropriate recognised industry cost models should be implemented if proceeding to a more detailed exploration or preliminary design.

Another area is the development of the launch site location IVs. Currently this component has been made discrete to simplify the model, however, it could easily be made continuous. This would involve the development of a digital map of Australia made up of a number of sub maps that would provide information on:

- Monthly rainfall distribution,
- Rail and port infrastructure, and
- Population distribution.

These maps could then be used to accurately calculate the number of days on which a launch could occur, provide the launch assistance ΔV due to the rotation of the Earth, provide the launch inclination ranges available from any given location, and detail the support infrastructure already in place. This would ensure that a range of alternative sites could be traded off against each other based on the decision-maker's priorities.

A major part of the progression to preliminary design is the instigation of trade studies, an important systems engineering information tool. Studies into the following areas would provide the information required to progress the capability.

- Vehicle design
  - Reusable Vs expendable
  - Solid Vs liquid
  - Man Vs Un-manned
- Industry support and establishment studies
- In-country technology base build-up studies
- Government and industry support studies

Of course the first step is to get the support of the people of Australia. Then persuade the decision makers to agree that this is indeed what Australia really wants and more importantly needs in order to stay competitive in the international arena.

Appendix A: Space Launch Vehicle Mass Characteristics

Vehicle	Total	Mass	Dry	Cost per Kg		Average	Payload Mass			Payload Mass Fraction		
Type	Mass (kg)	Fraction	Mass (kg)	Lower	Upper	Cost	LEO	SSO	GTO	LEO	SSO	GTO
Ariane AR40	298280	0.92	23180	$ 218	$ 285	$ 251	5000	2845	2175	0.216	0.123	0.094
Ariane AR42P	339000	0.87	44900	$ 206	$ 265	$ 236	6600	3845	2890	0.147	0.086	0.064
Ariane AR44P	358000	0.87	44900	$ 223	$ 279	$ 251	7600	4560	3465	0.169	0.102	0.077
Ariane AR42L	400000	0.89	45900	$ 200	$ 250	$ 225	7900	4810	3590	0.172	0.105	0.078
Ariane AR44LP	420000	0.89	46900	$ 214	$ 262	$ 238	9100	5660	4290	0.194	0.121	0.091
Ariane AR44L	470000	0.92	36900	$ 213	$ 266	$ 239	10200	6485	4790	0.276	0.176	0.130
Ariane 5	737000	0.87	93700	$ 204	$ 244	$ 224	18000	12000	6800	0.192	0.128	0.073
Athena 1	66300	0.89	7466	$ 241	$ 256	$ 249	820	360		0.110	0.048	0.000
Athena 2	120700	0.89	13166	$ 182	$ 215	$ 199	2065	1165	590	0.157	0.088	0.045
Atlas 2A	187500	0.92	14320	$ 400	$ 453	$ 427	7316		3066	0.511	0.000	0.214
Atlas 2AS	237200	0.90	23620	$ 379	$ 443	$ 411	8618		3719	0.365	0.000	0.157
Atlas 3A	220700	0.90	21870	$ 408	$ 476	$ 442	8640	5671	4037	0.395	0.259	0.185
Atlas 3B	225400	0.90	22670	$ 399	$ 466	$ 433	10718	5885	4477	0.473	0.260	0.197
Atlas 5-400	333300	0.92	27970	$ 225	$ 270	$ 248	12500		5000	0.447	0.000	0.179
Delta 2-7320	151740	0.92	12332	$ 297	$ 362	$ 330	5140	3220	1870	0.417	0.261	0.152
Delta 2-7925	231870	0.91	21872	$ 216	$ 259	$ 237	5140	3220	1870	0.235	0.147	0.085
Delta 3	301450	0.88	35990	$ 249	$ 299	$ 274	8290	6100	3810	0.230	0.169	0.106
Delta 4-Medium	249500	0.88	29500	$ 301	$ 361	$ 331	8600	6300	3900	0.292	0.214	0.132
Delta 4-Medium +	404600	0.84	64984	$ 210	$ 247	$ 229	13600	9600	6120	0.209	0.148	0.094
Delta 4-Heavy	733400	0.85	107400	$ 191	$ 232	$ 211	25800	19200	12400	0.240	0.179	0.115
H 2	260000	0.84	41300	$ 635	$ 654	$ 644	10060	4220	3930	0.244	0.102	0.095
H 2A-202	289000	0.86	40300	$ 260	$ 260	$ 260	9940	4350	4100	0.247	0.108	0.102
H 2A-212	406000	0.84	64800	$ 185	$ 234	$ 209	17280		7500	0.267	0.000	0.116
Kosmos 3M	109000	0.92	8400	$ 110	$ 110	$ 110	1500	775		0.179	0.092	0.000
LM 2C	192000	0.93	14000	$ 104	$ 130	$ 117	3900		1400	0.279	0.000	0.100
LM 2C/2SD	213000	0.93	15000	$ 94	$ 117	$ 106	3900		1400	0.260	0.000	0.093
LM 2D	249500	0.93	16500	$ 40	$ 60	$ 50	3500			0.212	0.000	0.000
LM 2E	460000	0.93	30556	$ 98	$ 120	$ 109	9500		3500	0.311	0.000	0.115
LM 3	204000	0.92	16500	$ 172	$ 196	$ 184			1500	0.000	0.000	0.091
LM 3A	241000	0.91	21430	$ 187	$ 228	$ 207			2600	0.000	0.000	0.121
LM 3B	425800	0.87	55230	$ 117	$ 164	$ 141	11200	6000	5100	0.203	0.109	0.092
LM 3C	345000	0.86	49930	$ 159	$ 217	$ 188			3800	0.000	0.000	0.076
LM 4	249200	0.93	16200	$ 80	$ 120	$ 100		1650		0.000	0.102	0.000
LM 4B	249200	0.93	16200	$ 100	$ 140	$ 120		2800		0.000	0.173	0.000
Pegasus	23000	0.86	3256	$ 522	$ 652	$ 587	443	190		0.136	0.058	0.000
Proton K	691500	0.92	54350	$ 130	$ 142	$ 136	19760	3620	4910	0.364	0.067	0.090
Proton M	700000	0.92	58100	$ 143	$ 160	$ 151	21000		5500	0.361	0.000	0.095
PSLV	655720	0.92	49320	$ 23	$ 38	$ 31	3700	1200	800	0.075	0.024	0.016
GSLV	402000	0.84	63000	$ 87	$ 112	$ 100	5000	2200	2500	0.079	0.035	0.040
LK-1	30500	0.90	3041	$ 328	$ 492	$ 410	550			0.181	0.000	0.000
LK-2	70000	0.91	6421	$ 257	$ 286	$ 271	1550			0.241	0.000	0.000
Soyuz U	310000	0.89	33080	$ 97	$ 161	$ 129	7000	2750	1350	0.212	0.083	0.041
Soyuz ST & FG	305000	0.92	24465	$ 98	$ 164	$ 131	7800	4500	1450	0.319	0.184	0.059
Molniya M	305000	0.92	23400	$ 98	$ 131	$ 115		1500		0.000	0.064	0.000
Start 1	47000	0.86	6800	$ 191	$ 191	$ 191	632	167		0.093	0.025	0.000
Taurus	73000	0.89	8024	$ 247	$ 274	$ 260	1320	660	400	0.165	0.082	0.050
Titan 2	155000	0.94	10000	$ 194	$ 258	$ 226	1900			0.190	0.000	0.000
Titan 4B	925000	0.90	87900	$ 378	$ 486	$ 432	21680			0.247	0.000	0.000
Tsiklon 2	180000	0.93	12100	$ 111	$ 139	$ 125	3350	2100		0.277	0.174	0.000
Tsiklon 3	190000	0.90	19800	$ 105	$ 132	$ 118	4100			0.207	0.000	0.000
VLS	49600	0.83	8456	$ 161	$ 161	$ 161	380	80		0.045	0.009	0.000
VLM	15900	0.80	3156	$ 252	$ 252	$ 252	100	18		0.032	0.006	0.000

Vehicle	Total	Mass	Dry	Cost per Kg		Average	Payload Mass			Payload Mass Fraction		
Type	Mass (kg)	Fraction	Mass (kg)	Lower	Upper	Cost	LEO	SSO	GTO	LEO	SSO	GTO
Zenit 2	459000	0.92	37100	$ 76	$ 109	$ 93	13500	5000		0.364	0.135	0.000
Zenit 3SL	471000	0.90	49100	$ 159	$ 202	$ 180			5000	0.000	0.000	0.102
Averages	**304386**	**0.89**	**31607**	**207**	**250**	**225**	**7791**	**4020**	**3665**	**0.239**	**0.118**	**0.102**
Max	**925000**	**0.94**	**107400**	**635**	**654**	**644**	**25800**	**19200**	**12400**	**0.511**	**0.261**	**0.214**
Min	**15900**	**0.80**	**3041**	**23**	**38**	**31**	**100**	**18**	**400**	**0.032**	**0.006**	**0.016**

Table A-1 Space Launch Vehicle Mass Characteristics

Appendix B: Satellite Inclinations, Eccentricities, and Apogee Velocities

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
1967-048A	2807	89.5918	0.0018472	7440.120556	7305.949599
1967-092A	2965	89.2686	0.0048423	7430.262641	7288.930423
1968-012A	3133	90.0114	0.0076887	7437.537035	7264.656623
ABRIXAS	25721	48.4427	0.0031955	6928.668814	7560.598812
ACRIMSAT	26033	98.2437	0.0029787	7067.464538	7487.613731
ACTS	22796	1.8254	0.0003873	42087.8441	3076.255092
ADEOS	24277	98.466	0.0000984	7164.745086	7458.058432
AFRISTAR	25515	0.0406	0.0003451	42086.80851	3076.422761
ALOUETTE	1	80.4646	0.00224	7370.819704	7337.332034
AMOS	1	0.0763	0.000309	42087.29174	3076.51616
AMSC	1	0.0476	0.0001362	42087.29314	3077.047777
ANIK	E2	0.0567	0.0001674	42087.7859	3076.933762
ANIK	E1	0.0275	0.0001349	42087.52846	3077.043175
ANIK	D1	7.0121	0.0011665	42136.91301	3072.068713
ANIK	C3	6.824	0.0004733	42193.48446	3072.137434
ANIK	D2	5.5664	0.002924	42473.74964	3054.489987
ANIK	C1	2.8647	0.0002054	42088.23362	3076.800476
ANIK	E2	0.0567	0.0001674	42087.7859	3076.933762
ANIK-E1		0.0275	0.0001349	42087.52846	3077.043175
AO-10	14129	26.7172	0.6008132	26054.7923	1953.18256
AO-16	20439	98.4331	0.0010942	7154.623541	7455.903683
AO-21	21087	82.9476	0.0036958	7347.341334	7338.354823
AO-27	22825	98.3873	0.000827	7162.594754	7453.745087
AO-37	26065	100.1955	0.0038612	7142.262849	7441.732711
APSTAR	1	0.0414	0.0000909	42088.56662	3077.140616
APSTAR	A1	0.0463	0.0000772	42087.56988	3077.219211
APSTAR	2R	0.0021	0.0003934	42087.94176	3076.232758
ARABSAT	2A	0.0548	0.0000574	42086.79144	3077.308599
ARABSAT	2B	0.0219	0.0001458	42086.81466	3077.035728
ARABSAT	3A	0.045	0.0004376	42087.01249	3076.130751
ARABSAT	1	7.2601	0.0007545	42040.68013	3076.850153
ARABSAT	1B	6.6156	0.0017508	42039.98031	3073.811792
ARABSAT	1C	0.0921	0.0005606	42087.18709	3075.74603
ARGOS	25634	98.804	0.0008801	7197.055502	7435.483929
ASC	1	4.6835	0.000866	42080.7294	3075.04276
ASIASAT	1	1.3225	0.0001999	42086.82753	3076.868795
ASIASAT	3S	0.0582	0.0001377	42088.26804	3077.007524
ASIASAT	2	0.0426	0.0002324	42087.74169	3076.735384
ASIASAT	3	6.937	0.0048874	42088.2325	3062.428488
ASIASTAR	26107	0.0213	0.0003967	42089.38489	3076.169868
ASTRA	1A	0.0917	0.0045643	42087.43389	3063.447205
ASTRA	1B	0.1175	0.0061507	42089.15177	3058.528646
ASTRA	1C	0.0451	0.0054356	42088.31869	3060.746946
ASTRA	1D	0.0842	0.0022975	42086.84236	3070.420966
ASTRA	1E	0.0935	0.0064206	42088.34164	3057.732655
ASTRA	1F	0.0756	0.0063929	42088.2395	3057.82107

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
ASTRA	1G	0.0946	0.0004346	42086.57263	3076.156054
ASTRA	1H	0.1003	0.0003612	42087.23913	3076.357493
ASTRA-2A	25462	0.0748	0.0007679	42086.38181	3075.137913
ASTRID	2	82.9465	0.0024694	7359.515989	7341.280401
ASTRO	D	31.094	0.0020585	6787.266749	7647.639937
ASUSAT	26065	100.1955	0.0038612	7142.262849	7441.732711
ATS	1	13.3809	0.0002583	42075.82659	3077.091293
ATS	3	14.0791	0.0016448	42087.66502	3072.395664
AURORA	2	0.0733	0.0001411	42087.03263	3077.042222
BIRD-RUBIN/SL-8	R/B	87.25	0.0036232	6793.033755	7632.441054
BONUM	1	0.0437	0.0000805	42086.89385	3077.233771
BRASILSAT	1	4.583	0.0000799	42086.06396	3077.265957
BRASILSAT	2	3.2815	0.0002348	42087.8234	3076.725013
BRASILSAT	B1	0.0453	0.0003269	42089.31884	3076.387006
BRASILSAT	B2	0.0277	0.000152	42087.93756	3076.975603
BRASILSAT	B3	0.0333	0.0001287	42088.40712	3077.030133
BS-3N	23176	0.0213	0.0002143	42088.148	3076.776222
B-SAT	1A	0.0486	0.0000722	42091.73915	3077.082191
B-SAT	1B	0.0449	0.0000777	42088.75691	3077.174279
BSB	R-1	1.0355	0.0002302	42087.94876	3076.734584
BSB	R-2	0.0321	0.000189	42087.48145	3076.87843
CAKRAWARTA	1	0.1381	0.0002867	42089.29393	3076.51159
CALSPHERE	1	90.1958	0.0028049	7375.117851	7331.051153
CALSPHERE	2	90.2095	0.00182	7428.741007	7311.742062
CALSPHERE	4(A)	90.1106	0.0069715	7493.420798	7242.709964
CBERS-1	25940	98.5176	0.0000875	7138.533214	7471.819894
CELESTIS-01	24780	150.9694	0.001417	6879.991247	7600.804274
CELESTIS-02	25160	108.0096	0.0066201	7191.431564	7395.815986
CELESTIS-03	26034	98.2421	0.0025919	7057.393605	7495.853114
CERISE	23606	98.2823	0.0008403	7016.941241	7530.607808
CHAMP	26405	87.2653	0.0038417	6809.097807	7621.766933
CHINASTAR	1	0.0156	0.0000712	42087.83907	3077.227834
CLEMENTINE	25978	98.1082	0.0011085	7012.882661	7530.76657
CLUSTER	II/FM7	89.7077	0.6791392	75129.27551	1006.883602
CLUSTER	II/FM6	89.6973	0.6757112	75129.02653	1013.284491
CLUSTER	II/FM5	89.7191	0.6764002	75130.51209	1011.989447
CLUSTER	II/FM8	89.6959	0.6777426	75128.77636	1009.495793
COBE	20322	98.9032	0.0008145	7245.68241	7410.977723
COLUMBIA	515	2.5577	0.00038	42087.97646	3076.272711
COMSTAR	4	10.9055	0.000103	42088.56579	3077.103414
COMSTAR	2	12.1181	0.0003663	42167.41562	3073.415757
CORONAS	I	82.4671	0.0008353	6738.929367	7684.412493
COSMOS	2054	6.6551	0.0007657	42062.92519	3076.001994
COSMOS	2085	6.2461	0.0005965	42086.82138	3075.648975
COSMOS	2133	4.8435	0.0004247	42085.53263	3076.224516
COSMOS	2172	5.2923	0.0005784	42085.43723	3075.755223
COSMOS	2209	4.78	0.0002327	42089.05523	3076.68645
COSMOS	2224	3.5352	0.0001021	42083.95248	3077.274837

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
COSMOS	2282	2.4135	0.0012945	42116.11019	3072.43403
COSMOS	2291	3.1582	0.0005624	42091.08114	3075.598214
COSMOS	23653	2.4295	0.0001523	42088.3117	3076.961004
COSMOS	2345	1.1825	0.0165258	42053.99649	3028.220768
COSMOS	2350	0.4724	0.0005892	42091.68849	3075.493601
COSMOS	2371	1.1848	0.000314	42086.04213	3076.546451
COSMOS	2374	64.8214	0.0002146	25461.56337	3955.789334
COSMOS	2375	64.8201	0.0001853	25461.58543	3955.903526
COSMOS	2376	64.7921	0.0021239	25507.74444	3944.668026
COSMOS	2346	82.9225	0.0039708	7331.505451	7344.255909
COSMOS	1383	82.9299	0.0027999	7370.682549	7333.293214
COSMOS	1447	82.9415	0.0038702	7348.133544	7336.679588
COSMOS	1574	82.9566	0.002662	7350.685701	7344.27392
COSMOS	1791	82.9486	0.0042635	7345.751938	7334.98336
COSMOS	2074	82.9451	0.0027763	7349.503023	7344.025338
COSMOS	2123	82.919	0.0030534	7349.150483	7342.166669
COSMOS	2142	82.953	0.0036952	7354.829713	7334.62247
COSMOS	2154	82.9117	0.0023664	7353.998775	7344.7902
COSMOS	2173	82.9524	0.0048883	7346.580313	7329.988511
COSMOS	2180	82.9237	0.0039376	7352.577312	7333.967839
COSMOS	2181	82.9449	0.0029334	7357.180441	7339.039429
COSMOS	2184	82.9314	0.0032041	7354.633336	7338.3234
COSMOS	2218	82.9244	0.0034429	7355.539331	7336.119355
COSMOS	2230	82.9426	0.002325	7353.718907	7345.234051
COSMOS	2233	82.9393	0.0037272	7345.470909	7339.058617
COSMOS	2239	82.929	0.0024525	7346.717193	7347.796458
COSMOS	2266	82.95	0.004902	7348.550421	7328.90547
COSMOS	2279	82.9456	0.0037141	7345.846597	7338.967086
COSMOS	2310	82.9476	0.0021666	7359.620059	7343.451768
COSMOS	2315	82.9055	0.0029555	7355.823471	7339.554127
COSMOS	2327	82.9841	0.0049493	7350.368572	7327.652378
COSMOS	2334	82.9308	0.0030286	7353.388658	7340.232548
COSMOS	2336	82.9409	0.0022448	7360.037715	7342.669185
COSMOS	2341	82.9245	0.0024435	7360.130606	7341.164008
COSMOS	2346	82.9225	0.0039708	7331.505451	7344.255909
COSMOS	2361	82.9297	0.0031324	7355.670912	7338.331962
COSMOS	2366	82.9321	0.0032245	7350.058903	7340.456861
COSMOS	2265	82.8522	0.0582481	7059.33092	7088.618785
COSMOS	2332	82.9619	0.0656863	7121.308449	7005.201896
COSMOS	1602	82.5265	0.0020059	6963.810609	7550.474753
COSMOS	1766	82.5077	0.001903	6967.713897	7549.136351
CRRES	20712	18.1437	0.7164904	23623.80157	1669.387626
CXO	25867	33.6724	0.7614611	80669.98116	818.0050558
DBS	22930	0.0372	0.0002451	42087.63116	3076.70035
DBS	3	0.0381	0.0001854	42087.57855	3076.885957
DBS-1	22930	0.0372	0.0002451	42087.63116	3076.70035
DELTA	2	89.3831	0.7381476	29814.14345	1419.196961
DFH	3-F2	0.1281	0.0004333	42088.50646	3076.089382

