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DETERMINING THE ECONOMIC PLAUSIBILITY OF DUAL MANIFESTING REUSABLE LAUNCH VEHICLES AND REUSABLE ORBITAL TRANSFER VEHICLES FOR THE REPLENISHMENT OF MILITARY SATELLITES

THESIS

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THESIS

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ABSTRACT

Currently, the Air Force launches military satellites on expendable launch vehicles to low earth orbit (LEO), and with the use of a chemical upper stage or an apogee kick motor, moves the satellite to a higher orbit. This launch procedure is extremely costly because it requires additional launch preparations, technology considerations, equipment, and fuel. Also, the additional mass of the chemical upper stage causes a larger, and thus more expensive, launch vehicle to be required. An economical alternative is to utilize reusable launch vehicles (RLVs) and reusable orbital launch vehicles (ROTVs). This concept could possibly achieve even greater savings if satellites were dual manifested on the launch vehicles. This thesis determines - by varying mass capacity of RLVs, the cost per kg of RLV mass capacity, and the satellite cost per kg - when, within a given scenario, the savings of dual manifesting is at least ten percent of the cost of single manifesting by developing a dual manifesting algorithm and simulation to analyze possible savings.

DETERMINING THE ECONOMIC PLAUSIBILITY OF DUAL MANIFESTING REUSABLE LAUNCH VEHICLES AND REUSABLE ORBITAL TRANSFER VEHICLES FOR THE REPLENISHMENT OF MILITARY SATELLITES

1. Introduction

1.1 Background

Satellites have become an integral part of everyone's daily lives, being used for scientific exploration, communication (television, telephone, and data), weather forecasting, earth sensing/imaging, and navigation. Because satellites are expensive, only commercial enterprises, international coalitions, and national governments can afford to own and operate satellite systems. Air Force Space Command (AFSPC) is responsible for defining satellite system requirements for the Air Force, and once a satellite is built AFSPC launches and maintains most of the US military satellites. Based on orbital mechanics, satellites circle the earth in prescribed orbits, which dictate the time and duration a satellite is viewed by an earth station. Satellites orbit the Earth in specific bands such as low earth orbit (LEO) (earth sensing/imaging), sun-synchronous (weather), semisynchronous orbit (navigation), and GEO (communication). The mission of the satellite determines what orbit the satellite will be in. Since limiting the scope of any study is fundamental, for the purposes of this thesis only US military satellites operating in geosynchrounous orbit (GEO) are considered.

Currently, the Air Force launches military satellites on expendable launch vehicles to low earth orbit (LEO), and with the use of a chemical upper stage or an apogee kick motor, moves the satellite to a higher orbit. This launch procedure is extremely costly because it requires additional launch preparations, technology considerations, equipment, and fuel. Also, the additional mass of the chemical upper stage causes a larger and thus more expensive launch vehicle to be required. An economical alternative is to utilize reusable launch vehicles (RLVs) and reusable orbital launch vehicles (ROTVs) (Figure 1.1).

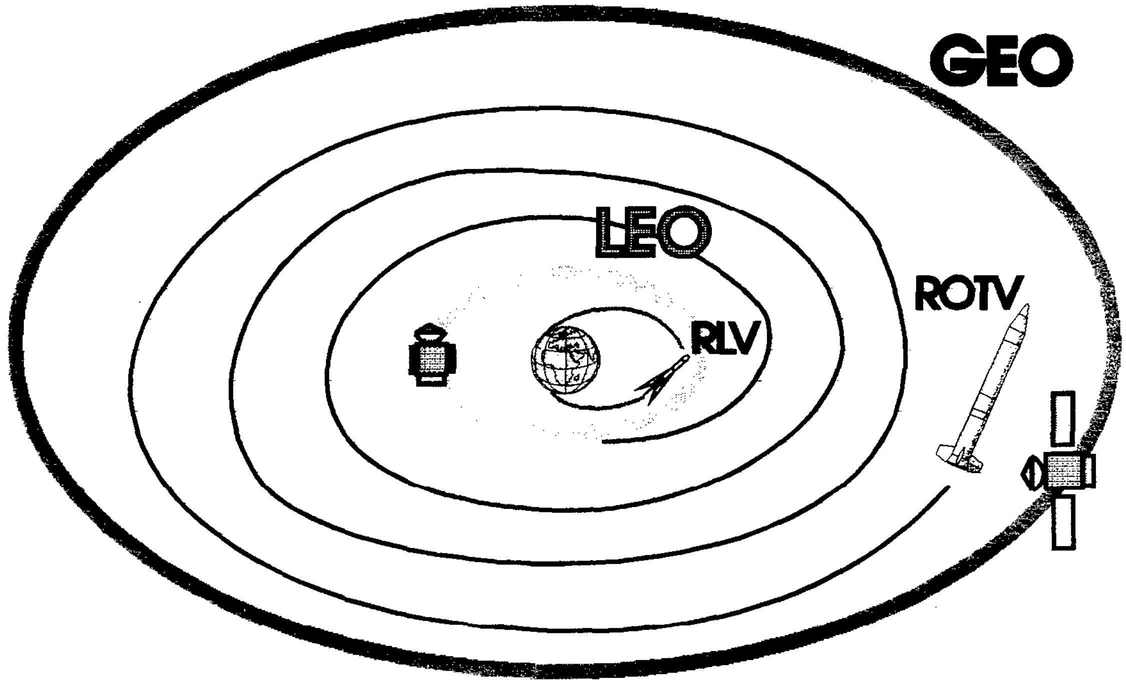

Figure 1.1 Reusable Launch Concept

Much research has been conducted to support the economics of RLVs and ROTVs (Feuchter and Giczy 1996; Wertz and Larson 1996). A logical follow-on question is what if the satellites are dual manifested? In theory, dual manifesting on RLVs would save money by dividing launch costs between two satellites that would normally be absorbed by just one. Dual manifesting on ROTVs will result in more satellites transferred to mission orbit per ROTV, thus dividing its cost among more satellites. The downside to dual manifesting is that satellites may be launched before they are actually needed, thus reducing mission life.