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
DFS	2	0.0143	0.0002777	42086.57711	3076.638577
DFS	3	0.0236	0.0002394	42087.19101	3076.733975
DFS	1	3.7636	0.0011407	41979.381	3077.906854
DIRECTV	2	0.0273	0.0001838	42087.54805	3076.891995
DIRECTV	1-R	0.0032	0.0001943	42079.96526	3077.1369
DMSP	F6	98.6203	0.0008914	7167.690769	7450.615085
DMSP	F8	98.7563	0.00143	7203.094348	7428.280498
DMSP	F9	98.5108	0.0006531	7176.492473	7447.819336
DMSP	F10	98.4181	0.007873	7143.606941	7411.239387
DO-17	20440	98.4445	0.0010968	7153.96335	7456.228316
DUMMY MASS	24925	86.3327	0.0005799	6989.282496	7547.458666
DUMMY MASS	24926	86.3329	0.0006927	6989.913737	7546.266596
ECHOSTAR	1	0.1066	0.0003581	42124.44596	3075.008114
ECHOSTAR	2	0.0853	0.0000771	42086.94113	3077.242504
ECHOSTAR	3	0.0728	0.0009596	42088.57222	3074.46846
ECHOSTAR	4	0.2569	0.0001371	42087.37233	3077.042113
ECHOSTAR	5	0.0733	0.0000027	42087.79066	3077.440401
ECHOSTAR	6	0.0058	0.0002262	42087.51895	3076.762601
EGP	16908	50.0107	0.0011032	7851.683383	7117.18713
EKRAN	1	15.0347	0.0067469	42099.88085	3056.316096
EKRAN	2	14.8909	0.0036912	42101.41405	3065.614005
EKRAN	3	14.5164	0.0035061	42091.86454	3066.529308
EKRAN	4	14.297	0.0011876	42096.12782	3073.491701
EKRAN	6	13.7707	0.0008505	42075.12922	3075.295064
EKRAN	7	13.5264	0.0004676	42096.2664	3075.700351
EKRAN	8	13.2748	0.0019827	42178.9295	3068.033056
EKRAN	9	12.7558	0.0021721	42069.37297	3071.443536
EKRAN	10	13.8039	0.0035061	43621.99579	3012.266805
EKRAN	11	12.1245	0.0002119	42099.05759	3076.38492
EKRAN	12	12.8729	0.0012068	43309.21311	3030.083765
EKRAN	13	12.1653	0.0013525	43320.77656	3029.237941
EKRAN	14	11.9503	0.0019381	43693.30897	3014.530712
EKRAN	15	10.8574	0.0014635	43163.65667	3034.409454
EKRAN	16	9.7402	0.000484	43182.10926	3036.73408
EKRAN	17	8.4377	0.0041438	43362.35637	3019.345495
EKRAN	18	9.3027	0.0014303	43585.3767	3019.793974
EKRAN	19	7.7225	0.0026147	43131.21105	3032.058032
EKRAN	20	4.4679	0.0002667	42090.9871	3076.51124
ELEKTRO	23327	3.3939	0.0006839	42093.7234	3075.128033
ERBS	15354	56.9894	0.0005756	6939.794253	7574.354205
ERS-1	21574	98.5328	0.003562	7143.025811	7443.562078
ERS-2	23560	98.5429	0.0001048	7149.319384	7466.05224
ETS	7	34.963	0.0002916	6903.639001	7596.31929
EUTELSAT	1-F5	4.8665	0.0012173	42687.57292	3052.034858
EUTELSAT	2-F1	1.537	0.0005073	42086.17559	3075.946934
EUTELSAT	2-F2	0.7473	0.0003573	42087.90594	3076.345121
EUTELSAT	2-F3	0.6118	0.0003542	42086.70218	3076.398652
EUTELSAT	2-F4	0.0747	0.0000429	42044.40937	3078.903864

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
EUTELSAT	W2	0.0516	0.000413	42087.18793	3076.200013
EUTELSAT	W3	0.0626	0.0007218	42087.29622	3075.246272
EUTELSAT	W4	0.0285	0.0003523	42086.54157	3076.410367
EUVE	21987	28.425	0.0007322	6809.263492	7645.410829
EXOS	D	75.1222	0.3403418	10058.371	4416.281667
EXPRESS	1	0.3315	0.0002471	42087.5973	3076.695434
EXPRESS	2	2.1543	0.000445	42092.2284	3075.917392
EXPRESS	2A	0.0324	0.0003763	42087.61801	3076.297194
EXPRESS	3A	0.0711	0.0003333	42088.35927	3076.402386
FAISAT	2V	82.9202	0.0039721	7331.514385	7344.241887
FALCONSAT	26064	100.1989	0.0039069	7142.947784	7441.035842
FASAT-B	25395	98.708	0.0002993	7180.173436	7448.544834
FAST	24285	82.9827	0.2133015	8537.195486	5502.132803
FENGYUN	2B	0.8063	0.0000729	42088.94693	3077.182103
FO-20	20480	99.0736	0.0540772	7692.400599	6819.139554
FO-29	24278	98.5738	0.0350809	7426.753942	7073.391144
FUSE	25791	24.9812	0.0011068	7124.638234	7471.482816
FY-2	24834	0.5908	0.0020412	42086.65349	3071.21491
GALAXY	6	0.0418	0.0001349	42088.32457	3077.014073
GALAXY	5	0.033	0.0001051	42087.35302	3077.141286
GALAXY	7	0.0524	0.0004142	42095.17401	3075.904507
GALAXY	1R	0.0418	0.0001185	42087.62388	3077.090151
GALAXY	3R	0.0311	0.0002429	42088.00053	3076.693618
GALAXY	9	0.0405	0.0000339	42087.76491	3077.345327
GALAXY	8I	0.0689	0.0002422	42088.42839	3076.680133
GALAXY	11	0.0456	0.0000276	42087.86089	3077.361206
GALAXY	10R	0.0178	0.0000636	42087.25312	3077.272642
GALAXY	4R	0.015	0.0000738	42088.00053	3077.213931
GALAXY	1	5.0758	0.0005386	42134.94107	3074.070204
GALAXY	2	4.9724	0.0008356	42101.96716	3074.36054
GALAXY	3	4.421	0.0009578	42211.37533	3069.998542
GALAXY	IV	1.9587	0.0010553	42085.8197	3074.274775
GALS	1	2.241	0.0002279	42084.67371	3076.861375
GALS	2	0.1684	0.0013684	42085.81046	3073.312706
GARUDA	1	2.4437	0.0007425	42087.32392	3075.181603
GE	3	0.0122	0.0000565	42087.66837	3077.27931
GE	5	0.023	0.0002491	42088.39481	3076.660131
GE	4	0.0107	0.0003045	42087.68097	3076.515779
GE	1	0.0196	0.0001293	42087.76631	3077.051712
GE	2	0.0678	0.0003304	42088.11581	3076.420205
GLOBALSTAR	M001	52.0013	0.0001452	7777.545408	7157.882264
GLOBALSTAR	M004	51.9978	0.0002596	7777.543203	7157.064464
GLOBALSTAR	M002	52.0048	0.0003076	7777.541987	7156.721492
GLOBALSTAR	M003	51.996	0.0002994	7777.541387	7156.780453
GLOBALSTAR	M014	51.9918	0.000276	7777.558418	7156.940088
GLOBALSTAR	M006	51.9954	0.000245	7777.552613	7157.164627
GLOBALSTAR	M015	51.9928	0.0001559	7777.557296	7157.800204
GLOBALSTAR	M008	51.9903	0.000235	7777.561133	7157.232279

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
GLOBALSTAR	M023	52.0055	0.0001489	7777.544492	7157.856201
GLOBALSTAR	M040	51.9954	0.0000778	7777.568297	7158.354188
GLOBALSTAR	M036	52.0025	0.0001975	7777.536224	7157.512142
GLOBALSTAR	M038	52.0046	0.0001012	7777.550099	7158.195059
GLOBALSTAR	M022	52.0072	0.0002329	7777.559153	7157.248221
GLOBALSTAR	M041	51.9966	0.0000841	7777.568966	7158.308782
GLOBALSTAR	M046	52.0047	0.0001793	7777.558874	7157.631988
GLOBALSTAR	M037	52.0026	0.0001292	7777.557148	7157.991388
GLOBALSTAR	M045	51.9998	0.0001577	7777.556479	7157.787696
GLOBALSTAR	M044	51.9974	0.0001425	7777.542981	7157.902707
GLOBALSTAR	M019	52.0078	0.0000921	7777.549163	7158.260629
GLOBALSTAR	M042	52.0025	0.0000377	7777.548292	7158.65045
GLOBALSTAR	M025	51.9968	0.0000667	7777.554417	7158.440034
GLOBALSTAR	M049	51.9944	0.0000479	7777.55364	7158.574971
GLOBALSTAR	M047	51.9954	0.0001093	7777.537127	7158.143047
GLOBALSTAR	M052	51.9911	0.0004583	7777.498926	7155.662864
GLOBALSTAR	M035	52.0014	0.0000784	7777.550457	7158.358103
GLOBALSTAR	M032	52.0029	0.0000511	7777.562078	7158.548181
GLOBALSTAR	M051	52.0024	0.0000362	7777.552026	7158.65947
GLOBALSTAR	M030	52.0033	0.0000791	7777.555793	7158.350636
GLOBALSTAR	M048	52.013	0.0000553	7777.553201	7158.5222
GLOBALSTAR	M026	52.0103	0.0000486	7777.558068	7158.567922
GLOBALSTAR	M043	52.0101	0.0000217	7777.550523	7158.763963
GLOBALSTAR	M028	52.0098	0.0000104	7777.552741	7158.843837
GLOBALSTAR	M053	52.0099	0.0001204	7777.538134	7158.063129
GLOBALSTAR	M027	52.0123	0.0000252	7777.565347	7158.732085
GLOBALSTAR	M054	52.0165	0.0000514	7777.558631	7158.547619
GLOBALSTAR	M024	52.0171	0.0000152	7777.558459	7158.806843
GLOBALSTAR	M058	52.0023	0.0002824	7777.551069	7156.897665
GLOBALSTAR	M050	52.0004	0.0002183	7777.565401	7157.349842
GLOBALSTAR	M033	52.0037	0.0001666	7777.560919	7157.721949
GLOBALSTAR	M055	52.0019	0.0001392	7777.555333	7157.920644
GLOBALSTAR	M057	51.9951	0.0002017	7777.353551	7157.566137
GLOBALSTAR	M059	52.0016	0.0001743	7777.551825	7157.67102
GLOBALSTAR	M056	51.9917	0.0002591	7777.547943	7157.065861
GLOBALSTAR	M031	51.9953	0.0001744	7777.549208	7157.671508
GLOBALSTAR	M039	51.9969	0.0000749	7777.539686	7158.388114
GLOBALSTAR	M034	52	0.0001239	7777.429758	7158.087948
GLOBALSTAR	M029	51.9667	0.0032249	7285.513823	7372.898132
GLOBALSTAR	M061	52.0035	0.0001385	7777.537407	7157.933904
GLOBALSTAR	M063	52.0044	0.0012828	7286.897871	7386.529442
GLOBALSTAR	M062	52.01	0.0001404	7777.569299	7157.905628
GLOBALSTAR	M060	52.0068	0.0006049	7291.420907	7389.245546
GLOBALSTAR	M064	52.0089	0.0009896	7285.182308	7389.565411
GLONASS	72	63.9241	0.0006318	25461.75709	3954.12428
GLONASS	75	64.8574	0.0017468	25461.50124	3949.737726
GLONASS	76	64.8431	0.0032827	25461.52872	3943.673813
GLONASS	79	64.8484	0.0014383	25461.53652	3950.953674

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
GLONASS	78	64.8434	0.0004696	25461.52099	3954.784027
GLONASS	82	65.0707	0.00106	25461.54282	3952.448116
GLONASS	80	65.0616	0.0010697	25461.51852	3952.411663
GLONASS	81	65.0815	0.0003279	25461.49622	3955.346384
GMS	5	0.7045	0.0002521	42089.72854	3076.602154
GO-32	25397	98.7082	0.0002186	7181.976474	7448.210842
GOES	7	6.0563	0.0002921	42084.81416	3076.658713
GOES	8	0.3084	0.0002257	42085.00133	3076.856168
GOES	9	0.2784	0.0006884	42087.01612	3075.359221
GOES	10	0.1039	0.0001132	42090.70583	3076.993802
GOES	11	0.1708	0.0004053	42088.85262	3076.162864
GOES	6	9.3662	0.000344	42072.14657	3076.962158
GORIZONT	19	6.8836	0.0001734	42082.59122	3077.105202
GORIZONT	20	6.3366	0.0006679	42075.53914	3075.841681
GORIZONT	21	6.0903	0.0002162	42118.38045	3075.66593
GORIZONT	22	6.0038	0.0002793	42094.49096	3076.344434
GORIZONT	25	4.9827	0.0001551	42087.449	3076.983924
GORIZONT	26	4.7121	0.0001567	42088.28455	3076.948458
GORIZONT	27	4.5079	0.0005069	42087.89531	3075.885322
GORIZONT	28	3.8061	0.0002312	42088.32653	3076.7177
GORIZONT	29	3.7579	0.0002533	42091.67001	3076.527508
GORIZONT	30	3.5045	0.0001679	42089.70756	3076.861982
GORIZONT	31	2.1235	0.000218	42089.36837	3076.720232
GORIZONT	32	1.9129	0.0001571	42086.08718	3077.027552
GORIZONT	33	1.1252	0.0001963	42090.75005	3076.736498
GORIZONT	1	25.2276	0.3309111	42092.37927	2181.898478
GORIZONT	2	14.2163	0.0003008	42095.12026	3076.255299
GORIZONT	3	14.0267	0.0009974	42108.44981	3073.626527
GORIZONT	4	14.0318	0.0002971	42554.60951	3059.613399
GORIZONT	5	13.4112	0.0031871	42582.19477	3049.795521
GORIZONT	6	12.4067	0.0002269	42064.37762	3077.606657
GORIZONT	7	11.7657	0.0008691	42635.41168	3054.96481
GORIZONT	8	11.455	0.0026854	42657.46329	3048.6328
GORIZONT	9	10.9602	0.0003913	42089.79319	3076.171559
GORIZONT	10	10.7211	0.000262	42107.94383	3075.906184
GORIZONT	11	10.3491	0.0004824	42055.85117	3077.132312
GORIZONT	12	9.4134	0.0001829	42070.82065	3077.506392
GORIZONT	13	9.4307	0.0015032	43110.4926	3036.159363
GORIZONT	14	10.8296	0.002777	42835.71958	3042.004244
GORIZONT	15	8.4399	0.003354	42786.61942	3041.993429
GORIZONT	16	7.7497	0.0016684	42168.2335	3069.386695
GORIZONT	17	7.3947	0.0020599	42428.1591	3058.772585
GORIZONT	19	6.8836	0.0001734	42082.59122	3077.105202
GORIZONT	23	5.6153	0.0005717	42473.87818	3061.678914
GORIZONT	24	5.3177	0.0017142	42607.40462	3053.38719
GPS	BI-01	64.8796	0.0055897	26734.02951	3839.804163
GPS	BI-02	62.8403	0.0279584	26418.67333	3777.183131
GPS	BI-03	62.6493	0.0054676	27152.96123	3810.532902

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
GPS	BI-04	64.9722	0.0053886	27210.11687	3806.829468
GPS	BI-05	65.2402	0.0189926	26511.7822	3804.521589
GPS	BI-06	62.0469	0.0280365	26260.08657	3788.27521
GPS	BI-08	64.5584	0.008229	27321.35042	3788.296102
GPS	BI-09	64.4999	0.0089462	27265.86463	3789.429763
GPS	BI-10	61.8822	0.0108703	27236.10567	3784.210491
GPS	BI-11	65.2731	0.0163125	27546.94233	3742.373513
GPS	BII-01	56.2777	0.0004823	26512.86423	3875.530006
GPS	BII-02	53.4817	0.020612	26512.03309	3798.345146
GPS	BII-03	56.1078	0.0013688	27869.76724	3776.658834
GPS	BII-04	53.157	0.0061624	26511.83992	3853.653151
GPS	BII-05	56.3492	0.0123573	26512.20493	3829.825473
GPS	BII-06	55.3172	0.0015726	26525.0235	3870.419394
GPS	BII-07	53.7975	0.0036236	27385.873	3801.297645
GPS	BII-08	55.9176	0.0169623	26512.0315	3812.238337
GPS	BII-09	56.2504	0.0073597	26506.64981	3849.418532
GPS	BIIA-10	56.0949	0.0153599	26511.74254	3818.374373
GPS	BIIA-11	56.4747	0.0095429	26511.73302	3840.654801
GPS	BIIA-12	53.6543	0.0076401	26510.75155	3848.041527
GPS	BIIA-13	54.8683	0.0016842	26511.45421	3870.977734
GPS	BIIA-14	55.3052	0.0122473	26511.24122	3830.316457
GPS	BIIA-15	53.9345	0.0145628	26512.78385	3821.344849
GPS	BIIA-16	55.3867	0.0257701	26511.82361	3778.807741
GPS	BIIA-17	55.1092	0.0080761	26513.16	3846.189337
GPS	BIIA-18	53.4676	0.013506	26511.67698	3825.466033
GPS	BIIA-19	54.3196	0.0096428	26512.89516	3840.186937
GPS	BIIA-20	54.3493	0.0117834	26511.33524	3832.087215
GPS	BIIA-21	54.0997	0.0109555	26511.71443	3835.234097
GPS	BIIA-22	53.6617	0.0024081	26511.04384	3868.206474
GPS	BIIA-23	55.9017	0.005502	26510.98718	3856.261049
GPS	BIIA-24	54.2439	0.0070348	26511.40512	3850.324116
GPS	BIIA-25	53.8179	0.0012837	26512.02348	3872.486798
GPS	BIIA-26	55.9461	0.0040538	26512.42975	3861.744795
GPS	BIIA-27	54.0805	0.0053487	26511.11072	3856.84329
GPS	BIIR-02	61.4955	0.2767486	26511.83824	2918.373772
GPS	BIIA-28	54.8928	0.0076419	26511.8831	3847.952481
GPS	BIIR-03	52.9448	0.0029141	26516.50163	3865.851734
GPS	BIIR-04	55.0019	0.0029782	26512.16422	3865.920134
GPS	BIIR-05	55.4301	0.0388478	26511.39199	3729.690053
GSTAR	1	3.4619	0.0010033	42087.95016	3074.356828
GSTAR	3	9.9382	0.0007309	42087.88608	3075.196738
GSTAR	4	0.0103	0.0002047	42087.82787	3076.81746
GSTAR	2	4.2594	0.000404	42221.05652	3071.346992
GSTAR	3	9.9382	0.0007309	42087.88608	3075.196738
HEALTHSAT	1	98.3875	0.000861	7161.06302	7454.288763
HELIOS	1A	98.1352	0.000071	7046.275074	7520.699849
HELIOS	1B	98.1055	0.0001564	7045.867154	7520.275292
HETE-2	26561	1.9489	0.0029993	6980.471432	7533.97071

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
HISPASAT	1A	0.0625	0.0002337	42088.01843	3076.721269
HISPASAT	1B	0.0068	0.0003558	42087.89867	3076.350001
HISPASAT	1C	0.0624	0.0000547	42088.4698	3077.25555
HOT BIRD	1	0.062	0.0009577	42087.16778	3074.525598
HOT BIRD	4	0.0581	0.0008592	42086.9985	3074.834638
HOT BIRD	2	0.1127	0.0095959	42110.02078	3047.253508
HOT BIRD	3	0.1033	0.0043548	42087.34406	3064.092347
HOTBIRD	5	0.0711	0.0001559	42086.98143	3076.998554
HST	20580	28.4696	0.0013718	6957.102441	7558.905627
IKONOS-2	25919	98.21	0.0001218	7044.227351	7521.410787
IMAGE	26113	89.3888	0.7377738	29761.34928	1421.621548
INMARSAT	2-F1	1.7157	0.0002956	42087.46187	3076.551168
INMARSAT	2-F3	1.0316	0.000438	42088.20872	3076.085805
INMARSAT	2-F4	2.515	0.0002766	42087.57463	3076.605501
INMARSAT	3-F1	0.0457	0.0004512	42088.12953	3076.048095
INMARSAT	3-F2	0.0815	0.0003293	42087.80381	3076.434992
INMARSAT	3-F3	0.0235	0.0006045	42087.21647	3075.609934
INMARSAT	3-F4	0.0498	0.0003165	42088.83359	3076.436735
INMARSAT	3-F5	0.9795	0.0003476	42087.09503	3076.404598
INSAT	1D	2.2604	0.0005457	42087.20164	3075.791327
INSAT	2DR	0.0921	0.0005606	42087.18709	3075.74603
INSAT	2A	2.7105	0.0050298	42086.80907	3062.044199
INSAT	2B	0.1142	0.0005152	42088.90635	3075.822849
INSAT	2C	0.346	0.0005752	42088.29938	3075.660482
INSAT	2E	0.0944	0.0006084	42088.19501	3075.562186
INSAT	26108	0.0783	0.0003544	42088.27504	3076.340553
INTELSAT	511	5.7608	0.0007127	42088.4754	3075.231177
INTELSAT	602	0.0263	0.0002908	42087.30685	3076.571601
INTELSAT	603	0.0168	0.0001244	42088.15695	3077.052509
INTELSAT	604	0.0078	0.0001673	42087.66865	3076.938356
INTELSAT	605	0.0043	0.0004712	42088.00668	3075.991064
INTELSAT	601	0.0047	0.0000382	42087.98989	3077.32387
INTELSAT	701	0.0034	0.0002403	42087.38352	3076.724169
INTELSAT	702	0.04	0.0002741	42086.6949	3076.645347
INTELSAT	704	0.0129	0.0002982	42087.5973	3076.538219
INTELSAT	705	0.0206	0.0002818	42089.26791	3076.527616
INTELSAT	706	0.0083	0.000287	42088.46588	3076.54093
INTELSAT	707	0.0077	0.0003309	42087.75456	3076.43187
INTELSAT	709	0.0109	0.0002086	42087.86285	3076.804182
INTELSAT	801	0.0846	0.0007273	42088.38445	3075.189602
INTELSAT	802	0.0586	0.0002178	42087.2078	3076.79982
INTELSAT	804	0.0672	0.0013448	42087.42073	3073.326442
INTELSAT	805	0.0577	0.0004108	42088.59209	3076.155466
INTELSAT	5	8.8305	0.0013038	42479.85944	3059.222881
INTELSAT	5A	4.0524	0.0002962	42087.60877	3076.543952
INTELSAT	515	2.5577	0.00038	42087.97646	3076.272711
INTELSAT	6	0.0168	0.0001244	42088.15695	3077.052509
INTELSAT	VI-F1	0.0047	0.0000382	42087.98989	3077.32387

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
INTELSAT	K	0.0658	0.0003744	42089.47892	3076.235031
INTELSAT	VII	0.0034	0.0002403	42087.38352	3076.724169
INTELSAT	702	0.04	0.0002741	42086.6949	3076.645347
INTELSAT	705	0.0206	0.0002818	42089.26791	3076.527616
INTELSAT	706	0.0083	0.000287	42088.46588	3076.54093
INTERBOL	1	66.2182	0.9385991	102426.9819	351.0791715
INTERCOSMOS	24	82.5898	0.1231609	7829.821881	6304.228011
IO-26	22826	98.3917	0.0008739	7162.075479	7453.665707
IRAS	13777	99.0111	0.0012318	7260.276101	7400.43682
IRIDIUM	8	86.3972	0.0002966	7142.772085	7468.040763
IRIDIUM	7	86.398	0.0002337	7142.764824	7468.514313
IRIDIUM	6	86.393	0.0002668	7142.742632	7468.278711
IRIDIUM	5	86.3975	0.0002605	7142.764206	7468.314483
IRIDIUM	4	86.3988	0.00025	7142.767357	7468.391253
IRIDIUM	914	86.3984	0.0001816	7139.388905	7470.66909
IRIDIUM	12	86.4001	0.0002381	7142.761647	7468.483113
IRIDIUM	9	86.4545	0.0100406	6921.227681	7513.055484
IRIDIUM	10	86.4009	0.0002173	7142.77012	7468.634029
IRIDIUM	13	86.3996	0.00025	7142.763692	7468.393169
IRIDIUM	16	86.402	0.0002353	7142.77496	7468.497064
IRIDIUM	911	86.45	0.0017802	7122.94332	7467.341476
IRIDIUM	15	86.3998	0.0002336	7142.769608	7468.512559
IRIDIUM	17	86.4011	0.0002208	7142.768579	7468.608695
IRIDIUM	920	86.3989	0.0014412	7137.97879	7462.001906
IRIDIUM	18	86.4007	0.0002034	7142.770853	7468.73746
IRIDIUM	921	86.3923	0.0009702	6984.177735	7547.270119
IRIDIUM	26	86.3936	0.0002511	7142.771398	7468.380925
IRIDIUM	25	86.3955	0.0002374	7142.766922	7468.485583
IRIDIUM	46	86.3949	0.0002183	7142.765442	7468.629006
IRIDIUM	23	86.3939	0.0002345	7142.772663	7468.50424
IRIDIUM	22	86.3942	0.0002875	7142.77249	7468.10851
IRIDIUM	29	86.3934	0.0002524	7142.773304	7468.37022
IRIDIUM	32	86.3933	0.0002455	7142.766374	7468.425375
IRIDIUM	33	86.393	0.000219	7142.772855	7468.619902
IRIDIUM	27	86.6073	0.0006888	6859.211028	7617.854327
IRIDIUM	28	86.3902	0.0002562	7142.764844	7468.346263
IRIDIUM	30	86.3934	0.0002624	7142.765747	7468.299487
IRIDIUM	31	86.394	0.0002439	7142.766119	7468.437458
IRIDIUM	19	86.3991	0.0002368	7142.770475	7468.488207
IRIDIUM	35	86.3995	0.0002292	7142.770628	7468.544887
IRIDIUM	36	86.3981	0.0002457	7142.761301	7468.426533
IRIDIUM	37	86.4001	0.000229	7142.783563	7468.539619
IRIDIUM	34	86.3989	0.0002367	7142.770664	7468.488855
IRIDIUM	43	86.4011	0.0002374	7142.785744	7468.475743
IRIDIUM	41	86.4003	0.0002267	7142.782819	7468.557185
IRIDIUM	40	86.4005	0.0002229	7142.774253	7468.590044
IRIDIUM	39	86.4004	0.0002297	7142.770306	7468.541322
IRIDIUM	38	86.3994	0.000253	7142.768147	7468.368435

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
IRIDIUM	42	86.4001	0.0002285	7142.773327	7468.548704
IRIDIUM	44	86.3977	0.0003293	7140.435554	7469.018288
IRIDIUM	45	86.3942	0.0002257	7142.763307	7468.574855
IRIDIUM	24	86.3882	0.001435	7138.805645	7461.616011
IRIDIUM	47	86.3945	0.0002199	7142.7666	7468.616451
IRIDIUM	48	86.3914	0.0050213	6808.061137	7613.361001
IRIDIUM	49	86.3935	0.0002347	7142.769087	7468.504616
IRIDIUM	52	86.3975	0.0002054	7142.766404	7468.724849
IRIDIUM	56	86.402	0.0002051	7142.772709	7468.723793
IRIDIUM	54	86.4013	0.0002389	7142.761852	7468.477031
IRIDIUM	50	86.4021	0.000223	7142.775887	7468.588443
IRIDIUM	53	86.4006	0.0002298	7142.771766	7468.539811
IRIDIUM	51	86.4404	0.0001676	7114.545958	7483.805735
IRIDIUM	61	86.3969	0.0002466	7142.772427	7468.413995
IRIDIUM	55	86.3922	0.0002693	7142.771282	7468.245063
IRIDIUM	57	86.3931	0.0002543	7142.775555	7468.354853
IRIDIUM	58	86.3886	0.0002623	7142.755464	7468.30561
IRIDIUM	59	86.3942	0.0002859	7142.775296	7468.118993
IRIDIUM	60	86.395	0.0002542	7142.776259	7468.355232
IRIDIUM	62	86.3982	0.0002415	7142.765644	7468.45563
IRIDIUM	63	86.4001	0.0002513	7142.767566	7468.381435
IRIDIUM	64	86.3983	0.000302	7142.764724	7468.004283
IRIDIUM	65	86.3964	0.0002401	7142.76574	7468.466036
IRIDIUM	66	86.3987	0.00008	7142.773679	7469.657682
IRIDIUM	67	86.399	0.0002413	7142.756809	7468.461743
IRIDIUM	68	86.3991	0.0002428	7142.775531	7468.440752
IRIDIUM	69	86.3928	0.0003711	7141.984526	7467.896129
IRIDIUM	71	86.3926	0.0004684	7139.210573	7468.620088
IRIDIUM	70	86.3987	0.000243	7142.766199	7468.444138
IRIDIUM	72	86.3989	0.0002546	7142.772885	7468.354009
IRIDIUM	73	86.4427	0.0003465	7110.470137	7484.611222
IRIDIUM	74	86.3981	0.0002349	7142.767736	7468.503829
IRIDIUM	75	86.3996	0.0002368	7142.771524	7468.487658
IRIDIUM	3	86.3939	0.0002546	7142.771444	7468.354762
IRIDIUM	76	86.3937	0.000243	7142.775253	7468.439404
IRIDIUM	82	86.5205	0.0002094	7074.800346	7504.484284
IRIDIUM	81	86.3994	0.0002081	7142.762414	7468.70677
IRIDIUM	80	86.4018	0.0001773	7142.768772	7468.933485
IRIDIUM	79	85.983	0.0008427	6686.545265	7714.397506
IRIDIUM	77	86.5192	0.0001948	7074.534555	7504.734823
IRIDIUM	2	85.5619	0.00119	6987.265949	7543.94373
IRIDIUM	86	86.5203	0.0002774	7075.004959	7503.865485
IRIDIUM	85	85.9939	0.0010017	6739.369929	7682.882779
IRIDIUM	84	86.5953	0.0002955	7040.01441	7522.354216
IRIDIUM	83	86.4012	0.0002454	7142.783357	7468.417243
IRIDIUM	11	86.394	0.0002358	7142.769638	7468.496113
IRIDIUM	20	86.5279	0.0020497	7065.833729	7495.437832
IRIDIUM	14	86.5189	0.0003914	7074.772577	7503.133316

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IRIDIUM	21	86.5188	0.0003401	7077.609426	7502.014306
IRS-1A	18960	98.8681	0.0014286	7272.703905	7392.656057
IRS-1B	21688	99.0671	0.0018692	7271.831106	7389.843003
IRS-1C	23751	98.6884	0.0001304	7184.81274	7447.397405
IRS-1D	24971	98.5223	0.0058286	7147.351001	7424.461767
IRS-P2	23323	98.5797	0.0000897	7183.043062	7448.617905
IRS-P3	23827	98.5999	0.0001823	7184.639148	7447.10086
ISS	25544	51.5718	0.0005568	6747.88362	7681.451288
ITALSAT	1	2.8761	0.0002859	42087.60765	3076.575682
ITALSAT	F2	0.0857	0.0004785	42087.67173	3075.980849
IUE	10637	38.1003	0.1501657	42147.34428	2643.447577
JAWSAT	26061	100.1951	0.0036986	7140.068597	7444.08643
JCSAT	2	0.0362	0.0001655	42089.18871	3076.888331
JCSAT	3	0.0328	0.0002886	42088.48267	3076.535394
JCSAT	4	0.0538	0.0003267	42090.01764	3076.362083
JCSAT	5	0.0271	0.0002391	42088.05061	3076.703478
JCSAT	6	0.0458	0.0003104	42087.82815	3076.492248
JCSAT	1	2.6411	0.0006106	42296.01458	3067.990314
JERS-1	21867	97.6559	0.0003356	6858.94673	7620.69225
KITSAT-3	25756	98.3926	0.0016602	7090.392369	7485.360775
KO-23	22077	66.0869	0.0014713	7680.152875	7193.578339
KO-25	22828	98.3872	0.0009138	7160.6935	7454.087509
KOREASAT	1	1.2443	0.0007226	42089.87743	3075.149514
KOREASAT	2	0.0396	0.0001456	42089.76661	3076.928439
KOREASAT	3	0.0075	0.0002296	42088.28623	3076.724095
KRISTALL	20635	51.6438	0.001892	6703.461814	7696.577234
KVANT	1	51.6448	0.0018934	6703.453015	7696.57151
KVANT	2	51.6438	0.001892	6703.461814	7696.577234
LAGEOS	1	109.8197	0.0044433	12248.83717	5679.259901
LAGEOS	2	52.6695	0.0137405	12139.73338	5651.92662
LANDSAT	4	98.3023	0.0005895	7067.78934	7505.35213
LANDSAT	5	98.2365	0.0000868	7067.765097	7509.138898
LANDSAT	7	98.2175	0.0002513	7067.781146	7507.895222
LCS	1	32.1417	0.0008859	9149.633492	6594.50645
LCS	4	87.6309	0.0071396	7166.129681	7405.012821
LEASAT	5	3.9838	0.0006619	42088.30834	3075.393507
LES	9	12.2228	0.0021532	42086.83089	3070.86448
LMI-1	25924	0.0534	0.0004844	42088.03942	3075.949264
LO-19	20442	98.4507	0.0011714	7153.831262	7455.740932
LUCH	23426	2.0656	0.0006296	42093.88967	3075.288943
LUCH	1	1.1909	0.0012113	42086.28639	3073.778182
MABUHAY	24901	0.0369	0.0003022	42090.02967	3076.437015
MACSAT	2	89.8891	0.0100156	7034.790342	7452.35343
MAQSAT	H	7.5485	0.6514412	19897.77355	2056.236737
MAQSAT	B	7.5567	0.6518101	19889.97846	2055.321463
MARECS	B2	8.9377	0.0003394	42087.96051	3076.398193
MARISAT	3	12.933	0.0000917	42088.03103	3077.157734
MEASAT	1	0.0208	0.0001348	42088.31953	3077.014565

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MEASAT	2	0.0355	0.000396	42087.74812	3076.231836
MEGSAT	25722	48.4439	0.0031513	6913.64158	7569.145622
MEGSAT-1	26546	64.5563	0.0007242	7006.724874	7536.970915
METEOR	3-Jun	82.5621	0.0014435	7561.287364	7250.101916
METEOSAT	5	3.816	0.0002012	42089.63479	3076.762184
METEOSAT	6	0.7655	0.0002016	42088.37606	3076.806961
METEOSAT	7	0.4077	0.0000222	42089.12519	3077.331603
MIGHTYSAT	II.1	97.7733	0.0028049	6922.747084	7566.786832
MINISAT	1	150.9603	0.0010233	6875.869908	7606.075789
MIR	16609	51.6436	0.0018298	6702.841937	7697.411881
MO-30	24305	82.9337	0.0031374	7352.638306	7339.808459
MOLNIYA	Mar-35	62.1095	0.7398512	25495.59637	1528.942526
MOLNIYA	Jan-76	63.21	0.2248535	8327.172291	5503.892389
MOLNIYA	Mar-37	62.716	0.7469123	26489.75707	1476.487819
MOLNIYA	Jan-77	64.3296	0.7383326	26537.03798	1503.664813
MOLNIYA	Mar-38	63.8349	0.7439339	26505.3677	1485.980138
MOLNIYA	Jan-78	64.552	0.7106297	26508.32075	1594.875376
MOLNIYA	Mar-39	64.4799	0.684346	26507.20923	1678.714643
MOLNIYA	Jan-79	63.7223	0.7287676	26502.36318	1536.133865
MOLNIYA	Jan-80	64.5166	0.663912	26508.95998	1742.745096
MOLNIYA	Mar-40	64.4906	0.6626012	26528.9507	1746.170205
MOLNIYA	Jan-81	63.8565	0.693679	26507.07111	1649.152625
MOLNIYA	Jan-82	63.7381	0.7431436	26502.71026	1488.683437
MOLNIYA	Mar-41	63.9794	0.6968765	26495.35605	1639.338709
MOLNIYA	Jan-83	64.9922	0.6963125	26502.816	1640.904871
MOLNIYA	Jan-84	64.7223	0.6860786	26508.2982	1673.206401
MOLNIYA	Mar-42	64.0493	0.6881533	26508.03321	1666.651395
MOLNIYA	Mar-43	64.3135	0.7220603	26539.64236	1556.942127
MOLNIYA	Jan-85	64.5889	0.7318054	26507.2752	1526.025582
MOLNIYA	Mar-44	64.7701	0.7001076	26510.81491	1628.552916
MOLNIYA	Jan-86	64.0907	0.6951308	26509.19847	1644.469252
MOLNIYA	Mar-45	64.4997	0.694501	26526.2096	1645.944819
MOLNIYA	Jan-87	64.3859	0.7023683	26495.27299	1621.800833
MOLNIYA	Mar-46	64.8751	0.6838671	26542.33966	1679.114177
MOLNIYA	Mar-47	63.8403	0.7168674	26510.964	1574.645112
MOLNIYA	Mar-48	64.8725	0.71966	26510.02551	1565.615293
MOLNIYA	Mar-49	63.1443	0.7299072	26506.61784	1532.275403
MOLNIYA	Jan-91	63.1663	0.7039243	26510.63709	1616.348631
MOLNIYA-1T	24960	63.2885	0.7142571	26506.42653	1583.22647
MORELOS	2	1.7597	0.000211	42087.63927	3076.80497
MOS	1B	98.9359	0.000555	7278.561972	7396.138963
MSAT-M1	23846	0.0267	0.000498	42087.85306	3075.914242
MTI	26102	97.4047	0.0026607	6951.726326	7552.087698
MUBLCOM	25736	97.6859	0.0004638	7132.997466	7471.906474
NADEZHDA	2	82.9534	0.0043652	7351.100467	7331.5688
NADEZHDA	3	82.9286	0.0041187	7351.016252	7333.418294
NADEZHDA	4	82.945	0.0036178	7343.374416	7340.909235
NADEZHDA	5	82.9451	0.0026063	7359.382326	7340.3421