1.2 Dual Manifesting (DM)

Conceptually, there are three ways in which GEO satellites could be dual manifested (Figure 1.2). The first is to DM on both the launch and orbital transfer vehicles. The second option would be to DM on the RLV, then single manifest on the ROTV. The third would be to single manifest on the RLV, then DM on the ROTV. Intuitively, the case that would appear to create the greatest savings would be to dual

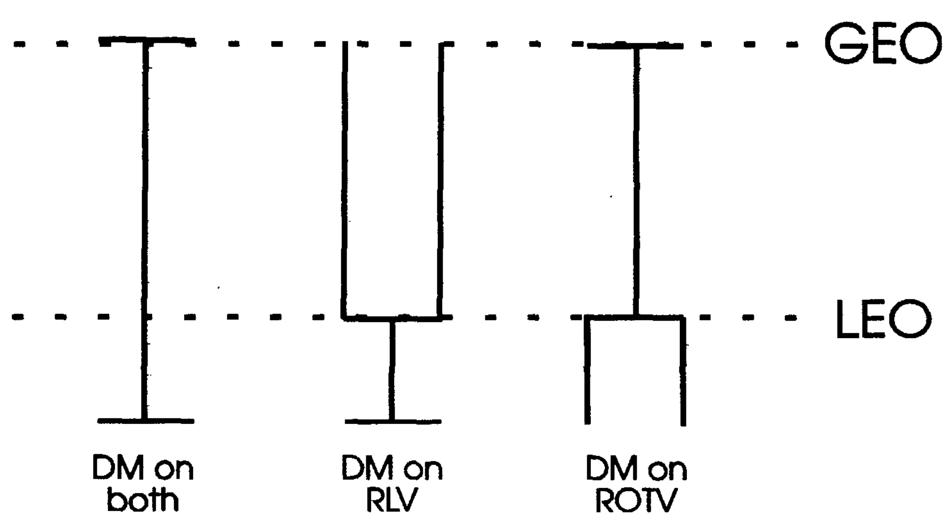

Figure 1.2 Dual Manifesting Concepts

manifest on both vehicles; therefore, this thesis will deal only with that option.

1.3 Scenarios

Recapping, the satellites will be launched to GEO using RLVs and ROTVs. The two scenarios used are comprised of constellations predetermined by the Office of Aerospace Studies (OAS) (Grobman 1996). Each constellation consists of four satellites plus the appropriate number of on-orbit spares needed to maintain constellation availability because of the slow transfer time on the ROTV (which is discussed in Section 3.1.2).

This thesis will determine - by varying mass capacity of RLVs, the cost per kg of RLV mass capacity, and the satellite cost per kg - when, within a given scenario, the savings of dual manifesting is at least ten percent of the cost of single manifesting.

2. Literature Review

2.1 Space Launches

Reducing the cost of space launch is a well-researched area in the space community. Wertz and Larson (1996) summarized many of the ideas on how to reduce launch costs, such as alternative launch methods, improving the efficiency of boosters, exploring reusable launch vehicle concepts, and adopting a design for minimum cost methodology. None of these concepts, however, look at the problem from an OR point of view. An article by Krell (1979) reduces costs through a closed form probabilistic model that compares the costs of launching a satellite to repositioning an on-orbit spare, and analyzes the cost of these replenishment strategies. He greatly simplifies the parameters involved, and shows that the results were comparable to those found using the simulation packages available at that time.

2.2 Possible Approaches to Dual Manifesting

Krell, however, did not look at the possibility of launching more than one satellite at a time. Shipment consolidation techniques are available that explore the question of reducing costs by combining shipments. Higginson and Bookbinder (1994) look at three common policies :

- a time policy ships at a predetermined date;
- a quantity policy ships when a minimum weight is reached; and,

- a time and quantity policy ships when either a predetermined date or a minimum weight is reached, whichever occurs first.

In simplified terms, a time policy is currently employed by the space launch community. At a predetermined date, the replacement satellite is launched with no thought of consolidating. Higginson and Bookbinder look at consolidating shipments that are already needed. In this thesis, the consolidation would include satellites that are not yet needed; thus, an opportunity cost from the satellite is incurred. Higginson and Bookbinder do not consider such a cost.

Another approach to the scheduling algorithm (Neuberger and Praprost 1992) is to develop a vehicle routing and scheduling problem. Neuberger and Praprost discuss the development of a Replenishment Scheduling Algorithm (RSA) for supplying combat ships at sea. Again, three methods of supply are presented:

- a "service station" method where the combat ship travels to the supply ship;
- a "delivery boy" method where the supply ship travels to the combat ship; and,
- a "moving service station" method which is a combination of the two above methods.

Obviously, the "moving service station" method is employed in this thesis' environment, where the supply ship becomes the launch vehicles, the satellite is the cargo, and the combat ship becomes the final mission orbit. The RSA developed by Neuberger and Praprost includes considerations of the combat ships' routes (direction, speed, etc.), and the priority and current inventory of the needed cargo (fuel, food, recreational equipment) As such, an analogy of cargo ships resupplying combat ships is not congruent with launching satellites.

Sivazlian (1974) applies stochastic processes to determine a satellite launch policy for multiple manifesting. First he defines the average lifetime of each satellite, the required number of satellites, the expected launch cost per satellite, and the expected loss per time unit when the constellation is not functioning. A constellation requires s satellites to be operational. Sivazlian suggests minimizing total operational costs by maintaining $s + Q$ on-orbit satellites and launching Q satellites each time the number of satellites reaches s.

Gavish and Kalvenes (1996) also introduce a means of deciding when and in what manner to multiple manifest for large LEO constellations. Their article offers a simple background of how LEO satellites operate, and explains the potential savings associated with using the presented launch policies. They develop a dynamic programming model and give numerical examples. Their optimal launch policy consists of a list of specific actions to take each time the model is in a particular state. The state space is the number of on-orbit dead satellites. The action space, or decision set, consists of the different actions available at each time period; namely, how many satellites to launch and on which launch vehicles. Because of the size of constellations at LEO (Iridium with 66 satellites and Teledesic with 840 satellites), the state space needs to be bounded to keep the dynamic program computationally tractable. The objective is to choose the best action for each state to minimize total cost.