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NADEZHDA	1	82.9621	0.0036252	7349.888569	7337.601117
NADEZHDA	6	98.1437	0.0016258	7059.409556	7502.026986
NAHUEL	I1	2.8647	0.0002054	42088.23362	3076.800476
NAHUEL	1A	0.0225	0.000326	42088.01843	3076.437301
NATO	4A	3.0457	0.0002586	42088.58901	3076.623805
NATO	4B	1.4969	0.0002737	42087.86957	3076.603643
NILESAT	25311	0.0533	0.0002676	42087.76156	3076.626359
NIMIQ	1	0.0071	0.0001152	42088.13372	3077.081667
NINA	(MITA-0)	87.2564	0.0039691	6794.555824	7628.946776
NNSS	19	89.9861	0.0173457	7439.0578	7194.092604
NNSS	20	89.7861	0.0160325	7369.165752	7237.628749
NOAA	9	98.7713	0.001585	7209.407775	7423.876444
NOAA	10	98.6562	0.0013133	7170.18184	7446.178513
NOAA	11	98.99	0.0012609	7211.505474	7425.202751
NOAA	12	98.558	0.0012083	7177.811539	7443.001456
NOAA	13	99.2118	0.0010611	7219.359481	7422.645577
NOAA	14	99.1581	0.0010314	7215.839114	7424.676497
NOAA	15	98.625	0.0009991	7178.934992	7443.976163
NOAA	16	98.7976	0.0010927	7221.09754	7421.517715
NOAA	9	98.7713	0.001585	7209.407775	7423.876444
NOVA	1	90.1571	0.0014414	7540.116883	7260.288129
NOVA	3	89.8784	0.0033208	7540.927997	7246.266135
NOVA	11	90.039	0.0032255	7541.101641	7246.873309
NSS	513	4.0524	0.0002962	42087.60877	3076.543952
NSS	K	0.0658	0.0003744	42089.47892	3076.235031
NSS	703	0.0114	0.0002221	42087.10259	3076.790435
NSS	803	0.0723	0.0003136	42089.4764	3076.422164
NSS	806	0.0579	0.00058	42088.27588	3075.646578
N-STAR-A	23651	0.0039	0.0001749	42088.47764	3076.8854
N-STAR-B	23781	0.0271	0.000918	42089.3653	3074.567394
OCEANSAT	25758	98.2904	0.0001721	7088.149358	7497.694067
OCS	26062	100.2261	0.0031603	7036.310605	7502.808837
OFEQ	3	143.2896	0.0003112	6564.836576	7789.718716
OKEAN	1	82.5117	0.0016302	6972.830583	7548.424989
OKEAN	2	82.5227	0.0019181	6986.175447	7539.041302
OKEAN	3	82.5181	0.0019477	6994.824001	7534.156127
OLYMPUS	20122	6.261	0.0014866	41784.09212	3084.02422
OO-38	26063	100.1961	0.0038265	7142.028108	7442.113246
OPAL	26063	100.1961	0.0038265	7142.028108	7442.113246
OPS	5712	69.9286	0.0007147	7170.666222	7450.385484
OPS	5712	69.9722	0.0004906	7274.844267	7398.505016
OPTUS	A2	5.4968	0.0001657	42113.42883	3076.002074
OPTUS	A3	3.3003	0.000346	42087.77219	3076.384772
OPTUS	B1	0.0385	0.0003687	42088.18129	3076.299988
OPTUS	B3	0.0372	0.0005323	42087.67341	3075.815304
ORBCOMM FM	1	69.9645	0.000882	7090.300243	7491.236827
ORBCOMM FM	2	69.9694	0.0008008	7090.042468	7491.981331
ORBCOMM FM	8	45.0202	0.0009478	7171.985141	7447.96407

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ORBCOMM FM	10	45.023	0.0005411	7171.966797	7451.003303
ORBCOMM FM	11	45.0227	0.0005154	7171.918393	7451.219941
ORBCOMM FM	12	45.0202	0.0004626	7171.923106	7451.610928
ORBCOMM FM	9	45.0239	0.0003708	7171.802463	7452.357698
ORBCOMM FM	5	45.0233	0.0002074	7171.923924	7453.512397
ORBCOMM FM	6	45.02	0.0002979	7172.03943	7452.77787
ORBCOMM FM	7	45.0249	0.0003605	7171.992162	7452.335898
ORBCOMM FM	3	108.0005	0.0057585	7190.744358	7402.54491
ORBCOMM FM	4	108.0005	0.0053777	7190.773883	7405.34922
ORBCOMM FM	17	44.9977	0.0000945	7179.797646	7450.265417
ORBCOMM FM	18	45.0009	0.0004287	7179.770581	7447.789992
ORBCOMM FM	19	44.9971	0.0004053	7179.729667	7447.985494
ORBCOMM FM	20	44.9965	0.0002024	7179.785952	7449.467644
ORBCOMM FM	16	45.0005	0.0002145	7179.790176	7449.375314
ORBCOMM FM	15	44.9968	0.0003313	7179.90429	7448.446086
ORBCOMM FM	14	44.9937	0.0002711	7179.84097	7448.927343
ORBCOMM FM	13	45.0039	0.0001839	7179.840862	7449.576973
ORBCOMM FM	21	45.0146	0.0010121	7174.064148	7446.405981
ORBCOMM FM	22	45.0124	0.0006897	7174.035425	7448.822003
ORBCOMM FM	23	45.0119	0.0008375	7173.987379	7447.746087
ORBCOMM FM	24	45.0153	0.0006478	7173.96685	7449.169717
ORBCOMM FM	25	45.0109	0.0011252	7174.019461	7445.587028
ORBCOMM FM	26	45.0101	0.000934	7175.842148	7446.06492
ORBCOMM FM	27	45.0112	0.000676	7174.04912	7448.916942
ORBCOMM FM	28	45.016	0.0006987	7174.160328	7448.690122
ORBCOMM FM	30	45.0312	0.0005916	7184.520069	7444.115076
ORBCOMM FM	31	45.0226	0.000607	7184.516707	7444.002179
ORBCOMM FM	32	45.0221	0.0006214	7184.428692	7443.940582
ORBCOMM FM	33	45.0306	0.0006253	7184.404538	7443.924064
ORBCOMM FM	36	45.0466	0.0006091	7184.449074	7444.021585
ORBCOMM FM	35	45.0482	0.0005375	7184.375927	7444.592493
ORBCOMM FM	34	45.0446	0.0005081	7184.460524	7444.767536
ORBCOMM-X	21576	98.1468	0.0003764	7131.660912	7473.259736
ORBVIEW	24883	98.2193	0.0000678	7068.175185	7509.06373
ORBVIEW	1	69.9867	0.0008941	7094.639212	7488.8551
ORION	1	0.0655	0.0001732	42087.7554	3076.917031
ORION	2	0.0304	0.0002282	42088.06489	3076.736493
ORIZURU	20479	99.0725	0.0540328	7691.637737	6819.781388
ORSTED	25635	96.451	0.0152176	7116.283291	7371.109175
OSCAR	30	89.9838	0.0171302	7493.339588	7169.53355
OSCAR	24	89.9807	0.017124	7493.664242	7169.422706
OSCAR	27	90.3074	0.0108159	7460.621581	7230.759434
OSCAR	29	90.3066	0.0109736	7461.763653	7229.065807
OSCAR	23	90.3705	0.0192479	7523.62884	7139.945837
OSCAR	32	90.3687	0.0190412	7522.775998	7141.827151
OSCAR	25	89.8094	0.0098265	7469.000442	7233.856898
OSCAR	31	89.8097	0.0096312	7468.504924	7235.50996
PALAPA	B2R	0.4399	0.0004133	42087.01025	3076.205584

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
PALAPA	B4	0.0502	0.0000692	42088.04978	3077.226285
PALAPA	C1	1.3593	0.0002195	42086.94197	3076.804306
PALAPA	C2	0.0694	0.0001248	42088.89963	3077.02413
PANAMSAT	3R	0.05	0.0002503	42088.45441	3076.654261
PANAMSAT	22	6.937	0.0048874	42088.2325	3062.428488
PANAMSAT	2	0.036	0.0002357	42087.51279	3076.733597
PAS	1	0.0482	0.0007752	42087.61717	3075.070334
PAS	2	0.036	0.0002357	42087.51279	3076.733597
PAS	4	0.023	0.0003695	42087.54805	3076.320669
PAS	6	0.0106	0.0003783	42087.99661	3076.277205
PAS	5	0.0611	0.0001495	42088.19109	3076.974028
PAS	7	0.0857	0.0002673	42087.47278	3076.637836
PAS	8	0.0958	0.0003841	42087.60569	3076.273649
PAS	6B	0.0112	0.0000829	42087.67957	3077.197661
PAS	9	0.0286	0.0001324	42087.81136	3077.040526
PAS	1	0.0482	0.0007752	42087.61717	3075.070334
PICOSAT	1&2	100.1979	0.0034841	7137.066982	7447.248918
PICOSAT	3	100.1926	0.0035573	7138.755179	7445.82323
PICOSAT	4	100.1865	0.0038225	7139.033808	7443.703568
PICOSAT	5	100.1913	0.0037952	7137.592349	7444.658409
PICOSAT	6	100.1915	0.0037866	7139.961233	7443.487333
PO-34	25520	28.4614	0.0006122	6911.339197	7589.652798
POLAR BEAR	17070	89.5792	0.0040989	7350.879528	7333.6317
POSAT	22829	98.3888	0.0009043	7160.566514	7454.22442
PRIRODA	23848	51.6438	0.001892	6703.461814	7696.577234
PROGRESS	M1-3	51.5739	0.0006386	6749.384791	7679.968754
PROGRESS	M-43	51.6438	0.001892	6703.461814	7696.577234
QUIKSCAT	25789	98.6291	0.0001486	7170.013472	7454.943664
RADARSAT	23710	98.5787	0.0001278	7156.859045	7461.946881
RADCAL	22698	89.588	0.0091453	7183.932084	7381.012058
RADCAT	6212	98.5588	0.0009185	6970.189528	7555.230083
RADUGA	21	8.5374	0.0003521	42107.94972	3075.628842
RADUGA	22	7.5556	0.0003223	42119.7774	3075.28862
RADUGA	23	7.2244	0.0018239	42085.52648	3071.923491
RADUGA	26	5.9305	0.0008776	42086.54325	3074.794691
RADUGA	27	6.1425	0.0004021	42064.68472	3077.056275
RADUGA	28	5.1983	0.0004543	42073.81677	3076.561721
RADUGA	29	4.2339	0.0000066	42085.97386	3077.494822
RADUGA	30	3.8341	0.0002444	42090.66497	3076.59162
RADUGA	31	3.555	0.0008359	42079.81199	3075.168842
RADUGA	32	2.9379	0.0001695	42086.41594	3076.977379
RADUGA	1	15.0412	0.0005483	42084.6228	3075.877567
RADUGA	2	15.0532	0.0022073	42095.16478	3070.394371
RADUGA	3	14.9305	0.0007238	42090.61935	3075.118722
RADUGA	4	14.6916	0.0008212	42109.7078	3074.122228
RADUGA	5	14.4783	0.0002496	42087.06621	3076.707154
RADUGA	6	14.1203	0.0002548	42102.97596	3076.109795
RADUGA	7	13.8188	0.0005103	42085.26096	3075.971131

Sat Name	Sat Num	Inclination	Eccentricity	Semi Major Axis	Orbital Velocity at Apogee (m/s)
RADUGA	8	13.7894	0.0082987	42048.53696	3053.439228
RADUGA	9	13.4581	0.0004157	42075.68118	3076.612313
RADUGA	10	13.3419	0.0004347	42092.80556	3075.927986
RADUGA	11	12.27	0.0039281	42821.92783	3038.993837
RADUGA	12	11.9006	0.000613	42089.69048	3075.493399
RADUGA	13	11.8301	0.0019304	42685.80955	3049.922217
RADUGA	14	11.2161	0.0004256	42088.0176	3076.130933
RADUGA	15	10.9952	0.0005273	42108.84233	3075.057447
RADUGA	16	10.1305	0.0001663	42057.89348	3078.030411
RADUGA	17	9.9114	0.0011332	42116.15167	3072.928141
RADUGA	18	10.0049	0.0068946	42501.22635	3041.40197
RADUGA	19	9.3473	0.0012592	42602.73581	3054.944182
RADUGA	20	9.9384	0.0028491	43338.58707	3024.08617
RADUGA	21	8.5374	0.0003521	42107.94972	3075.628842
RADUGA	22	7.5556	0.0003223	42119.7774	3075.28862
RADUGA	23	7.2244	0.0018239	42085.52648	3071.923491
RADUGA	24	6.8196	0.0001701	42080.37613	3077.196344
RADUGA	25	6.5578	0.0006766	42118.00677	3074.263856
RADUGA	26	5.9305	0.0008776	42086.54325	3074.794691
RADUGA	27	6.1425	0.0004021	42064.68472	3077.056275
RADUGA	28	5.1983	0.0004543	42073.81677	3076.561721
RADUGA	29	4.2339	0.0000066	42085.97386	3077.494822
RADUGA	30	3.8341	0.0002444	42090.66497	3076.59162
RADUGA	31	3.555	0.0008359	42079.81199	3075.168842
RADUGA	32	2.9379	0.0001695	42086.41594	3076.977379
RADUGA	33	47.4728	0.729281	24686.36438	1589.889364
RCA/SATCOM	3R	7.2268	0.000454	42138.63623	3074.195483
RCA/SATCOM	4	6.6556	0.0001081	42279.79651	3070.121029
RCA/SATCOM	5	7.0927	0.0007928	42087.64487	3075.015201
RCA/SATCOM	6	5.9018	0.0012029	42204.01446	3069.513821
RESURS	O1-3	97.7678	0.000116	7020.301095	7534.260641
RESURS	O1-N4	98.7117	0.0001792	7180.488211	7449.276173
REX	2	90.0194	0.0023002	7180.796514	7433.333394
ROCSAT-1	25616	34.9731	0.0029642	6985.005839	7531.78929
ROSAT	20638	52.9777	0.0010005	6883.338334	7602.121698
RS-10/11	18129	82.9269	0.0012985	7355.223283	7352.025853
RS-12/13	21089	82.919	0.0030534	7349.150483	7342.166669
RS-15	23439	64.8179	0.0167953	8385.370697	6779.738804
S80/T	22078	66.0844	0.0016254	7679.042697	7192.989789
SAC-B/HETE/PEGASUS	24645	37.9688	0.0034307	6830.318751	7613.046146
SAFIR	2	98.7092	0.000126	7180.422412	7449.706618
SAMPEX	22012	81.6686	0.0097886	6926.912002	7511.86513
SARA	21578	98.1848	0.0005076	7113.904484	7481.598965
SAT	MEX	0.0066	0.0001676	42087.60094	3076.939908
SATCOM	5	7.0927	0.0007928	42087.64487	3075.015201
SATCOM	K2	2.8037	0.0002448	42087.97198	3076.688815
SATCOM	C1	0.0751	0.0004466	42087.84774	3076.072542
SATCOM	C4	0.0605	0.0002463	42087.70531	3076.693947

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SATCOM	C3	0.0756	0.0003057	42088.55963	3076.479973
SATCOM	KU-2	2.8037	0.0002448	42087.97198	3076.688815
SATCOM	KU-1	3.1118	0.0003093	42288.90248	3069.172891
SAUDISAT	1A	64.5551	0.0006129	7008.303551	7536.960802
SAUDISAT	1B	64.551	0.0013785	7014.772843	7527.71913
SAX	23857	3.953	0.0010459	6914.7064	7584.514515
SBS	4	5.6772	0.000087	42087.6334	3077.186733
SBS	5	0.5996	0.0006421	42221.02352	3070.616991
SBS	6	0.0414	0.0001054	42087.88692	3077.120845
SBS	2	9.3339	0.0003805	42131.86449	3074.668507
SBS	3	6.7724	0.0010055	42183.7518	3070.85707
SEASAT	1	108.0108	0.0002071	7125.116989	7477.956693
SESAT	26243	0.0407	0.0050621	42086.87034	3061.943065
SICH-1	23657	82.5317	0.0025184	7007.062192	7523.279076
SINOSAT	1	0.0461	0.0001871	42088.82771	3076.835066
SIRIUS MARCOPOL	O 1	1.0355	0.0002302	42087.94876	3076.734584
SIRIUS	2	0.0103	0.0000622	42087.5058	3077.267712
SIRIUS	3	0.0236	0.0000973	42088.2006	3077.134303
SIRIUS	1	63.1076	0.2642054	42087.07936	2347.81553
SIRIUS	2	63.3565	0.2661113	42082.58787	2343.132384
SKYNET	4A	4.5347	0.0001576	42088.72893	3076.929445
SKYNET	4C	3.1441	0.0002412	42087.94708	3076.700802
SKYNET	4D	2.46	0.0000779	42088.6363	3077.178072
SKYNET	4E	2.7868	0.0002567	42086.14034	3076.719152
SNOE	25233	97.6522	0.002796	6887.506273	7586.187869
SO-33	25509	31.4393	0.0364302	7172.781132	7187.81116
SO-35	25636	96.4504	0.015362	7118.516486	7368.888472
SOLAR	A	31.349	0.0133608	6951.25528	7471.957653
SOLIDARIDAD	1	0.1187	0.0002049	42086.89077	3076.851099
SOLIDARIDAD	2	0.0463	0.0002157	42087.48929	3076.795992
SOYUZ	TMA-1	51.5771	0.0016568	6623.973971	7744.440358
SPACENET	4	0.0612	0.0003349	42223.24701	3071.479554
SPACENET	1	3.5963	0.0002097	42166.90113	3073.915844
SPACENET	2	2.8329	0.001251	42234.34346	3068.263908
SPACENET	3R	0.96	0.0000434	42258.06562	3071.109015
SPEKTR	23579	51.6438	0.001892	6703.461814	7696.577234
SPOT	1	98.7327	0.0000836	7190.276441	7444.915741
SPOT	2	98.7378	0.0001455	7190.270244	7444.458124
SPOT	3	98.5583	0.0018008	7198.550966	7427.869544
SPOT	4	98.7129	0.0001267	7190.214546	7444.626915
SSN-23	DEB	78.8721	0.0127454	6801.026984	7558.682133
ST-1	25460	0.0188	0.000086	42088.35927	3077.163275
STARLETTE	7646	49.824	0.0205777	7320.802566	7228.555125
STELLA	22824	98.3791	0.000573	7166.273876	7453.724494
STEP	M4	44.9489	0.0015533	6722.939207	7688.023561
STRV	1A	7.2186	0.7137125	23064.54688	1699.137931
STRV	1B	7.1796	0.7115341	22896.0627	1712.943143
STTW-2	18922	5.5414	0.0005763	42085.39302	3075.763298

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STTW-3	19710	4.1972	0.0007647	42089.94515	3075.017579
STTW-4		4.0177	0.0004864	42094.69139	3075.700066
SUNSAT	25636	96.4504	0.015362	7118.516486	7368.888472
SUNSAT	25636	96.4504	0.015362	7118.516486	7368.888472
SUPERBIRD	B1	0.0208	0.0001888	42088.2728	3076.850119
SUPERBIRD	A1	0.018	0.0003232	42087.85166	3076.45201
SUPERBIRD	C	0.0305	0.0000112	42088.66933	3077.38212
SUPERBIRD	4	0.0215	0.0002121	42086.51527	3076.842672
SUPERBIRD	A	7.3129	0.0007095	42236.9199	3069.832191
SURCAL	150B	69.948	0.0003909	7153.145411	7461.920116
SWAS	25560	69.9058	0.0013173	6999.676174	7536.293732
TDF	1	3.4266	0.0004372	42391.57897	3065.061674
TDF	2	1.6678	0.0049668	42560.95101	3045.13222
TDRS	1	10.833	0.0002389	42089.70504	3076.643625
TDRS	3	5.5452	0.0003433	42090.1279	3076.306987
TDRS	4	3.227	0.0001972	42088.28315	3076.823895
TDRS	5	2.3384	0.0002092	42086.82501	3076.840272
TDRS	6	1.5654	0.0002409	42088.44518	3076.683519
TDRS	7	3.9753	0.0003529	42086.60565	3076.406179
TDRS	8	6.8	0.0029206	42090.53399	3068.373802
TEAMSAT	25025	7.574	0.6520946	19925.08337	2052.494222
TECHSAT	1B	98.7082	0.0002186	7181.976474	7448.210842
TELE	X	2.9613	0.0007297	42394.99755	3064.041731
TELECOM	2A	0.0829	0.0002881	42087.6944	3076.565743
TELECOM	2B	0.0376	0.0004438	42087.59982	3076.090215
TELECOM	2D	0.0119	0.000481	42087.75232	3075.970214
TELKOM	1	0.0178	0.00014	42087.40646	3077.031942
TELSTAR	402R	0.0648	0.0001958	42087.80996	3076.845499
TELSTAR	5	0.0202	0.0002051	42088.2798	3076.799711
TELSTAR	6	0.0633	0.0002994	42089.53712	3076.46363
TELSTAR	7	0.0675	0.0000969	42087.11742	3077.175131
TELSTAR	3A	5.2529	0.0023783	42297.89804	3062.503617
TELSTAR	3C	4.3466	0.000382	42225.15878	3071.265362
TELSTAR	3D	4.1222	0.0000986	42200.57368	3073.03063
TELSTAR	401	2.9572	0.0006042	42087.47194	3075.601522
TELSTAR	402	7.1664	0.606073	16635.81481	2424.220297
TEMPO	2	0.025	0.0002292	42087.76044	3076.744544
TEMPSAT	1	89.938	0.0068193	7499.698953	7240.779833
TERRA	25994	98.1747	0.0000765	7067.77235	7509.212389
TERRIERS	25735	97.6419	0.0008047	6901.757712	7593.457322
THAICOM	1	0.0817	0.0008939	42088.89628	3074.658623
THAICOM	2	0.1026	0.0003301	42088.24034	3076.416577
THAICOM	3	0.0952	0.0036714	42085.23215	3066.26403
THOR	1	0.0321	0.000189	42087.48145	3076.87843
THOR	2A	0.0668	0.0002174	42087.39275	3076.79429
THOR	3	0.0401	0.0001816	42087.40003	3076.904175
TIUNGSAT-1	26545	64.5575	0.0009089	7011.925303	7532.784046
TMSAT	25396	98.7095	0.0003022	7180.908838	7448.141819

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TOMS-EP	23940	98.3186	0.0030848	7101.341817	7468.939872
TOPEX	22076	66.0386	0.000795	7701.814064	7188.315144
TOPEX/POSEIDON	22076	66.0386	0.000795	7701.814064	7188.315144
TRACE	25280	97.8153	0.0028009	6971.244283	7540.450939
TRANSAT	10457	89.7347	0.0024722	7444.781844	7299.098675
TRMM	25063	34.9809	0.0005349	6712.746735	7701.697427
TRMM	25063	34.9809	0.0005349	6712.746735	7701.697427
TSIKADA	23463	82.9244	0.0037892	7357.085703	7332.808507
TUBSAT	N	78.9012	0.0191804	6875.523857	7469.388137
TUBSAT	N1	78.8583	0.0006651	6517.354066	7815.277096
TUBSAT	25757	98.3898	0.0016478	7091.690154	7484.768641
TUBSAT	A	98.1431	0.0007018	7132.969606	7470.14296
TUBSAT	B	82.5632	0.0015239	7561.089037	7249.614106
TURKSAT	1B	0.0118	0.0034697	42087.94064	3066.783882
TURKSAT	1C	0.143	0.0012196	42088.21907	3073.682096
TV SAT	2	1.8774	0.0015319	42208.78616	3068.330663
UARS	21701	56.9817	0.0004552	6935.480413	7577.621738
UARS	21701	56.9817	0.0004552	6935.480413	7577.621738
UFO	10	5.4171	0.0003931	42087.11238	3076.263991
UFO	1	22.2292	0.0010555	42375.48805	3063.748653
UNISAT	26547	64.5603	0.0017345	7017.07397	7523.805778
UO-11	14781	98.0022	0.0011284	7017.123177	7528.340953
UO-14	20437	98.3935	0.001115	7154.937454	7455.585044
UO-15	20438	98.3658	0.00102	7157.893971	7454.753316
UO-22	21575	98.1411	0.0008295	7130.564672	7470.448548
UO-36	25693	64.561	0.0050743	7015.113635	7499.767037
UOSAT-12	25693	64.561	0.0050743	7015.113635	7499.767037
UPM/LBSAT	23607	98.2868	0.000651	7027.293874	7526.483334
WESTAR	4	6.7192	0.0003069	42229.97258	3071.320957
WESTAR	5	6.4628	0.0013725	42386.09325	3062.394412
WESTPAC	25398	98.7107	0.0001794	7182.045843	7448.466846
WIRE	25646	97.5051	0.0028589	6910.20919	7573.239347
WO-18	20441	98.4419	0.0012107	7154.303499	7455.201865
WO-39	26061	100.1951	0.0036986	7140.068597	7444.08643
XMM	25989	34.452	0.8091897	66816.31194	793.206915
XTE	23757	22.982	0.0012244	6916.747313	7582.041941
YAMAL	101	0.9329	0.0095472	42199.7548	3044.160188
ZHONGXING-22	26058	0.1325	0.0002276	42087.49824	3076.759051