Gavish and Kalvenes use probabilistic dynamic programming (Winston 1994) to develop a policy to maximize the long-term revenues of a satellite constellation using the following recursion in which $V_n^*(i)$ is the optimal value of the system in state i at time n

$$V_n^*(i) = w_{ia*} + \Sigma\, q_{ij}(a)\, V_{n+1}^*(j)$$
$$= \min \{w_{ia*} + \Sigma\, q_{ij}(a)\, V_{n+1}^*(j)\}$$

where w_{ia} is the cost associated with launching i satellites using action a and the summation is over the minimized expected cost of future actions. The cost is based on the lost revenues of having dead on-orbit satellites and the cost of launching the replacement satellites. To calculate $q_{ij}(a)$ (i.e., the probability of moving from state i to state j given action a is taken), the probability of ℓ successful satellites launches (denoted by $p_\ell(a)$) is multiplied by the probability that r satellites will be dead in the next time period (denoted by $\pi_r(i)$). To calculate $\pi_r(i)$ Gavish and Kalvenes assume that satellite life is memoryless, thus allowing a tractable Markov decision process and transition matrix from which to calculate the π. They develop a method to bound the state space to avoid calculating a large number of transition probabilities, thus reducing the size of the problem.

One major assumption that Gavish and Kalvenes make is that the satellite lifetime distribution is memoryless, i.e., how long the satellite has already lived has no bearing on whether or not it will die in the next time period. Military satellite lifetimes are modeled using a Weibull distribution (Feuchter and others 1989; Feuchter and Giczy 1996; Chan and others 1996) and therefore a memoryless lifetime does not hold. Since the memoryless property is a crucial underlying assumption for Gavish and Kalvenes' model, their approach would not apply to this problem.

Another important factor in their article is an opportunity cost for lost revenues. Gavish and Kalvenes' algorithm looks for a balance between minimizing launch costs and minimizing opportunity costs. For the applications addressed in this thesis, the opportunity cost dominates because the required availability of 98% enforces an on-orbit spare. Since Gavish and Kalvenes deal with satellites in LEO that take one day to launch, the concept is reasonable; however, it is not applicable when launching a satellite to GEO on a Xe Ion ROTV that takes months to complete the trip.

3. Problem Definition

3.1 Launch Vehicles (LVs)

Satellites are placed into their mission orbits by LVs. Air Force Space Command (Chan and others 1993) set forth the following requirements for newly developed launch systems:

- LVs will be built with a reliability of at least 98%. This "zero tolerance for failure" (Wertz and Larson 1996) will force designers to incorporate redundant systems, thus driving costs upward.
- LVs will adhere to the launch schedule manifest (satellites that are being launched based on the replacement schedule) within 10 days of its appointed launch time.
- LVs will be able to launch on need (satellites that are being launched in response to a random failure) in 30 days.

Because of these requirements, it is assumed in this thesis that

- there is no time delay for a launch; and,
- there are no random failures (i.e., neither LV will experience a random failure and the ROTV will always make exactly six trips before needing replaced).

At the present time, satellites are launched to LEO and to GEO on expendable launch vehicles (ELVs). As the name implies, the launch vehicle deorbits and burns up after delivering and releasing the satellite in LEO. Choosing a particular LV is based primarily on the mass of the satellite. Launch costs and payload capacities of common ELVs (Wertz and Larson 1996) are summarized below.

Table 3.1 Current Expendable Launch Vehicles

Launch vehicle	*Launch cost*	*Payload capacity*	*Average cost per kg*
Delta 7920	$45M - $50M	5035 kg	$9,400
Atlas IIA	$80M - $90M	6760 kg	$12,600
Titan IV	$230M - $325M	17700 kg	$15,700
Space Shuttle	$350M - $547M	23500 kg	$19,100

Note that while the Space Shuttle is listed as an ELV, it actually has both reusable and expendable components (Wertz and Larson 1996). For typical Air Force payloads, the current ELVs do not offer cost savings by dual manifesting because launch costs roughly double as vehicle capacity doubles. Therefore, even if AFSPC was to place two small satellites on one large ELV, it would cost the same as putting them on two small ELVs.

3.1.1 Reusable Launch Vehicles(RLVs)

It is becoming increasingly important to find cheaper ways to inject the satellites into their mission orbits. A study conducted by NASA highlights the need to reduce transportation costs for satellites (Huether 1996). A Single Stage To Orbit (SSTO) technology (Griffin and Claybaugh 1996; Wertz and Larson 1996) promises to create substantial savings in launch costs. The idea of SSTO is to develop a launch vehicle that operates much like a cargo aircraft. The RLV would transport the payload to LEO before returning to earth, fully intact, for reuse. Because the RLV will be reused numerous times, they are expected to have much lower life cycle costs and higher reliability than current ELVs (Noor and Venneri 1994).

Reusable Launch Vehicles (RLVs) are considered in this thesis because they lend themselves well to dual manifesting even though the current generation of RLVs may not necessarily be cheaper to launch than ELVs. For the RLVs in this thesis, it is assumed that

- mass capacity will be a parameter, varied from 5000 kg to 10000 kg;
- an RLV will be available for every launch (infinite fleet); and,
- trip time to LEO for RLVs will be one day.

3.1.2 Reusable Orbital Transfer Vehicles (ROTVs)

While the RLV is generic in this thesis, the ROTV has more specific characteristics. Theoretically, the most cost efficient thruster for the ROTV will have a high thrust and a high specific impulse (I_{sp}). I_{sp} is a measure of how efficient the engine is, and thrust is a measure of the amount of force the engine is able to exert. With today's technology, however, thrust and I_{sp} are inversely proportional such that current chemical thrusters possess a high thrust and a low I_{sp}. Although the propellants used (O_2 and H_2) have low molecular weights, a great deal of mass flow is necessary to produce high thrust. Since more fuel is necessary, a high cost is incurred trying to keep enough liquid O_2 and H_2 fuel in the tanks. One way to reduce these costs is to use electric thrusters which have lower thrust and higher I_{sp}. Although less fuel is used because of the propellant's high density, the trade off is much longer trip times.

The *Solar Electric Propulsion Assessment* (Chan and others 1993) compares four electric propulsion (EP) technologies for upper stage thrusters - arcjets, resistojets, ion engines, and stationary plasma thrusters. By comparing the thrusters' stationkeeping, maneuvering, and orbit transfer abilities to those of current chemical propulsion (CP) technologies, they determined that EP provides significant savings in propellant at the expense of much longer trip times. Hurdato (1996) shows that the Solar Electric Xenon Ion technology provides the greatest potential for using a smaller less expensive launch vehicle.

Solar Electric Xe Ion ROTVs employ a fuel efficient low thrust-high I_{sp} technology which results in much slower transfer times from LEO to GEO because a spiral orbit is needed (Figure 1.1). The solar energy captured by the ROTV's solar panels creates an electric field which accelerates the Xenon ion propellant to produce thrust (Chan and others 1993). For the ROTVs in this thesis it is assumed that

- mass capacity will be such that if the RLV is dual manifested, the ROTV can also handle the package; and,
- the ROTV fleet size will be set at a number that allows 98% constellation availability to be maintained.

The trip time for the ROTV to transport the satellites to GEO is governed by a series of equations provided by Glenn Law of Aerospace Corporation (1996). To aid in explaining the equations, notation is outlined in Table 3.2.

Table 3.2 Notation for Trip Time Equations

Variable	*Interpretation*
ΔV	the change in velocity to maneuver from one orbit to another, given as 5913.2 m/sec
I_{sp}	specific impulse, given as 3200 sec for Xe Ion engines
g_e	gravity, a constant of 9.81 m/sec^2
M_o	initial mass
M_b	burnout mass
M_{sat}	mass of satellite(s)
M_{ROTV}	mass of ROTV
$Mprop_{up}$	mass of propellant needed for trip from LEO to GEO
$Mprop_{down}$	mass of propellant needed for trip from GEO back to LEO
T	thruster performance based on engine efficiency, BOL power, and specific impulse, given as 2.230 N
mf	mass flow, the amount of fuel used per sec
$Triptime_{up}$	trip time from LEO to GEO
$Triptime_{down}$	trip time from GEO to LEO

First, the amount of propellant needed for the trip is calculated. From Hill and Peterson (1992),

$$\Delta V = I_{sp} * g_e * \ln R \quad 3.1$$

where R is the mass ratio of initial mass to burnout mass, M_o/M_b. Solving for R,

$$R = \exp(\Delta V / (I_{sp} * g_e)) = 1.2073 \quad 3.2$$

From GEO to LEO,

$$M_o = M_{ROTV} + Mprop_{down} \quad 3.3$$

$$M_b = M_{ROTV} \quad 3.4$$

Substituting 3.3 and 3.4 for R in 3.1 and solving algebraically for $Mprop_{down}$ results in the amount of fuel needed by the ROTV to return to LEO. Similarly, from LEO to GEO,

$$M_o = M_{sat} + M_{ROTV} + Mprop_{down} + Mprop_{up} \quad 3.5$$

$$M_b = M_{sat} + M_{ROTV} + Mprop_{down} \quad 3.6$$

Again, substituting 3.5 and 3.6 into 3.1, the amount of propellant needed to travel from LEO to GEO can be determined by solving for $Mprop_{up}$.

Next, mass flow is calculated as (Hill and Peterson 1992)

$$mf = T / g_e * I_{sp} = 2.230/(9.81*3200) = 0.00007104. \quad 3.7$$

For the trip time from LEO to GEO,

$$Triptime_{up} = [(Mprop_{up} / mf) / 86400] * 1.134 * 1.017 = 0.1879 * Mprop_{up}. \quad 3.8$$

As shown, the equation contains three constants. The first, 86400, converts the time from seconds to days. The equation is multiplied by 1.134 for account for the inefficiency of the thrusters and then by 1.017 because of eclipses (Law 1996). The trip time from GEO to LEO is calculated the same way after substituting $Mprop_{down}$ for $Mprop_{up}$.

3.2 Satellites

3.2.1 Mass

Satellite masses are based on current GEO satellite masses. In the range of actual satellite masses in GEO (1000 to 6000 kg), satellites are normally lighter (1000 to 2000 kg), with Space Command estimating that satellite masses will remain constant (Grobman 1996). Even though technological advances in microelectronics, composites, and metallic structures will produce satellite components of smaller mass (Noor and Venneri 1994), it is expected that satellite masses will remain constant since satellites mission capability will increase, thus offsetting the gain in lighter components.

3.2.2 Satellite Life

A Weibull probability density function (pdf) is used to model the satellite lifetimes. This is the distribution specified by Space Command for modeling the lifetime of geosynchronous satellites (Feuchter and others 1989; Feuchter and Giczy 1996; Chan and others 1996). The exact time that satellite life begins is open to debate since some components are activated upon launch and others wait until the satellite is in mission orbit (Grobman 1996).