Table B-1 Satellite Inclinations, Eccentricities, and Apogee Velocities

Appendix C: Brute Force FORTRAN Program

```
C       Launch Program Optimisation
C       FLTLT Tony Rogers
C
C
      INTEGER   N, I, A, B, C, D, E, F, G, TMCOUNT, COUNT
C
      PARAMETER  (N=7)
C
      REAL      FCN, BESTFCN, SITE(17,6), VAR(N), BESTVAR(11), NL, DV,
     &          MP, PADV, PAMP, PANL, PAPR, PAD, PA, DNL, DDI, DSI,
     &          DDT, DRNDPR, DRNDMT, DRNDMF, DRNDISP, DRNDPMF, DRND,
     &          DOLLARS, ETBISP, ETBMF, ETBPR, ETBNL, ETBPMF, ETB,SEC,
     &          CF, NUML, DOLNL, DOLDI, DOLSI, DOLDT, DOLRNDPR,
     &          DOLRNDMT, DOLRNDMF, DOLRNDISP, DOLRNDPMF, DOLRND, DOLM,
     &          DOLVAL, CPYEAR, DELTAVRE, DELTAV, CFTD, CFPY, ETBD
     &
C
        COMMON  SITE, I
C
        CHARACTER  *16 LOCATION(17)
        CHARACTER  *10 DATE1, TIME1, DATE2, TIME2, DATE3, TIME3
C
C       Location Matrix
C
C       (X, 1) = Delta V due to the Earth's rotation
C       (X, 2) = Delta V due to the cost of achieving popular inclinations
C       (X, 3) = Number of Rainy Days per year
C       (X, 4) = Percentage of site infrastructure required already in place
C       (X, 5) = Distance to nearest major rail line or heavy port facility
C       (X, 6) = Distance to nearest industrial centre (Capital City)
C
C       Christmas Island
        SITE(1, 1) = 4.57E2
        SITE(1, 2) = 2.49E2
        SITE(1, 3) = 1.73E2
        SITE(1, 4) = 0.0E0
        SITE(1, 5) = 2.5E1
        SITE(1, 6) = 2.8E3
C       Borroloola, NT
        SITE(2, 1) = 4.47E2
        SITE(2, 2) = 3.166E3
        SITE(2, 3) = 5.15E1
        SITE(2, 4) = 0.0E0
        SITE(2, 5) = 2.5E2
        SITE(2, 6) = 6.5E2
C       Gunn Point, NT
        SITE(3, 1) = 4.55E2
        SITE(3, 2) = 3.641E3
        SITE(3, 3) = 1.107E2
        SITE(3, 4) = 0.0E0
        SITE(3, 5) = 2.5E1
        SITE(3, 6) = 5.0E1
```

```
C       Katherine, NT
        SITE(4, 1) = 4.5E2
        SITE(4, 2) = 2.826E3
        SITE(4, 3) = 8.16E1
        SITE(4, 4) = 0.0E0
        SITE(4, 5) = 2.5E1
        SITE(4, 6) = 3.0E2
C       Nhulunbuy, NT
        SITE(5, 1) = 4.55E2
        SITE(5, 2) = 2.662E3
        SITE(5, 3) = 9.79E1
        SITE(5, 4) = 0.0E0
        SITE(5, 5) = 4.75E2
        SITE(5, 6) = 9.0E2
C       Broome, WA
        SITE(6, 1) = 4.36E2
        SITE(6, 2) = 3.368E3
        SITE(6, 3) = 4.66E1
        SITE(6, 4) = 0.0E0
        SITE(6, 5) = 2.5E1
        SITE(6, 6) = 1.1E3
C       Port Headland, WA
        SITE(7, 1) = 4.36E2
        SITE(7, 2) = 3.335E3
        SITE(7, 3) = 3.1E1
        SITE(7, 4) = 0.0E0
        SITE(7, 5) = 2.5E1
        SITE(7, 6) = 1.25E3
C       Wyndham, WA
        SITE(8, 1) = 4.48E2
        SITE(8, 2) = 3.168E3
        SITE(8, 3) = 6.45E1
        SITE(8, 4) = 0.0E0
        SITE(8, 5) = 4.5E2
        SITE(8, 6) = 8.5E2
C       Woomera, SA
        SITE(9, 1) = 3.98E2
        SITE(9, 2) = 6.84E2
        SITE(9, 3) = 5.0E1
        SITE(9, 4) = 7.0E1
        SITE(9, 5) = 7.5E1
        SITE(9, 6) = 5.5E2
C       Cape York, QLD
        SITE(10, 1) = 4.57E2
        SITE(10, 2) = 1.851E3
        SITE(10, 3) = 1.081E2
        SITE(10, 4) = 0.0E0
        SITE(10, 5) = 8.0E2
        SITE(10, 6) = 1.25E3
C       Cooktown, QLD
        SITE(11, 1) = 4.48E2
        SITE(11, 2) = 1.101E3
        SITE(11, 3) = 1.293E2
        SITE(11, 4) = 0.0E0
        SITE(11, 5) = 1.75E2
        SITE(11, 6) = 1.175E2
```

```
C       Hummock Hill, QLD
        SITE(12, 1) = 4.25E2
        SITE(12, 2) = 1.402E3
        SITE(12, 3) = 7.51E1
        SITE(12, 4) = 0.0E0
        SITE(12, 5) = 2.5E1
        SITE(12, 6) = 4.5E2
C       Mt. Isa, QLD
        SITE(13, 1) = 4.35E2
        SITE(13, 2) = 6.74E2
        SITE(13, 3) = 3.35E1
        SITE(13, 4) = 0.0E0
        SITE(13, 5) = 2.5E1
        SITE(13, 6) = 1.6E3
C       Townsville, QLD
        SITE(14, 1) = 4.39E2
        SITE(14, 2) = 6.41E2
        SITE(14, 3) = 9.13E1
        SITE(14, 4) = 0.0E0
        SITE(14, 5) = 2.5E1
        SITE(14, 6) = 1.1E3
C       Weipa, QLD
        SITE(15, 1) = 4.54E2
        SITE(15, 2) = 2.398E3
        SITE(15, 3) = 1.069E2
        SITE(15, 4) = 0.0E0
        SITE(15, 5) = 6.5E2
        SITE(15, 6) = 1.15E3
C       Orange, NSW
        SITE(16, 1) = 3.88E2
        SITE(16, 2) = 2.7723
        SITE(16, 3) = 1.247E2
        SITE(16, 4) = 0.0E0
        SITE(16, 5) = 2.5E1
        SITE(16, 6) = 1.5E2
C       Wilson's Promontory VIC
        SITE(17, 1) = 3.61E2
        SITE(17, 2) = 2.692E3
        SITE(17, 3) = 1.801E2
        SITE(17, 4) = 0.0E0
        SITE(17, 5) = 1.0E2
        SITE(17, 6) = 1.5E2
C
C       Location names
        LOCATION(1) =  'Christmas Island'
        LOCATION(2) =  'Borroloola NT'
        LOCATION(3) =  'Gunn Point NT'
        LOCATION(4) =  'Katherine NT'
        LOCATION(5) =  'Nhulunbuy NT'
        LOCATION(6) =  'Broome WA'
        LOCATION(7) =  'Port Hedland WA'
        LOCATION(8) =  'Wyndham WA'
        LOCATION(9) =  'Woomera SA'
        LOCATION(10) = 'Cape York QLD'
        LOCATION(11) = 'Cooktown QLD'
        LOCATION(12) = 'Hummock Hill QLD'
```

```
      LOCATION(13) = 'Mt Isa QLD'
      LOCATION(14) = 'Townsville QLD'
      LOCATION(15) = 'Weipa QLD'
      LOCATION(16) = 'Orange NSW'
      LOCATION(17) = 'Wilsons VIC'
C
C     Open the Results File
      OPEN (UNIT=1, FILE = 'Christmas Island.txt')
C
C     Select Location
      I = 11
C
C     Get the Start Date and Time
      CALL DATE_AND_TIME(DATE1, TIME1)
      WRITE(*, *) 'Start Date: ', DATE1
      WRITE(*, *) 'Start Time: ', TIME1
C
C     Initialise BESTFCN, Counters and BESTVAR
      BESTFCN = 0.0E0
      TMCOUNT = 0
      COUNT = 0
      BESTVAR(1) = 1.0E-8
      BESTVAR(2) = 1.0E-8
      BESTVAR(3) = 1.0E-8
      BESTVAR(4) = 1.0E-8
      BESTVAR(5) = 1.0E-8
      BESTVAR(6) = 1.0E-8
      BESTVAR(7) = 1.0E-8
      BESTVAR(8) = 1.0E-8
      BESTVAR(9) = 1.0E-8
      BESTVAR(10) = 1.0E-8
      BESTVAR(11) = 1.0E-8
C
C     VAR(1) = Specific Impulse (ISP) Range = 0 to 1,000 seconds
C     VAR(2) = Mass Fraction              Range = 0 to 1
C     VAR(3) = Payload Mass Fraction   Range = 0 to 0.9
C     VAR(4) = Total Mass                 Range = 10,000 to 700,000 kg
C     VAR(5) = Percent Reusable           Range = 0 to 100 %
C     VAR(6) = Percent Indigenous         Range = 0 to 100 %
C     VAR(7) = Program Duration           Range = 5 to 40 years
C
C     Total Mass Loop (100,000 to 500,000 kg)
      DO 70 D = 1, 50
C     Total Mass Variable
      VAR(4) = D*1.0E4
C
C     Percent Reusable Loop (0 to 100 %)
      DO 60 E = 1, 5
C     Percent Reusable Variable (0 to 100 %)
      VAR(5) = (E*4.0E0)+8.0E1
C
C     Percent Indigenous Loop (0 to 100 %)
      DO 50 F = 1, 5
C     Percent Indigenous Variable (0 to 100 %)
      VAR(6) = (F*4.0E0)+8.0E1
C
```

```
C       Specific Impulse Loop (200 to 600 s)
        DO 40 A = 1, 21
C       Specific Impulse Variable
        VAR(1) = 2.0E2+(A*2.0E1)-2.0E1
C
C       Payload Mass Fraction Loop (0 to 0.6)
        DO 30 C = 1, 30
C       Payload Mass Fraction Variable
        VAR(3) = C*2.0E-2
C
C       Mass Fraction Loop (0.7 to 0.99)
        DO 20 B = 1, 30
C       Mass Fraction Variable
        VAR(2) = (B*1.0E-2)+(7.0E-1)
C
C       Program Duration Loop (0 to 30 years)
        DO 10 G = 1, 30
C       Program Duration Variable (0 to 30 years)
        VAR(7) = G*1.0E0
C
C       Number of launches per year (Range = 1 to 11 per year)
        NL = ((3.65E2-SITE(I, 3))/3.65E2)*(((1.0E1*(TANH(-(4.2E0*VAR(5)/
   &    1.00E2)-2.1E0)+TANH(2.1E0)))/(2.0E0*TANH(2.1E0)))+1.0E0)
C
C       Rocket Equation Delta V (VAR(1) = ISP, VAR(4) = Total Mass, VAR(2) = Mass Fraction)
        DVRE = 9.8E0*VAR(1)*LOG(VAR(4)/(VAR(4)*(1-VAR(2))))
C
C       Overall Delta V
        DV = SITE(I, 1)-SITE(I, 2)+DVRE
C
C       Mass of the Payload (VAR(3) = Payload Mass Fraction, VAR(4) = Total Mass, VAR(2) = MF)
        MP = VAR(3)*VAR(4)*(1-VAR(2))
C
C       Political Advantage due to Delta V
        PADV =          (TANH(2.1E0)+TANH((4.2E0*DV/2.0E1)-2.1E0))/
   &     (2.0E0*TANH(2.1E0))
C
C       Political Advantage due to Mass of the Payload
        PAMP = (TANH(2.1E0)+TANH((4.2E0*MP/5.0E3)-2.1E0))/
   &    (2.0E0*TANH(2.1E0))
C
C       Political Advantage due to the Number of Launches
        PANL = TANH(NL/6.0E0)
C
C       Political Advantage due to Percentage Reusability of the System
        PAPR = (TANH(2.1E0)+TANH((4.2E0*VAR(5)/1.0E2)-2.1E0))/
   &    (2.0E0*TANH(2.1E0))
C
C       Political Advantage due to the Program's duration ((TANH(2.1E0)+TANH(-((4.2E0*VAR(7)
C       /3.5E1)-2.1E0)))/(2.0E0*TANH(2.1E0))
        PAD = -VAR(7)/4.0E1+1
C
C       Political Advantage (VAR(6) = Percent Indigenous)
        PA = (VAR(6)/1.0E2)*(3.0E-1*PADV+2.0E-1*PAMP+1.0E-1*PANL+
   &    1.5E-1*PAPR+2.5E-1*PAD)
C
```

```
C       Cost due to the Number of Launches per year (VAR(4) = Total Mass, VAR(7) = Duration)
        DNL = 2.5E-1*NL*VAR(4)*2.25E-4*VAR(7)
C
C       Cost due to the distance to the nearest industry centre (capital city, VAR(7) = Duration)
        DDI = SITE(I, 6)*5.0E-4*VAR(7)
C
C       Cost due to the work required to construct the launch facility
        DSI = 2.5E2*((TANH(-((4.2E0*SITE(I, 4)/1.0E2)-2.1E0))+
     &  TANH(2.1E0))/TANH(2.1E0))
C
C       Cost due to the distance to the nearest major rail line or heavy port facility
        DDT = SITE(I, 5)*3.0E-1
C
C       R&D Cost due to the Percent Reusable
        DRNDPR = (EXP(VAR(5)/2.0E1)/3.0E-1)-(1.0E1/3.0E0)
C
C       R&D Cost due to the Total Mass of the Vehicle
        DRNDMT = VAR(4)*1.0E-3
C
C       R&D Cost due to the Mass Fraction of the vehicle
        DRNDMF = 1.0E2*TAN(1.0E2*3.1415926535898E0*VAR(2)/2.01E2)
C
C       R&D Cost due to the Specific Impulse, ISP
        DRNDISP = 1.0E1*EXP(VAR(1)/7.0E1)
C
C       R&D Cost due to the Payload Mass Fraction (VAR(3) = Payload Mass Fraction)
        DRNDPMF = 200*EXP(4*VAR(3))-200
C
C       Cost due to Research and Development (VAR(6) = Percent Indigenous, VAR(7) = Duration)
        DRND = (VAR(6)/1.00E2)*(DRNDPR+DRNDMT+DRNDMF+DRNDISP+
     &  DRNDPMF)
C       *(-3.0E0*VAR(7)/7.0E1+1.2E1/7.0E0)
C
C       Cost due to system maintenance (VAR(5) = % Reusable, VAR(7) = Duration)
        DM = 2.5E-1*NL*2.5E1*(TANH((4.2E0*VAR(5)/1.0E2)-2.1E0)+
     &  TANH(2.1E0))/TANH(2.1E0)*VAR(7)
C
C       Overall Program Cost
        DOLLARS = DNL+DDI+DSI+DDT+DRND+DM
C
C       Technology Base required to achieve the Specific Impulse, ISP, employed
        ETBISP = TANH(VAR(1)/6.00E2)
C
C       Technology Base required to achieve the Vehicle's Mass Fraction
        ETBMF = EXP(8.0E0*VAR(2))/EXP(8.0E0)
C
C       Technology Base required to achieve the Percentage Reusable (VAR(5) = % Reusable)
        ETBPR = VAR(5)/1.0E2
C
C       Technology Base required to achieve the Number of Launches per year
        ETBNL = (TANH((4.2E0*NL/2.0E1)-2.1E0)+TANH(2.1E0))/
     &  (2.0E0*TANH(2.1E0))
C
C       Technology Base required to achieve the Payload Mass Fraction (VAR(3) = Payload MF)
        ETBPMF = TANH(2*VAR(3))
C
```

```
C       Technology Base due to the duration of the program, the longer the lower
        ETBD = -VAR(7)/4.0E1+1
C
C       Elevated Technology Base ((VAR(6) = Percent Indigenous)
        ETB = (VAR(6)/1.0E2)*(2.25E-1*ETBISP+2.5E-1*ETBMF+1.25E-1*ETBPR
     &  +1.0E-1*ETBNL+1.5E-1*ETBPMF+1.5E-1*ETBD)
C
C       Security (VAR(6) = Percent Indigenous)
        SEC = (VAR(6)/1.00E2)*(5E-1*((TANH(2.1E0)+TANH(4.2E0*DV/
     &  2.0E1-2.1E0)))/(2E0*TANH(2.1E0))+5E-1*
     &  TANH(MP/1.000E3))
C
C       Cost Factor Dollars per Year EXP(-((2*DOLLARS/VAR(7))/1000))
        CFPY = (-1.0E0/5.0E2)*(DOLLARS/VAR(7))+1
C       Cost Factor Total Dollars (0 to $15 billion)
        CFTD = (-1.0E0/1.0E4)*DOLLARS+1
C       Overall cost Factor (7.0E-1*CFTD+3.0E-1*CFPY)
        CF = 7.0E-1*CFTD+3.0E-1*CFPY
C
C       Benefits
        FCN = (4.0E-1*PA+3.0E-1*CF+2.0E-1*ETB+1.0E-1*SEC)
C
C
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(1) = VAR(1)
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(2) = VAR(2)
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(3) = VAR(3)
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(4) = VAR(4)
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(5) = VAR(5)
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(6) = VAR(6)
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(7) = VAR(7)
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(8) = PA
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(9) = ETB
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(10) = SEC
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTVAR(11) = CF
        IF (FCN .GT. BESTFCN .AND. DV .GT. 8.0E3 .AND. DV .LT. 2.0E4)
     &  BESTFCN = FCN
C
10      CONTINUE
20      CONTINUE
30      CONTINUE
40      CONTINUE
50      CONTINUE
60      CONTINUE
C
C       Total Mass Loop Counter
```

```
        TMCOUNT = TMCOUNT+1
C       Time to complete one Total Mass Loop
        CALL DATE_AND_TIME(DATE3, TIME3)
        WRITE(*, *) 'Mass Tot Loop(50): ', TMCOUNT, ' Completed, Time: '
    &   , TIME3
        WRITE(*, *) 'Function Value:  ', BESTFCN
        WRITE(*, *) ' '
C
C
C       Calculate the Number of Launches for that Location (Range = 1 to 11 per year)
        NUML = ((3.65E2-SITE(I, 3))/3.65E2)*(((1.0E1*(TANH(-(4.2E0*
    &   BESTVAR(5)/1.00E2)-2.1E0)+TANH(2.1E0)))/(2.0E0*
    &   TANH(2.1E0)))+1.0E0)
C
C       Calculate the Systems Delta V
C       Rocket Equation Delta V (VAR(1) = ISP, VAR(4) = Total Mass, VAR(2) = Mass Fraction)
        DELTAVRE=9.8E0*BESTVAR(1)*LOG(BESTVAR(4)/(BESTVAR(4)*
    &   (1-BESTVAR(2))))
C
C       Overall Delta V
        DELTAV = (SITE(I, 1)-SITE(I, 2)+DELTAVRE)/1.0E3
C
C       Calculate the Program Cost for that location
C       Cost due to the Number of Launches per year (VAR(4) = Total Mass, VAR(7) = Duration)
        DOLNL = 2.5E-1*NUML*BESTVAR(4)*2.25E-4*BESTVAR(7)
C
C       Cost due to the distance to the nearest industry centre (capital city, VAR(7) = Duration)
        DOLDI = SITE(I, 6)*5.0E-4*BESTVAR(7)
C
C       Cost due to the work required to construct the launch facility
        DOLSI = 2.5E2*((TANH(-((4.2E0*SITE(I, 4)/1.0E2)-2.1E0))+
    &   TANH(2.1E0))/TANH(2.1E0))
C
C       Cost due to the distance to the nearest major rail line or heavy port facility
        DOLDT = SITE(I, 5)*3.0E-1
C
C       R&D Cost due to the Percent Reusable
        DOLRNDPR = (EXP(BESTVAR(5)/2.0E1)/3.0E-1)-(1.0E1/3.0E0)
C
C       R&D Cost due to the Total Mass of the Vehicle
        DOLRNDMT = BESTVAR(4)*1.0E-3
C
C       R&D Cost due to the Mass Fraction of the vehicle
        DOLRNDMF = 1.0E2*TAN(1.0E2*3.1415926535898E0*BESTVAR(2)/2.01E2)
C
C       R&D Cost due to the Specific Impulse, ISP
        DOLRNDISP = 1.0E1*EXP(BESTVAR(1)/7.0E1)
C
C       R&D Cost due to the Payload Mass Fraction (VAR(3) = Payload Mass Fraction)
        DOLRNDPMF = 200*EXP(4*BESTVAR(3))-200
C
C       Cost due to Research and Development (VAR(6) = Percent Indigenous, VAR(7) = Duration)
        DOLRND = (BESTVAR(6)/1.00E2)*(DOLRNDPR+DOLRNDMT+DOLRNDMF+DOLRNDISP
    &   +DOLRNDPMF)
C       *(-3.0E0*BESTVAR(7)/7.0E1+1.2E1/7.0E0)
C
```

```
C       Cost due to system maintenance (VAR(7) = Duration)
        DOLM = 2.5E-1*NUML*2.5E1*(TANH((4.2E0*BESTVAR(5)/1.0E2)-2.1E0)+
     &  TANH(2.1E0))/TANH(2.1E0)*BESTVAR(7)
C
C       Overall Program Cost (VAR(7) = Duration)
        DOLVAL = DOLNL+DOLDI+DOLSI+DOLDT+DOLRND+DOLM
C
C       Cost per Year
        CPYEAR = DOLVAL/BESTVAR(7)
C
C       Write results to the Results File
    WRITE (1, 99999) LOCATION(I), DATE1, TIME1, DATE3, TIME3,
     &  BESTVAR(8), BESTVAR(9), BESTVAR(10), BESTVAR(11),
     &  BESTVAR(1), BESTVAR(2), BESTVAR(3), BESTVAR(4),
     &  BESTVAR(5), BESTVAR(6), BESTVAR(7), NUML, DELTAV,
     &  DOLVAL, CPYEAR, BESTFCN
    WRITE (*, 99999) LOCATION(I), DATE1, TIME1, DATE3, TIME3,
     &  BESTVAR(8), BESTVAR(9), BESTVAR(10), BESTVAR(11),
     &  BESTVAR(1), BESTVAR(2), BESTVAR(3), BESTVAR(4),
     &  BESTVAR(5), BESTVAR(6), BESTVAR(7), NUML, DELTAV,
     &  DOLVAL, CPYEAR, BESTFCN
C
70      CONTINUE
C
C       End time
        CALL DATE_AND_TIME(DATE2, TIME2)
        WRITE(*, *) 'Finish Date: ', DATE2
        WRITE(*, *) 'Finish Time: ', TIME2
C
C       Calculate the Number of Launches for that Location (Range = 1 to 11 per year)
        NUML = ((3.65E2-SITE(I, 3))/3.65E2)*(((1.0E1*(TANH(-(4.2E0*
     &  BESTVAR(5)/1.00E2)-2.1E0)+TANH(2.1E0)))/(2.0E0*
     &  TANH(2.1E0)))+1.0E0)
C
C       Calculate the Systems Delta V
C       Rocket Equation Delta V (VAR(1) = ISP, VAR(4) = Total Mass, VAR(2) = Mass Fraction)
        DELTAVRE=9.8E0*BESTVAR(1)*LOG(BESTVAR(4)/(BESTVAR(4)*
     &  (1-BESTVAR(2))))
C
C       Overall Delta V
        DELTAV = (SITE(I, 1)-SITE(I, 2)+DELTAVRE)/1.0E3
C
C       Calculate the Program Cost for that location
C       Cost due to the Number of Launches per year (VAR(4) = Total Mass, VAR(7) = Duration)
        DOLNL = 2.5E-1*NUML*BESTVAR(4)*2.25E-4*BESTVAR(7)
C
C       Cost due to the distance to the nearest industry centre (capital city, VAR(7) = Duration)
        DOLDI = SITE(I, 6)*5.0E-4*BESTVAR(7)
C
C       Cost due to the work required to construct the launch facility
        DOLSI = 2.5E2*((TANH(-((4.2E0*SITE(I, 4)/1.0E2)-2.1E0))+
     &  TANH(2.1E0))/TANH(2.1E0))
C
C       Cost due to the distance to the nearest major rail line or heavy port facility
        DOLDT = SITE(I, 5)*3.0E-1
C
```

```
C       R&D Cost due to the Percent Reusable
        DOLRNDPR = (EXP(BESTVAR(5)/2.0E1)/3.0E-1)-(1.0E1/3.0E0)
C
C       R&D Cost due to the Total Mass of the Vehicle
        DOLRNDMT = BESTVAR(4)*1.0E-3
C
C       R&D Cost due to the Mass Fraction of the vehicle
        DOLRNDMF = 1.0E2*TAN(1.0E2*3.1415926535898E0*BESTVAR(2)/2.01E2)
C
C       R&D Cost due to the Specific Impulse, ISP
        DOLRNDISP = 1.0E1*EXP(BESTVAR(1)/7.0E1)
C
C       R&D Cost due to the Payload Mass Fraction (VAR(3) = Payload Mass Fraction)
        DOLRNDPMF = 200*EXP(4*BESTVAR(3))-200
C
C       Cost due to Research and Development (VAR(6) = Percent Indigenous, VAR(7) = Duration)
        DOLRND = (BESTVAR(6)/1.00E2)*(DOLRNDPR+DOLRNDMT+DOLRNDMF+DOLRNDISP
     &  +DOLRNDPMF)
C       *(-3.0E0*BESTVAR(7)/7.0E1+1.2E1/7.0E0)
C
C       Cost due to system maintenance (VAR(7) = Duration)
        DOLM = 2.5E-1*NUML*2.5E1*(TANH((4.2E0*BESTVAR(5)/1.0E2)-2.1E0)+
     &  TANH(2.1E0))/TANH(2.1E0)*BESTVAR(7)
C
C       Overall Program Cost (VAR(7) = Duration)
        DOLVAL = DOLNL+DOLDI+DOLSI+DOLDT+DOLRND+DOLM
C
C       Cost per Year
        CPYEAR = DOLVAL/BESTVAR(7)
C
C       Write results to the Results File
        WRITE (1, *) 'Best Overall Result:'
        WRITE (1, *) ''
      WRITE (1, 99999) LOCATION(I), DATE1, TIME1, DATE2, TIME2,
     &  BESTVAR(8), BESTVAR(9), BESTVAR(10), BESTVAR(11),
     &  BESTVAR(1), BESTVAR(2), BESTVAR(3), BESTVAR(4),
     &  BESTVAR(5), BESTVAR(6), BESTVAR(7), NUML, DELTAV,
     &  DOLVAL, CPYEAR, BESTFCN
C
99999 FORMAT ('Site: ', A16, /, ' Start Date and Time:  ', A10, ' ',
     &  A10, /, ' Run Date and Time:    ', A10, ' ', A10, /,
     &  ' Independent Variables: ', /,
     &  '  Political Advantage      ', F6.4, /,
     &  '  Elevated Technology Base ', F6.4, /,
     &  '  Security                 ', F6.4, /,
     &  '  Cost Factor              ', F6.4, /,
     &  '  Specific Impulse:        ', F5.0, ' s', /,
     &  '  Mass Fraction:           ', F5.3, /,
     &  '  Payload Mass Fraction:   ', F5.3, /,
     &  '  Total Mass:              ', F10.1, ' kg', /,
     &  '  Percent Reusable:        ', F5.1, ' %', /,
     &  '  Percent Indigenous:      ', F5.1, ' %', /,
     &  '  Program Duration:        ', F4.1, ' Years', /,
     &  '  Number of Launches:      ', F4.1, ' per Year', /,
     &  '  System Delta V:          ', F4.1, ' km/s', /,
     &  '  Program Cost:           $', F10.1, ' million', /,
```

```
   &    '  Program Cost per Annum: $', F10.1, ' million', //,
   &    ' Benefits Value ', F7.5, /)
C
C       Zeroise BESTFCN
        BESTFCN = 0
C80     CONTINUE
C
        ENDFILE(UNIT = 1)
        CLOSE (UNIT = 1)
C
   END
```

Appendix D: Non-Linear Optimiser Routine - NCONF

NCONF/DNCONF (Single/Double precision)

Solve a general non-linear programming problem using the successive quadratic programming algorithm and a finite difference gradient.

Usage

CALL NCONF (FCN, M, ME, N, XGUESS, IBTYPE, XLB, XUB,
XSCALE, IPRINT, MAXITN, X, FVALUE)

Arguments

FCN - User-supplied SUBROUTINE to evaluate the functions at a given point. The usage is CALL FCN (M, ME, N, X, ACTIVE, F, G), where

M - Total number of constraints. (Input)
ME - Number of equality constraints. (Input)
N - Number of variables. (Input)
X - The point at which the functions are evaluated. (Input)
X should not be changed by FCN.
ACTIVE - Logical vector of length MMAX indicating the active constraints. (Input)
MMAX = MAX(1, M)
F - The computed function value at the point X. (Output)
G - Vector of length MMAX containing the values of constraints at point X. (Output)

FCN must be declared EXTERNAL in the calling program.
M - Total number of constraints. (Input)
ME - Number of equality constraints. (Input)
N - Number of variables. (Input)
XGUESS - Vector of length N containing an initial guess of the computed solution. (Input)
IBTYPE - Scalar indicating the types of bounds on variables. (Input)

IBTYPE Action

0 User will supply all the bounds.
1 All variables are non-negative.
2 All variables are non-positive.
3 User supplies only the bounds on 1st variable; all other variables will have the same bounds.

XLB - Vector of length N containing the lower bounds on variables. (Input, if IBTYPE = 0; output, if IBTYPE = 1 or 2; input/output, if IBTYPE = 3)
If there is no lower bound for a variable, then the corresponding XLB value should be set to -1.0E6.
XUB - Vector of length N containing the upper bounds on variables. (Input, if IBTYPE = 0; output, if IBTYPE = 1 or 2; input/output, if IBTYPE = 3)
If there is no upper bound for a variable, then the corresponding XLB value should be set to 1.0E6.
XSCALE - Vector of length N containing the diagonal scaling matrix for the variables. (Input)
All values of XSCALE must be greater than zero. In the absence of other information, set all entries to 1.0.
IPRINT - Parameter indicating the desired output level. (Input)

IPRINT	Action
0	No output printed.
1	Only a final convergence analysis is given.
2	One line of intermediate results is printed in each iteration.
3	Detailed information is printed in each iteration.