Replacement of a satellite occurs when one of two types of failure occurs -- random and design life (Feuchter and others 1996). For a geosynchronous satellite, random failure is modeled as a Weibull distribution (Figure 3.1), with the scale parameter, α, equal to 18.306 and the shape parameter, β, equal to 1.6. The pdf is

$$f(x) = \alpha\beta^{-\alpha}\, x^{(\alpha-1)}\, e^{-(x/\beta)^{\wedge}\alpha}.$$

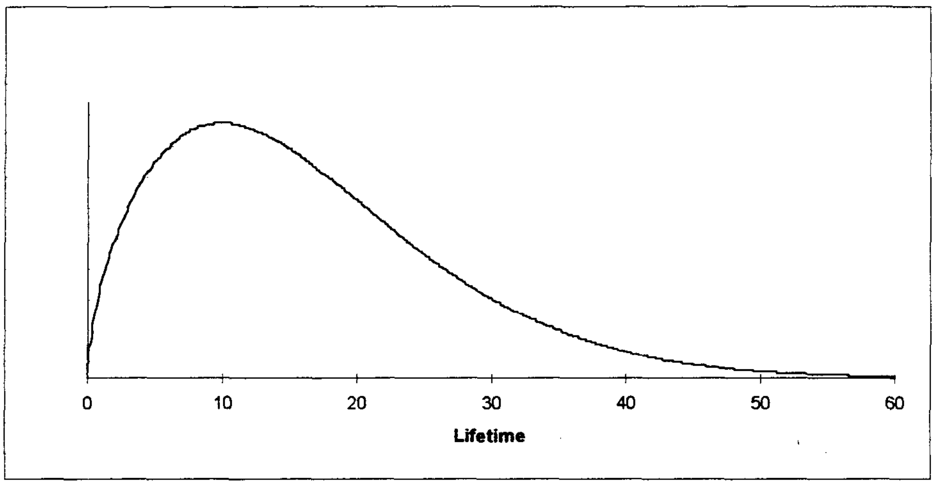

Figure 3.1 pdf for Weibull (18.306,1.6)

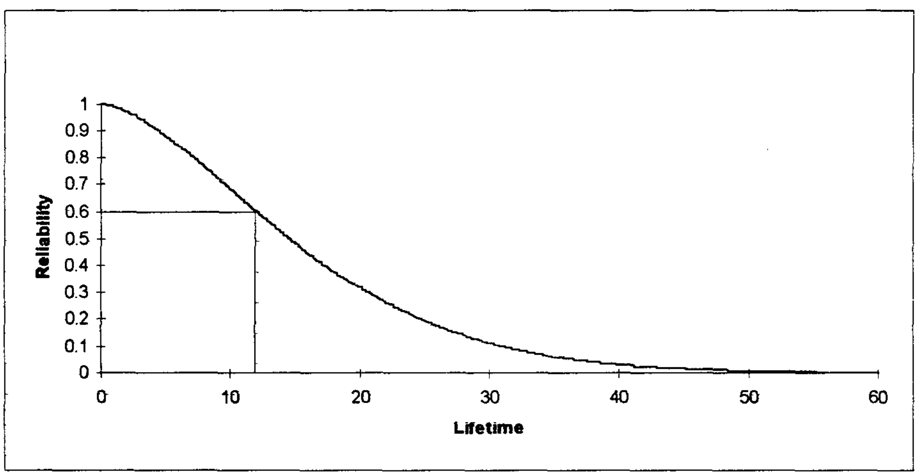

Figure 3.2 Reliability

The other type of failure, design life failure, occurs within a relatively small time due to predicted failures of one or more components of the satellite. This time interval is related to the reliability of the satellite $R(\tau)$ (Figure 3.2), which is defined as $1 - F(\tau)$ where

$$R(\tau) = \exp[-(\tau/\alpha)]^{\beta}.$$

OAS specified satellite reliability to be sixty percent; therefore, by setting $R(\tau) = .60$ and solving for τ, the truncation point for the Weibull distribution is 12.03 years. Although any satellite that lives longer than 12.03 years may still be functioning, it is considered unreliable and no longer able to support the constellation.

3.2.3 Constellation Size

Geosynchronous orbit is typically used for communications; thus, constellations need to provide full earth coverage. A constellation of four satellites will provide this coverage (Wertz and Larson 1991). Because of the trip time involved when using Solar Electric Xe Ion ROTVs, the number of on-orbit spares will initially be set at one. Consequently, the constellations will be initialized with five satellites each.

3.2.4 Constellation Availability

To ensure the uncompromising operation of the constellations (Feuchter and Giczy 1996), AFSPC has placed a minimum availability of 98% on the constellations, i.e., a minimum of four satellites will be available in each constellation 98% of the time. This availability will be maintained by first increasing the number of ROTVs in orbit to insure that the replacement satellites are reaching GEO before their predecessors fail; then, if necessary, increasing the number of on-orbit spares.

3.2.5 Satellite Cost

For this thesis, satellite costs are based only on the mass of the satellite since mass is the only characteristic of the satellite defined. In reality, of course, satellite costs depend on several factors such as mission, orbit, manufacturer, user, and production size. A satellite cost per kg is developed using data from Wertz and Larson (1991). Using their order of magnitude cost estimates for eight satellite systems and adjusting the values to 1996 dollars, an average satellite cost per kg of \$.138M/kg emerges.

4. Methodology

4.1 Introduction

The objective of this thesis is to determine when, within a given scenario, the savings of dual manifesting is at least ten percent of the cost of single manifesting. OAS expects that a ten percent increase in funding would be required to implement dual manifesting, so anything above that would be actual savings. Several factors influence the economic plausibility of dual manifesting satellites on RLVs and ROTVs. These factors include fleet size, mass capacity, and homogeneity of RLVs and ROTVs; number and mass of satellites within a constellation; satellite cost; and, number of constellations. OAS has limited the scope of this project by restricting several of the parameters. Decision variables and their ranges are listed in Table 4.1 and the restricted parameters are in Table 4.2.

Table 4.1 Decision Variables' Range of Values

Factor	***Range***
RLV mass capacity	5000 kg to 10000 kg
cost per kg of RLV mass capacity	\$10,000/kg to \$20,000/kg
satellite cost	\$.05M/kg to \$.25M/kg

Table 4.2 Vehicle Restrictions

Vehicle characteristic	***Restrictions***
RLV fleet size	infinite
RLV homogeneity	completely homogenous within a scenario
ROTV fleet size	minimize to maintain 98% availability
ROTV mass capacity	based on RLV mass capacity
ROTV homogeneity	completely homogenous within a scenario
ROTV cost	$45 M
number of satellites within a constellation	four + one on-orbit spare

Additionally, constellation availability must be maintained 98 percent of the time.

Simulation is the chosen OR technique because of the need to incorporate satellite lifetimes and the movement of time in the problem. A linear program would not be satisfactory because it would involve a very large scale multi-period formulation with satellite lifetime represented by random variables. Stochastic processes become intractable since unless the satellite lifetimes follow an exponential distribution the state space for the problem becomes too large. Dynamic programming is not an option for the same reason. The problem could be viewed as a basic inventory problem, but for this thesis that avenue is not considered.

Simulation, however, is not the only OR technique employed. Even with the code, a decision has to be made on what values of each parameter to examine. Complete enumeration would not be feasible, and although trial and error would produce results, a better technique would be to use an experimental design to choose the parameter values.

4.2 Maintaining 98% Availability

Maintaining a 98% availability will be accomplished by setting the fleet size of the ROTVs at a number such that they are capable of transporting the satellites to GEO before their predecessors fail. Tolerance limits (Conover 1971) are used to determine what the minimum fleet size is. As will be discussed, a 2^3 factorial experimental design will be utilized. The minimum fleet size for the entire scenario will be based on the results of the point most likely to dual manifest - high RLV capacity, high cost per kg of RLV mass capacity, and low satellite cost per kg. For a constellation to be considered available there must be at least four satellites in GEO. Referring to a table for sample sizes for one-sided nonparametric tolerance limits in Conover, for a probability of 95 percent that at least 98 percent availability is maintained, a sample of 149 constellations is needed, and all of these constellations have to meet availability requirements. If not, the ROTV fleet size needs to be increased until they do. If, however, increasing fleet size does not improve the constellation availability, another on-orbit spare is required.

4.3 Dual Manifesting Criteria

To dual manifest satellites, three criteria must be met (Figure 4.1). First, the LVs must have the capacity to carry the combined mass of the satellites. Second, there must be