MAXITN - Maximum number of iterations allowed. (Input)
X - Vector of length N containing the computed solution. (Output)
FVALUE - Scalar containing the value of the objective function at the computed solution. (Output)

Appendix E: Optimisation FORTRAN Program

```
C       Launch Program Optimisation
C       FLTLT Tony Rogers
C       Date Started: 1 Dec 2000
C
        INTEGER    N, I, IPARAM(7), ITP, L, NOUT, IBTYPE, IPRINT, MAXITN,
  &       ME, A
C
        PARAMETER  (IBTYPE = 0, IPRINT = 0, M = 2, MAXITN = 10000, ME = 0
  &       ,N = 7)
C
        REAL       FSCALE, RPARAM(7), VAR(N), VARGUESS(N), FCNVAL,
  &                VARLB(N), VARSCALE(N), VARUB(N), SITE(17,6),
  &          NUML, DOLNL, DOLDI, DOLSI, DOLDT, DOLRNDPR, DOLRNDMT,
  &          DOLRNDMF, DOLRNDISP, DOLRNDPMF, DOLRND, DOLM, DOLS,
  &          CPY, DELTAVRE, DELTAV, BEST(8), GUESS(17, N), REL(4),
  &                MASSP, POLADV, POLAMP, POLANL, POLAPR, POLAD, POLA,
  &                ELTBISP, ELTBMF, ELTBPR, ELTBNL, ELTBPMF, ELTBD, ELTB,
  &                SECURITY, COSTFPY, COSTFTD, COSTF, BESTPA, BESTETB,
  &                BESTSEC, BESTCF
C
        COMMON          SITE, I, REL
C
        CHARACTER  *16 LOCATION(17)
        CHARACTER  *10 DATE1, TIME1, DATE2(17), TIME2(17), DATE3, TIME3
C
   EXTERNAL   NCONF, LAUNCHSYSTEM
C
C       VAR(1) = Specific Impulse (ISP)  Range = 0 to 1,000 seconds
C       VAR(2) = Mass Fraction           Range = 0 to 0.95
C       VAR(3) = Payload Mass Fraction   Range = 0 to 0.9
C       VAR(4) = Total Mass                     Range = 15,000 to 700,000 kg
C       VAR(5) = Percent Reusable               Range = 0 to 100 %
C       VAR(6) = Percent Indigenous      Range = 0 to 100 %
C       VAR(7) = Program Duration               Range = 5 to 40 years
C
        DATA VARSCALE/1.0E0, 1.0E0, 1.0E0, 1.0E0, 1.0E0, 1.0E0, 1.0E0/
C       Variable Lower Bounds
        DATA VARLB/0E0, 0E0, 0E0, 1.5E4, 0E0, 0E0, 5.0E0/
C       Variable Upper Bounds
        DATA VARUB/1.E3, 0.95E0, 9.0E-1, 7.0E5, 1.0E2, 1.0E2, 4.0E1/
C
C       Open the results file
        OPEN (UNIT=1, FILE = 'NCONF Run Results.txt')
        OPEN (UNIT=2, FILE = 'NCONF Run Summary.txt')
C
C       Date/Time Stamp
        CALL DATE_AND_TIME(DATE1, TIME1)
        WRITE(1, 4000) DATE1, TIME1
        WRITE(2, 4000) DATE1, TIME1
C
C       Set BEST(8) to zero (Best FCNVAL)
        BEST(8) = 0.0E0
```

```
C
C       Location Matrix
C
C       SITE(X, 1) = Delta V due to the Earth's rotation
C       SITE(X, 2) = Delta V due to the cost of achieving popular inclinations
C       SITE(X, 3) = Number of Rainy Days per year
C       SITE(X, 4) = Percentage of site infrastructure required already in place
C       SITE(X, 5) = Distance to nearest major rail line or heavy port facility
C       SITE(X, 6) = Distance to nearest industrial centre (Capital City)
C
C       Independent Variable Initial Conditions
C       GUESS(X, 1) = Specific Impulse (ISP)
C       GUESS(X, 2) = Mass Fraction
C       GUESS(X, 3) = Payload Mass Fraction
C       GUESS(X, 4) = Total Mass
C       GUESS(X, 5) = Percent Reusable
C       GUESS(X, 6) = Percent Indigenous
C       GUESS(X, 7) = Program Duration
C
C       Christmas Island
        SITE(1, 1) = 4.57E2
        SITE(1, 2) = 2.49E2
        SITE(1, 3) = 1.73E2
        SITE(1, 4) = 0.0E0
        SITE(1, 5) = 2.5E1
        SITE(1, 6) = 2.8E3
        GUESS(1, 1) = 3.0E2
        GUESS(1, 2) = 9.3E-1
        GUESS(1, 3) = 2.8E-1
        GUESS(1, 4) = 2.5E5
        GUESS(1, 5) = 8.8E1
        GUESS(1, 6) = 1.0E2
        GUESS(1, 7) = 1.2E1
C       Borroloola, NT
        SITE(2, 1) = 4.47E2
        SITE(2, 2) = 3.166E3
        SITE(2, 3) = 5.15E1
        SITE(2, 4) = 0.0E0
        SITE(2, 5) = 2.5E2
        SITE(2, 6) = 6.5E2
        GUESS(2, 1) = 3.4E2
        GUESS(2, 2) = 9.6E-1
        GUESS(2, 3) = 3.2E-1
        GUESS(2, 4) = 3.6E5
        GUESS(2, 5) = 8.8E1
        GUESS(2, 6) = 1.0E2
        GUESS(2, 7) = 1.5E1
C       Gunn Point, NT
        SITE(3, 1) = 4.55E2
        SITE(3, 2) = 3.641E3
        SITE(3, 3) = 1.107E2
        SITE(3, 4) = 0.0E0
        SITE(3, 5) = 2.5E1
        SITE(3, 6) = 5.0E1
        GUESS(3, 1) = 3.6E2
        GUESS(3, 2) = 9.6E-1
```

```
          GUESS(3, 3) = 3.2E-1
          GUESS(3, 4) = 3.6E5
          GUESS(3, 5) = 8.8E1
          GUESS(3, 6) = 1.0E2
          GUESS(3, 7) = 1.5E1
C         Katherine, NT
          SITE(4, 1) = 4.5E2
          SITE(4, 2) = 2.826E3
          SITE(4, 3) = 8.16E1
          SITE(4, 4) = 0.0E0
          SITE(4, 5) = 2.5E1
          SITE(4, 6) = 3.0E2
          GUESS(4, 1) = 3.4E2
          GUESS(4, 2) = 9.6E-1
          GUESS(4, 3) = 3.2E-1
          GUESS(4, 4) = 3.6E5
          GUESS(4, 5) = 8.8E1
          GUESS(4, 6) = 1.0E2
          GUESS(4, 7) = 1.5E1
C         Nhulunbuy, NT
          SITE(5, 1) = 4.55E2
          SITE(5, 2) = 2.662E3
          SITE(5, 3) = 9.79E1
          SITE(5, 4) = 0.0E0
          SITE(5, 5) = 4.75E2
          SITE(5, 6) = 9.0E2
          GUESS(5, 1) = 3.0E2
          GUESS(5, 2) = 9.7E-1
          GUESS(5, 3) = 3.4E-1
          GUESS(5, 4) = 4.4E5
          GUESS(5, 5) = 8.8E1
          GUESS(5, 6) = 1.0E2
          GUESS(5, 7) = 1.5E1
C         Broome, WA
          SITE(6, 1) = 4.36E2
          SITE(6, 2) = 3.368E3
          SITE(6, 3) = 4.66E1
          SITE(6, 4) = 0.0E0
          SITE(6, 5) = 2.5E1
          SITE(6, 6) = 1.1E3
          GUESS(6, 1) = 3.2E2
          GUESS(6, 2) = 9.7E-1
          GUESS(6, 3) = 3.4E-1
          GUESS(6, 4) = 4.3E5
          GUESS(6, 5) = 8.8E1
          GUESS(6, 6) = 1.0E2
          GUESS(6, 7) = 1.5E1
C         Port Hedland, WA
          SITE(7, 1) = 4.36E2
          SITE(7, 2) = 3.335E3
          SITE(7, 3) = 3.1E1
          SITE(7, 4) = 0.0E0
          SITE(7, 5) = 2.5E1
          SITE(7, 6) = 1.25E3
          GUESS(7, 1) = 3.2E2
          GUESS(7, 2) = 9.7E-1
```

```
      GUESS(7, 3) = 3.4E-1
      GUESS(7, 4) = 4.3E5
      GUESS(7, 5) = 8.8E1
      GUESS(7, 6) = 1.0E2
      GUESS(7, 7) = 1.5E1
C     Wyndham, WA
      SITE(8, 1) = 4.48E2
      SITE(8, 2) = 3.168E3
      SITE(8, 3) = 6.45E1
      SITE(8, 4) = 0.0E0
      SITE(8, 5) = 4.5E2
      SITE(8, 6) = 8.5E2
      GUESS(8, 1) = 3.4E2
      GUESS(8, 2) = 9.6E-1
      GUESS(8, 3) = 3.2E-1
      GUESS(8, 4) = 3.6E5
      GUESS(8, 5) = 8.8E1
      GUESS(8, 6) = 1.0E2
      GUESS(8, 7) = 1.5E1
C     Woomera, SA
      SITE(9, 1) = 3.98E2
      SITE(9, 2) = 6.84E2
      SITE(9, 3) = 5.0E1
      SITE(9, 4) = 7.0E1
      SITE(9, 5) = 7.5E1
      SITE(9, 6) = 5.5E2
      GUESS(9, 1) = 3.2E2
      GUESS(9, 2) = 9.3E-1
      GUESS(9, 3) = 2.8E-1
      GUESS(9, 4) = 2.5E5
      GUESS(9, 5) = 8.8E1
      GUESS(9, 6) = 1.0E2
      GUESS(9, 7) = 1.2E1
C     Cape York, QLD
      SITE(10, 1) = 4.57E2
      SITE(10, 2) = 1.851E3
      SITE(10, 3) = 1.081E2
      SITE(10, 4) = 0.0E0
      SITE(10, 5) = 8.0E2
      SITE(10, 6) = 1.25E3
      GUESS(10, 1) = 3.2E2
      GUESS(10, 2) = 9.5E-1
      GUESS(10, 3) = 3.0E-1
      GUESS(10, 4) = 3.1E5
      GUESS(10, 5) = 8.8E1
      GUESS(10, 6) = 1.0E2
      GUESS(10, 7) = 1.4E1
C     Cooktown, QLD
      SITE(11, 1) = 4.48E2
      SITE(11, 2) = 1.101E3
      SITE(11, 3) = 1.293E2
      SITE(11, 4) = 0.0E0
      SITE(11, 5) = 1.75E2
      SITE(11, 6) = 1.175E2
      GUESS(11, 1) = 3.0E2
      GUESS(11, 2) = 9.5E-1
```

```
      GUESS(11, 3) = 3.0E-1
      GUESS(11, 4) = 3.1E5
      GUESS(11, 5) = 8.8E1
      GUESS(11, 6) = 1.0E2
      GUESS(11, 7) = 1.3E1
C     Hummock Hill, QLD
      SITE(12, 1) = 4.25E2
      SITE(12, 2) = 1.402E3
      SITE(12, 3) = 7.51E1
      SITE(12, 4) = 0.0E0
      SITE(12, 5) = 2.5E1
      SITE(12, 6) = 4.5E2
      GUESS(12, 1) = 3.2E2
      GUESS(12, 2) = 9.5E-1
      GUESS(12, 3) = 3.0E-1
      GUESS(12, 4) = 3.1E5
      GUESS(12, 5) = 8.8E1
      GUESS(12, 6) = 1.0E2
      GUESS(12, 7) = 1.3E1
C     Mt. Isa, QLD
      SITE(13, 1) = 4.35E2
      SITE(13, 2) = 6.74E2
      SITE(13, 3) = 3.35E1
      SITE(13, 4) = 0.0E0
      SITE(13, 5) = 2.5E1
      SITE(13, 6) = 1.6E3
      GUESS(13, 1) = 3.0E2
      GUESS(13, 2) = 9.4E-1
      GUESS(13, 3) = 3.0E-1
      GUESS(13, 4) = 2.6E5
      GUESS(13, 5) = 8.8E1
      GUESS(13, 6) = 1.0E2
      GUESS(13, 7) = 1.3E1
C     Townsville, QLD
      SITE(14, 1) = 4.39E2
      SITE(14, 2) = 6.41E2
      SITE(14, 3) = 9.13E1
      SITE(14, 4) = 0.0E0
      SITE(14, 5) = 2.5E1
      SITE(14, 6) = 1.1E3
      GUESS(14, 1) = 3.0E2
      GUESS(14, 2) = 9.4E-1
      GUESS(14, 3) = 3.0E-1
      GUESS(14, 4) = 2.7E5
      GUESS(14, 5) = 8.8E1
      GUESS(14, 6) = 1.0E2
      GUESS(14, 7) = 1.3E1
C     Weipa, QLD
      SITE(15, 1) = 4.54E2
      SITE(15, 2) = 2.398E3
      SITE(15, 3) = 1.069E2
      SITE(15, 4) = 0.0E0
      SITE(15, 5) = 6.5E2
      SITE(15, 6) = 1.15E3
      GUESS(15, 1) = 3.2E2
      GUESS(15, 2) = 9.6E-1
```

```
      GUESS(15, 3) = 3.2E-1
      GUESS(15, 4) = 3.6E5
      GUESS(15, 5) = 8.8E1
      GUESS(15, 6) = 1.0E2
      GUESS(15, 7) = 1.4E1
C     Orange, NSW
      SITE(16, 1) = 3.88E2
      SITE(16, 2) = 2.7723
      SITE(16, 3) = 1.247E2
      SITE(16, 4) = 0.0E0
      SITE(16, 5) = 2.5E1
      SITE(16, 6) = 1.5E2
      GUESS(16, 1) = 2.8E2
      GUESS(16, 2) = 9.4E-1
      GUESS(16, 3) = 2.8E-1
      GUESS(16, 4) = 2.8E5
      GUESS(16, 5) = 8.8E1
      GUESS(16, 6) = 1.0E2
      GUESS(16, 7) = 1.2E1
C     Wilson's Promontory VIC
      SITE(17, 1) = 3.61E2
      SITE(17, 2) = 2.692E3
      SITE(17, 3) = 1.801E2
      SITE(17, 4) = 0.0E0
      SITE(17, 5) = 1.0E2
      SITE(17, 6) = 1.5E2
      GUESS(17, 1) = 3.4E2
      GUESS(17, 2) = 9.6E-1
      GUESS(17, 3) = 3.2E-1
      GUESS(17, 4) = 3.6E5
      GUESS(17, 5) = 8.8E1
      GUESS(17, 6) = 1.0E2
      GUESS(17, 7) = 1.5E1
C
C     Location names
      LOCATION(1) = 'Christmas Island'
      LOCATION(2) = 'Borroloola NT'
      LOCATION(3) = 'Gunn Point NT'
      LOCATION(4) = 'Katherine NT'
      LOCATION(5) = 'Nhulunbuy NT'
      LOCATION(6) = 'Broome WA'
      LOCATION(7) = 'Port Hedland WA'
      LOCATION(8) = 'Wyndham WA'
      LOCATION(9) = 'Woomera SA'
      LOCATION(10) = 'Cape York QLD'
      LOCATION(11) = 'Cooktown QLD'
      LOCATION(12) = 'Hummock Hill QLD'
      LOCATION(13) = 'Mt Isa QLD'
      LOCATION(14) = 'Townsville QLD'
      LOCATION(15) = 'Weipa QLD'
      LOCATION(16) = 'Orange NSW'
      LOCATION(17) = 'Wilsons Promontory VIC'
C
C     Benefit Component Relationships
C     Political Advantage
      REL(1) = 4.0E-1
```

```
C       Cost Factor
        REL(2) = 3.0E-1
C       Elevated Technology Base
        REL(3) = 2.0E-1
C       Security
        REL(4) = 1.0E-1
C
C       Record the Benefit Component Relationships
        WRITE(1, *) 'Benefit Component Relationships'
        WRITE(2, *) 'Benefit Component Relationships'
        WRITE(1,5000) REL(1), REL(2), REL(3), REL(4)
        WRITE(2,5000) REL(1), REL(2), REL(3), REL(4)
C
C       Loop through the 17 launch sites
        DO 10 I = 1, 17
C
C       Load in the Sites initial conditions
        VARGUESS(1) = GUESS(I, 1)
        VARGUESS(2) = GUESS(I, 2)
        VARGUESS(3) = GUESS(I, 3)
        VARGUESS(4) = GUESS(I, 4)
        VARGUESS(5) = GUESS(I, 5)
        VARGUESS(6) = GUESS(I, 6)
        VARGUESS(7) = GUESS(I, 7)
C
C       Optimisation Routine
        CALL NCONF (LAUNCHSYSTEM, M, ME, N, VARGUESS, IBTYPE,
   &       VARLB, VARUB, VARSCALE, IPRINT, MAXITN, VAR, FCNVAL)
C
        NUML = ((3.65E2-SITE(I, 3))/3.65E2)*(((1.0E1*(TANH(-(4.2E0*VAR(5)/
   &    1.00E2)-2.1E0)+TANH(2.1E0)))/(2.0E0*TANH(2.1E0)))+1.0E0)
C
C       Rocket Equation Delta V (VAR(1) = ISP, VAR(4) = Total Mass, VAR(2) = Mass
C       Fraction)
        DELTAVRE=9.8E0*VAR(1)*LOG(VAR(4)/(VAR(4)*(1-VAR(2))))
C
C       Overall Delta V
        DELTAV = SITE(I, 1)-SITE(I, 2)+DELTAVRE
C
C       Mass of the Payload (VAR(3) = Payload Mass Fraction, VAR(4) = Total Mass,
C       VAR(2) = MF)
        MASSP = VAR(3)*VAR(4)*(1-VAR(2))
C
C       Political Advantage due to Delta V
        POLADV = (TANH(2.1E0)+TANH((4.2E0*DELTAV/2.0E1)-2.1E0))/
   &     (2.0E0*TANH(2.1E0))
C
C       Political Advantage due to Mass of the Payload
        POLAMP = (TANH(2.1E0)+TANH((4.2E0*MASSP/5.0E3)-2.1E0))/
   &    (2.0E0*TANH(2.1E0))
C
C       Political Advantage due to the Number of Launches
        POLANL = TANH(NUML/6.0E0)
C
C       Political Advantage due to Percentage Reusability of the System
        POLAPR = (TANH(2.1E0)+TANH((4.2E0*VAR(5)/1.0E2)-2.1E0))/
```

```
   &     (2.0E0*TANH(2.1E0))
C
C        Political Advantage due to the Program's duration
         POLAD = -VAR(7)/4.0E1+1
C
C        Political Advantage (VAR(6) = Percent Indigenous)
         POLA = (VAR(6)/1.0E2)*(3.0E-1*POLADV+2.0E-1*POLAMP+1.0E-
   &              1*POLANL+
   &              1.5E-1*POLAPR+2.5E-1*POLAD)
C
C        Cost due to the Number of Launches per year (VAR(4) = Total Mass, VAR(7) =
C        Duration)
         DOLNL = 2.5E-1*NUML*VAR(4)*2.25E-4*VAR(7)
C
C        Cost due to the distance to the nearest industry centre (capital city, VAR(7) =
C        Duration)
         DOLDI = SITE(I, 6)*5.0E-4*VAR(7)
C
C        Cost due to the work required to construct the launch facility
         DOLSI = 2.5E2*((TANH(-((4.2E0*SITE(I, 4)/1.0E2)-2.1E0))+
   &      TANH(2.1E0))/TANH(2.1E0))
C
C        Cost due to the distance to the nearest major rail line or heavy port facility
         DOLDT = SITE(I, 5)*3.0E-1
C
C        R&D Cost due to the Percent Reusable
         DOLRNDPR = (EXP(VAR(5)/2.0E1)/3.0E-1)-(1.0E1/3.0E0)
C
C        R&D Cost due to the Total Mass of the Vehicle
         DOLRNDMT = VAR(4)*1.0E-3
C
C        R&D Cost due to the Mass Fraction of the vehicle
         DOLRNDMF = 1.0E2*TAN(1.0E2*3.1415926535898E0*VAR(2)/2.01E2)
C
C        R&D Cost due to the Specific Impulse, ISP
         DOLRNDISP = 1.0E1*EXP(VAR(1)/7.0E1)
C
C        R&D Cost due to the Payload Mass Fraction (VAR(3) = Payload Mass Fraction)
         DOLRNDPMF = 200*EXP(4*VAR(3))-200
C
C        Cost due to Research and Development (VAR(6) = Percent Indigenous, VAR(7)
C        = Duration)
         DOLRND = (VAR(6)/1.00E2) * (DOLRNDPR + DOLRNDMT + DOLRNDMF
   &      + DOLRNDISP + DOLRNDPMF) * (-3.0E0 * VAR(7)/3.5E1 + 3.1E1/7.0E0)
C
C        Cost due to system maintenance (VAR(7) = Duration)
         DOLM = 2.5E-1*NUML*2.5E1*(TANH((4.2E0*VAR(5)/1.0E2)-2.1E0)+
   &     TANH(2.1E0))/TANH(2.1E0)*VAR(7)
C
C        Overall Program Cost (VAR(7) = Duration)
         DOLS = DOLNL+DOLDI+DOLSI+DOLDT+DOLRND+DOLM
C
C        Technology Base required to achieve the Specific Impulse, ISP, employed
         ELTBISP = TANH(VAR(1)/6.00E2)
C
C        Technology Base required to achieve the Vehicle's Mass Fraction
```

```
      ELTBMF = EXP(8.0E0*VAR(2))/EXP(8.0E0)
C
C     Technology Base required to achieve the Percentage Reusable (VAR(5) = %
C     Reusable)
      ELTBPR = VAR(5)/1.0E2
C
C     Technology Base required to achieve the Number of Launches per year
      ELTBNL = (TANH((4.2E0*NUML/2.0E1)-2.1E0)+TANH(2.1E0))/
     &  (2.0E0*TANH(2.1E0))
C
C     Technology Base required to achieve the Payload Mass Fraction (VAR(3) =
C     Payload MF)
      ELTBPMF = TANH(2*VAR(3))
C
C     Technology base due to the duration of the program (the longer the lower)
      ELTBD = -VAR(7)/4.0E1+1
C
C     Elevated Technology Base ((VAR(6) = Percent Indigenous)
      ELTB = (VAR(6)/1.0E2)*(2.25E-1*ELTBISP+2.5E-1*ELTBMF
     &  +1.25E-1*ELTBPR+1.0E-1*ELTBNL+1.5E-1*ELTBPMF+1.5E-1*ELTBD)
C
C     Security (VAR(6) = Percent Indigenous)
      SECURITY = (VAR(6)/1.00E2)*(5E-1 * ((TANH(2.1E0) + TANH
     &    (4.2E0*DELTAV / 2.0E1-2.1E0))) / (2E0*TANH(2.1E0))+5E-1*
     &    TANH(MASSP/1.000E3))
C
C     Cost Factor Dollars per Year "EXP(-((2*DOLLARS/VAR(7))/1000))"
      COSTFPY = (-1.0E0/5.0E2)*(DOLS/VAR(7))+1
C     (TANH(-(((DOLLARS/VAR(7))/2.0E2)-3.0E0)) + TANH(3.0E0)) /
C     (2*TANH(3.0E0))
C     Cost Factor Total Dollars ($0 to $15 billion)
      COSTFTD = (-1.0E0/1.0E4)*DOLS+1
C     Overall cost Factor
      COSTF = 7.0E-1*COSTFTD+3.0E-1*COSTFPY
C
C     Cost per year
      COSTPY = DOLS/VAR(7)
C
C     Record the best result
      IF (FCNVAL .LT. BEST(8)) A = I
      IF (FCNVAL .LT. BEST(8)) BEST(1) = VAR(1)
      IF (FCNVAL .LT. BEST(8)) BEST(2) = VAR(2)
      IF (FCNVAL .LT. BEST(8)) BEST(3) = VAR(3)
      IF (FCNVAL .LT. BEST(8)) BEST(4) = VAR(4)
      IF (FCNVAL .LT. BEST(8)) BEST(5) = VAR(5)
      IF (FCNVAL .LT. BEST(8)) BEST(6) = VAR(6)
      IF (FCNVAL .LT. BEST(8)) BEST(7) = VAR(7)
      IF (FCNVAL .LT. BEST(8)) BESTPA  = POLA
      IF (FCNVAL .LT. BEST(8)) BESTETB = ELTB
      IF (FCNVAL .LT. BEST(8)) BESTSEC = SECURITY
      IF (FCNVAL .LT. BEST(8)) BESTCF  = COSTF
      IF (FCNVAL .LT. BEST(8)) BEST(8) = FCNVAL
C
C     Write results
  WRITE (1, 500) LOCATION(I), POLA, ELTB, SECURITY, COSTF,
     &  VARGUESS(1), VAR(1), VARGUESS(2), VAR(2),
```

```
   &     VARGUESS(3), VAR(3), VARGUESS(4), VAR(4),
   &     VARGUESS(5), VAR(5), VARGUESS(6), VAR(6),
   &     VARGUESS(7), VAR(7), NUML, DELTAV/1000, DOLS,
   &     COSTPY, -FCNVAL
         WRITE (2, 1000) LOCATION(I), -FCNVAL, POLA, ELTB, SECURITY, COSTF
C
10       CONTINUE
C
C        Write the best site to the summary file
         WRITE (2, *) ''
         WRITE (2, *) 'The Highest Scoring Site is:'
         WRITE (2, *) ''
   WRITE (2, 3000) LOCATION(A), -BEST(8), BESTPA, BESTETB, BESTSEC,
   &         BESTCF, BEST(1), BEST(2), BEST(3), BEST(4),
   &            BEST(5), BEST(6), BEST(7)
C
C        Date/Time Stamp
         CALL DATE_AND_TIME(DATE3, TIME3)
         WRITE(1, 4000) DATE3, TIME3
         WRITE(2, 4000) DATE3, TIME3
C
500  FORMAT ('Site: ', A16, /,
   &     ' Political Advantage:      ', F6.4, /,
   &     ' Elevated Technology Base:', F6.4, /,
   &     ' Security:                 ', F6.4, /,
   &     ' Cost Factor:              ', F6.4, /,
   &     ' Independent Variables:  (Guessed '
   &     '   Calculated)', /,
   &     ' Specific Impulse:      ', F4.0, ' s       ', F4.0,
   &     ' s ', /,
   &     ' Mass Fraction:         ', F5.3, '         ', F5.3, /,
   &     ' Payload Mass Fraction: ', F5.3, '         ', F5.3, /,
   &     ' Total Mass:            ', F8.1, ' kg   ', F8.1,
   &     ' kg', /,
   &     ' Percent Reusable:      ', F5.1, ' %      ', F5.1,
   &     ' %', /,
   &     ' Percent Indigenous:    ', F5.1, ' %      ', F5.1,
   &     ' %', /,
   &     ' Program Duration:      ', F4.1, ' Years   ', F4.1,
   &     ' Years', /, ' Calculations:', /,
   &     ' Number of Launches:    ', F4.1, ' per Year', /,
   &     ' System Delta V:        ', F4.1, ' km/s', /,
   &     ' Program Cost:          $', F10.1, ' million', /,
   &     ' Program Cost per Annum: $', F10.1, ' million', //,
   &     ' Benefits Value ', F5.3, /)
C
1000     FORMAT (A16, '  Benefit: ', F6.4, '  PA: ', F6.4,
   &     ' ETB: ', F6.4, '  SEC: ', F6.4, '  CF: ', F6.4)
C
2000 FORMAT ('Guesses', /,
   &     ' Specific Impulse:      ', F4.0, ' s', /,
   &     ' Mass Fraction:         ', F5.3, /,
   &     ' Payload Mass Fraction: ', F5.3, /,
   &     ' Total Mass:            ', F8.1, ' kg', /,
   &     ' Percent Reusable:      ', F5.1, ' %', /,
   &     ' Percent Indigenous:    ', F5.1, ' %', /,
```

```
     &     ' Program Duration:      ', F4.1, ' Years', /)
C
3000 FORMAT ('Best Site: ', A16, F5.3, /,
     &     ' Political Advantage:   ', F6.4, /,
     &     ' Elevated Technology Base:', F6.4, /,
     &     ' Security:              ', F6.4, /,
     &     ' Cost Factor:           ', F6.4, /,
     &     ' Specific Impulse:      ', F4.0, ' s', /,
     &     ' Mass Fraction:         ', F5.3, /,
     &     ' Payload Mass Fraction:  ', F5.3, /,
     &     ' Total Mass:            ', F8.1, ' kg', /,
     &     ' Percent Reusable:      ', F5.1, ' %', /,
     &     ' Percent Indigenous:    ', F5.1, ' %', /,
     &     ' Program Duration:      ', F4.1, ' Years', /)
C
C       Date/Time Stamp Format
4000    FORMAT ('Date: ', A10, ' Time: ', A10, /)
C
C       Benefit Component Relationships Write Format
5000    FORMAT (' PA:  ', F5.2, /, ' CF:  ', F5.2, /, ' ETB: ', F5.2,
     &  /, ' SEC: ',F5.2, /)
C
C       Terminate and close the results file
        ENDFILE(UNIT = 1)
        ENDFILE(UNIT = 2)
        CLOSE (UNIT = 1)
        CLOSE (UNIT = 2)
C
      END
C
C
C
C
C
C
C
      SUBROUTINE LAUNCHSYSTEM (M, ME, N, VAR, ACTIVE, FCN, G)
      INTEGER   M, ME, N, I
      REAL      VAR(N), G(*), FCN, SITE(17,6), NL, DVRE, DV, MP,
     &          PADV, PAMP,PANL, PAPR, PAD, PA, DNL, DDI, DSI, DDT,
     &          DRNDPR, DRNDMT, DRNDISP, DRNDPMF, DRND, DM,
     &          DOLLARS,ETBISP, ETBMF, ETBPR, ETBNL, ETBPMF,
     &          ETB, SEC, CF,REL(4)
        LOGICAL         ACTIVE(*)
        COMMON          SITE, I, REL
C
C       Function Equations
C       VAR(1) = Specific Impulse (ISP) Range = 0 to 1,000 seconds
C       VAR(2) = Mass Fraction              Range = 0 to 1
C       VAR(3) = Payload Mass Fraction   Range = 0 to 0.9
C       VAR(4) = Total Mass                       Range = 10,000 to 700,000 kg
C       VAR(5) = Percent Reusable           Range = 0 to 100 %
C       VAR(6) = Percent Indigenous         Range = 0 to 100 %
C       VAR(7) = Program Duration           Range = 5 to 40 years
C
C       Number of launches per year (Range = 1 to 11 per year)
```

```
      NL = ((3.65E2-SITE(I, 3))/3.65E2)*(((1.0E1*(TANH(-(4.2E0*VAR(5)/
   &  1.00E2)-2.1E0)+TANH(2.1E0)))/(2.0E0*TANH(2.1E0)))+1.0E0)
C
C     Rocket Equation Delta V (VAR(1) = ISP, VAR(4) = Total Mass, VAR(2) = Mass
C     Fraction)
      DVRE=9.8E0*VAR(1)*LOG(VAR(4)/(VAR(4)*(1-VAR(2))))
C
C     Overall Delta V
      DV = SITE(I, 1)-SITE(I, 2)+DVRE
C
C     Mass of the Payload (VAR(3) = Payload Mass Fraction, VAR(4) = Total Mass,
C     VAR(2) = MF)
      MP = VAR(3)*VAR(4)*(1-VAR(2))
C
C     Political Advantage due to Delta V
      PADV =       (TANH(2.1E0)+TANH((4.2E0*DV/2.0E1)-2.1E0))/
   &   (2.0E0*TANH(2.1E0))
C
C     Political Advantage due to Mass of the Payload
      PAMP = (TANH(2.1E0)+TANH((4.2E0*MP/5.0E3)-2.1E0))/
   &  (2.0E0*TANH(2.1E0))
C
C     Political Advantage due to the Number of Launches
      PANL = TANH(NL/6.0E0)
C
C     Political Advantage due to Percentage Reusability of the System
      PAPR = (TANH(2.1E0)+TANH((4.2E0*VAR(5)/1.0E2)-2.1E0))/
   &  (2.0E0*TANH(2.1E0))
C
C     Political Advantage due to the Program's duration
      PAD = -VAR(7)/4.0E1+1
C
C     Political Advantage (VAR(6) = Percent Indigenous)
      PA = (VAR(6)/1.0E2)*(3.0E-1*PADV+2.0E-1*PAMP+1.0E-1*PANL+
   &  1.5E-1*PAPR+2.5E-1*PAD)
C
C     Cost due to the Number of Launches per year (VAR(4) = Total Mass, VAR(7) = Duration)
      DNL = 2.5E-1*NL*VAR(4)*2.25E-4*VAR(7)
C
C     Cost due to the distance to the nearest industry centre (capital city, VAR(7) =
C     Duration)
      DDI = SITE(I, 6)*5.0E-4*VAR(7)
C
C     Cost due to the work required to construct the launch facility
      DSI = 2.5E2*((TANH(-((4.2E0*SITE(I, 4)/1.0E2)-2.1E0))+
   &  TANH(2.1E0))/TANH(2.1E0))
C
C     Cost due to the distance to the nearest major rail line or heavy port facility
      DDT = SITE(I, 5)*3.0E-1
C
C     R&D Cost due to the Percent Reusable
      DRNDPR = (EXP(VAR(5)/2.0E1)/3.0E-1)-(1.0E1/3.0E0)
C
C     R&D Cost due to the Total Mass of the Vehicle
      DRNDMT = VAR(4)*1.0E-3
C
```

```
C        R&D Cost due to the Mass Fraction of the vehicle
         DRNDMF = 1.0E2*TAN(1.0E2*3.1415926535898E0*VAR(2)/2.01E2)
C
C        R&D Cost due to the Specific Impulse, ISP
         DRNDISP = 1.0E1*EXP(VAR(1)/7.0E1)
C
C        R&D Cost due to the Payload Mass Fraction (VAR(3) = Payload Mass Fraction)
         DRNDPMF = 200*EXP(4*VAR(3))-200
C
C        Cost due to Research and Development (VAR(6) = Percent Indigenous, VAR(7)
C        = Duration)
         DRND = (VAR(6)/1.00E2) * (DRNDPR + DRNDMT + DRNDMF + DRNDISP
    &     + DRNDPMF) * (-3.0E0*VAR(7)/3.5E1 + 3.1E1/7.0E0)
C
C        Cost due to system maintenance (VAR(7) = Duration)
         DM = 2.5E-1*NL*2.5E1*(TANH((4.2E0*VAR(5)/1.0E2)-2.1E0)+
    &    TANH(2.1E0))/TANH(2.1E0)*VAR(7)
C
C        Overall Program Cost (VAR(7) = Duration)
         DOLLARS = DNL+DDI+DSI+DDT+DRND+DM
C
C        Technology Base required to achieve the Specific Impulse, ISP, employed
         ETBISP = TANH(VAR(1)/6.00E2)
C
C        Technology Base required to achieve the Vehicle's Mass Fraction
         ETBMF = EXP(8.0E0*VAR(2))/EXP(8.0E0)
C
C        Technology Base required to achieve the Percentage Reusable (VAR(5) = %
C        Reusable)
         ETBPR = VAR(5)/1.0E2
C
C        Technology Base required to achieve the Number of Launches per year
         ETBNL = (TANH((4.2E0*NL/2.0E1)-2.1E0)+TANH(2.1E0))/
    &     (2.0E0*TANH(2.1E0))
C
C        Technology Base required to achieve the Payload Mass Fraction (VAR(3) =
C        Payload MF)
         ETBPMF = TANH(2*VAR(3))
C
C        Technology base due to the duration of the program (the longer the lower)
         ETBD = -VAR(7)/4.0E1+1
C
C        Elevated Technology Base ((VAR(6) = Percent Indigenous)
         ETB = (VAR(6)/1.0E2)*(2.25E-1*ETBISP+2.5E-1*ETBMF+1.25E-1*ETBPR
    &    +1.0E-1*ETBNL+1.5E-1*ETBPMF+1.5E-1*ETBD)
C
C        Security (VAR(6) = Percent Indigenous)
         SEC = (VAR(6)/1.00E2)*(5E-1*((TANH(2.1E0)+TANH(4.2E0*DV/
    &    2.0E1-2.1E0)))/(2E0*TANH(2.1E0))+5E-1*
    &    TANH(MP/1.000E3))
C
C        Cost Factor Dollars per Year "EXP(-((2*DOLLARS/VAR(7))/1000))"
         CFPY = (-1.0E0/5.0E2)*(DOLLARS/VAR(7))+1
C        (TANH(-(((DOLLARS/VAR(7))/2.0E2)-3.0E0)) + TANH(3.0E0)) /
C        (2*TANH(3.0E0))
C        Cost Factor Total Dollars ($0 to $15 billion)
```

```
      CFTD = (-1.0E0/1.0E4)*DOLLARS+1
C     Overall cost Factor
      CF = 7.0E-1*CFTD+3.0E-1*CFPY
C
C     Benefits
   FCN = -(REL(1)*PA+REL(2)*CF+REL(3)*ETB+REL(4)*SEC)
C
C     Constraints (8 < Delta V < 20 km/s)
      IF (ACTIVE(1)) G(1) = SITE(I, 1)-SITE(I, 2)+9.8E0*VAR(1)*
   &          LOG(VAR(4)/(VAR(4)*(1-VAR(2))))-8.0E3
      IF (ACTIVE(2)) G(2) = 2.0E4-(SITE(I, 1)-SITE(I, 2)+9.8E0*VAR(1)*
   &          LOG(VAR(4)/(VAR(4)*(1-VAR(2)))))
C     Constraints DOLLARS/Year < $600 million
C     IF (ACTIVE(3)) G(3) = 6.0E2-(DOLLARS/VAR(7))
C     Constraint FCN < -0.7
C     IF (ACTIVE(4)) G(4) = -7.0E-1+(4.0E-1*PA+3.0E-1*CF+2.0E-1*ETB+
C  &                              1.0E-1*SEC)
C
   RETURN
   END
```