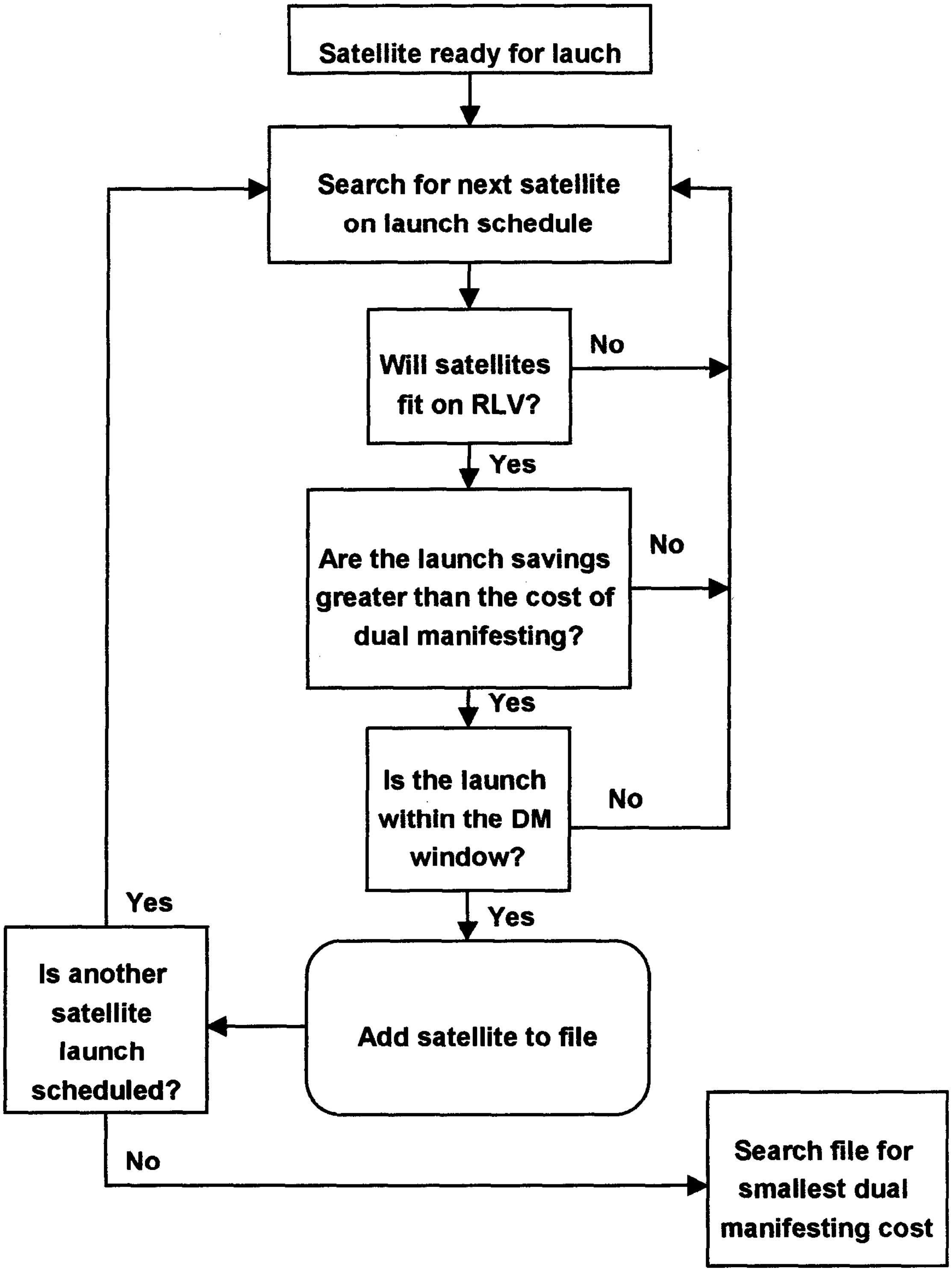

Figure 4.1 Dual Manifesting Flowchart

a savings incurred by dual manifesting. In other words, are the launch savings from dual manifesting greater than the cost associated with dual manifesting the satellites? To determine this, two values must be compared. The launch savings from dual manifesting is the cost of one entire launch sequence, i.e., the cost of an RLV launch and the cost of one trip for the ROTV, including one-sixth of the original RLV launch cost to get the ROTV to LEO. For the center point (RLV mass capacity of 7500 kg, $.15M/kg of RLV mass capacity, and $.015M/kg satellite cost) the launch savings will be $112.5M for the RLV launch, $7.5M for the ROTV trip, and $18.75M for the ROTV's launch. If dual manifesting occurs, $138.75M is saved in launch costs. Next, the cost of dual manifesting the satellites is calculated. The satellite's cost is assumed to amortize linearly. Thus, the expected yearly satellite cost is calculated by dividing the satellite cost by 12.03. Dual manifesting will cause the first satellite to arrive in GEO later than expected, and there is a cost associated with the additional lifetime that the satellite is not operational. This is calculated by multiplying the expected yearly satellite cost by the additional triptime incurred by dual manifesting (i.e., the triptime with both satellites minus the triptime if the satellite is alone). If this cost is less than the launch savings, then the second criteria for dual manifesting is met. Obviously, then, if the satellite cost is less than $138.75M at the center point then the early launch costs will always be less than $138.75M and the second satellite could be launched up to 12.03 years early. Therefore, a third criteria is needed that states when the second satellite has to be scheduled for launch.

If dual manifested, the satellite scheduled for launch (satellite A) will always unavoidably arrive at GEO later than its expected arrival date. Since late satellites result in lost lifetime (i.e., costs money) and constellation availability, the objective then would be to choose a second satellite (satellite B) such that it arrives at GEO as close as possible to its scheduled arrival. Using equations 3.1, 3.5, 3.6, and 3.8, triptime can be expressed as

$$Triptime = (0.1879)*(0.2073)*(M_{sat} + M_{ROTV} + Mprop_{down}). \qquad 4.1$$

M_{ROTV} is equal to 2000 kg and $Mprop_{down}$ is calculated to be 414.6 kg. By simplifying 4.1 and converting to years,

$$Triptime = 0.2577 + (0.0001067*M_{sat}) \qquad 4.2$$

If satellite A is dual manifested with satellite B, the two will arrive at GEO at triptime AB. Working backward, if B is scheduled to arrive at time AB, then it would have been on the launch calendar at time AB minus the triptime for B minus sixty days for an operational check.

Launch time = Triptime AB - Triptime B - Sixty days

$$= 0.2577 + (0.0001067*M_{satAB}) - 0.2577 - (0.0001067*M_{satB}) - (60/365).$$

$M_{satAB} = M_{satA} + M_{satB}$, so

$$Launch\ time = 0.0001067 * M_{satA} - 0.1644$$

By this, the launch window to search is based on what the mass of satellite A is. A sixty day window is placed around the launch time to search for a satellite B (Figure 4.2).

When a satellite is ready for launch, the entire launch schedule is searched for satellites that meet all dual manifesting criteria, which in turn are placed in a separate file. The satellite in the file that has smallest early launch cost becomes the second satellite.

4.4 Design Space

A full 2^3 factorial design is needed for analysis of all two factor interactions in the design. The 8 design points and two center points will be run through the SLAM model