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Vita

Flight Lieutenant Anthony Rogers was born in Canberra, Australia. He graduated from Canberra Boys Grammar in Canberra, Australian Capital Territory in December 1990. He entered undergraduate studies at the Australian Defence Force Academy, a college of the University of New South Wales, in Canberra, where he graduated with a Bachelor of Engineering in Electrical Engineering in December 1994 and was commissioned on 1 January 1995.

His first assignment was at No. 114 Mobile Control and Reporting Unit at RAAF Base Amberley in Brisbane Queensland where he was initially assigned as the Maintenance Officer and then later as the Senior Engineer. In June 1997 he was posted to Canberra as a Systems Engineer on Project 5333, the new Air Defence C^4I system. During his time in Canberra he was also appointed Project Manager of an Air Defence Capability Technology Demonstrator, Project Air 5407 – The Acoustic Detection of Aircraft. In August 1999, he entered the Graduate Space Operations program at the United States Air Force Institute of Technology in Dayton Ohio. Upon graduation, he will be assigned to Capability Division, Satellite Systems in Canberra Australia.

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14. ABSTRACT

This thesis explores the possiblity of establishing an Australian indigenous space launch capability through developing and examining an Australian space launch program model. The model is based around launch site location, vehicle design, program duration, and the percentage Australian indigenous input into the program. The model was opimised in an effort maximise the benefits of such a capability, namely political prestige, security and in country technological base, while minimising the program's overall cost.

15. SUBJECT TERMS

Systems Engineering, Concept Exploration, Space Launch Capability, Australia, Australian, Modeling, Optimisation

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