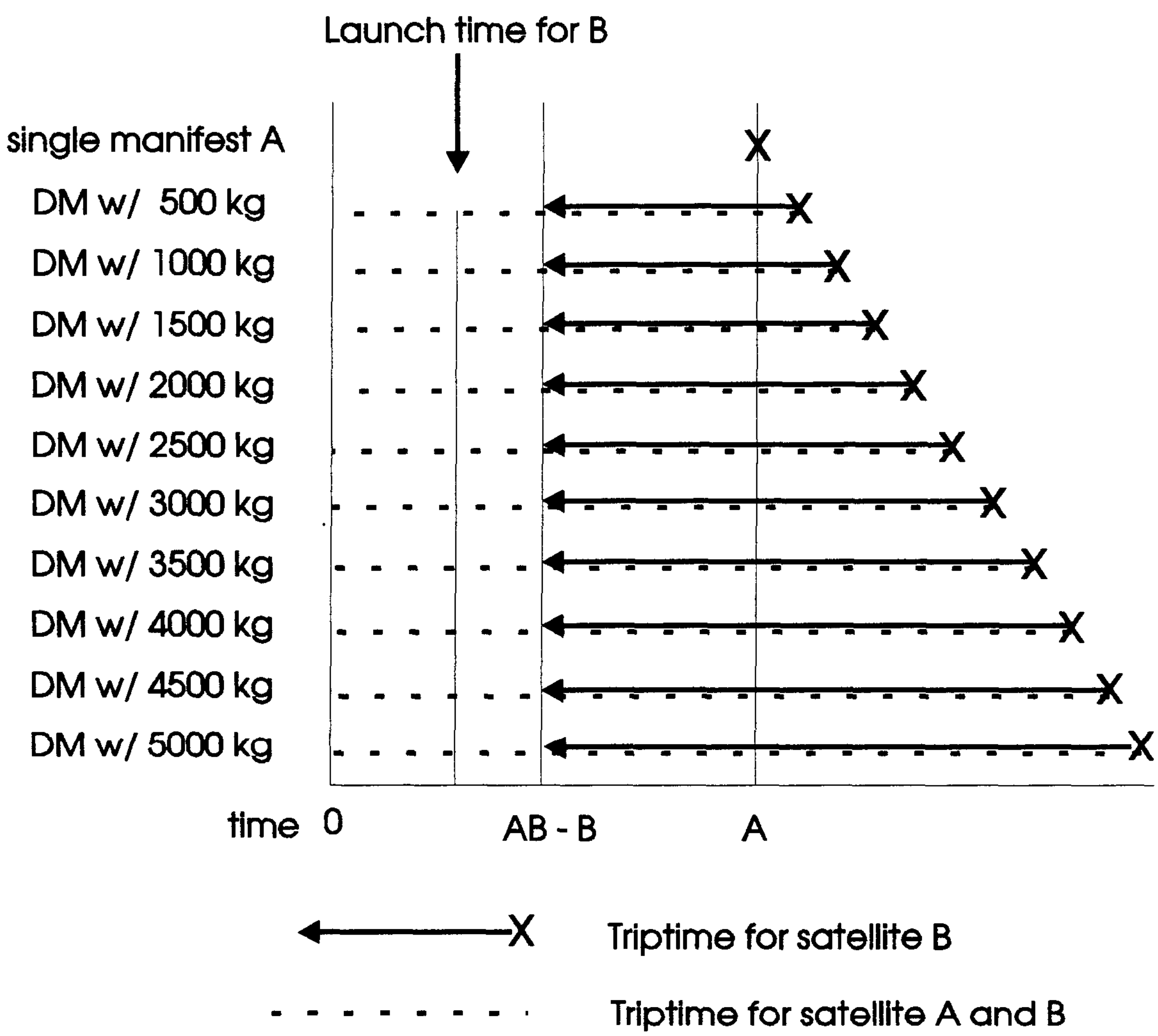

Figure 4.2 Calculating the Launch Window

twice, first with no dual manifesting occurring and then with the option to dual manifest available. The response for each run will be the percent of savings based on the difference between the total cost per year when dual manifesting and not dual manifesting. The region where dual manifesting is economically plausible will be identified, and the next scenario will be analyzed in the same manner. To analyze the responses, the variables are coded from -1 to +1 as listed in Table 4.3.

4.5 Regression

Once the responses for each point have been recorded, stepwise linear regression using forward selection is used to determine what variables and interactions are important

Table 4.3 Variables

Uncoded			***Coded***		
x RLV	**y RLV cost**	**z Sat cost**	**x RLV**	**y RLV cost**	**z Sat cost**
5000	0.01	0.05	-1	-1	-1
5000	0.01	0.25	-1	-1	1
5000	0.02	0.05	-1	1	-1
5000	0.02	0.25	-1	1	1
10000	0.01	0.05	1	-1	-1
10000	0.01	0.25	1	-1	1
10000	0.02	0.05	1	1	-1
10000	0.02	0.25	1	1	1
7500	0.015	0.15	0	0	0

to the model. Best subset regression models are also reviewed to aid in selecting an appropriate model. Adjusted R square, R square, and residual sums of squares are used to determine the significance of the chosen model (Montgomery and Peck 1992). The resulting regression plane can then be plotted to give a visual representation of where the savings from dual manifesting occur.

4.6 Simulation

An event-based simulation is developed using FORTRAN in the SLAM environment. The model creates satellite "entities" that carry attributes of satellite type, lifetime, ID number, mass, and replacement satellite's ID. The satellites are launched from earth to LEO on RLVs, and ROTV "resources" transport the satellites from LEO to GEO. The number of operational satellites in each constellation is tracked, along with the number of satellites launched by type, and the number of RLV and ROTV trips made. Output from SLAM's Summary Report is transcribed into an Excel spreadsheet to calculate the cost of maintaining the scenario.

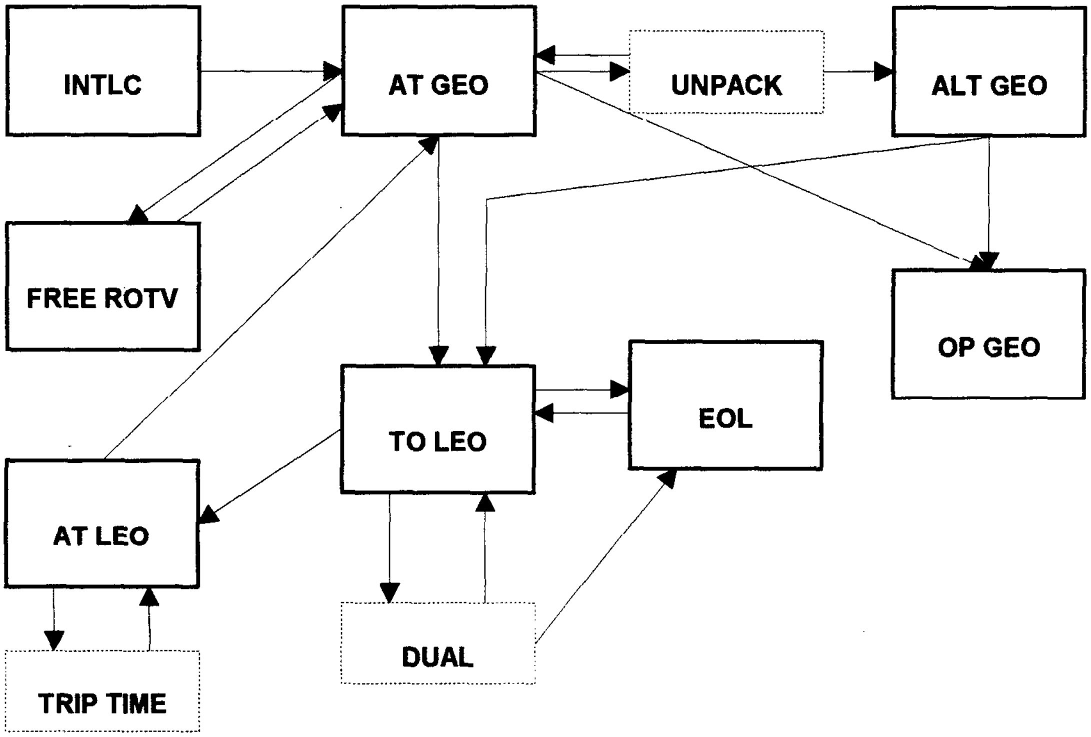

Figure 4.3 SLAM model

4.6.1 Subroutines and Functions

INTLC. This subroutine initializes the variables used in the simulation, establishes the fleet of ROTVs, assigns satellite attributes, and initializes the satellites in subroutine AT GEO. Satellite lifetimes for each constellation are assigned from different random number streams to allow for synchronization of the lifetimes between the baseline run and the dual manifesting run.

TO_LEO. Satellites are launched from earth to LEO in this subroutine. The entity's attributes are changed to track the new satellite, and if applicable, subroutine DUAL is evoked to search for a second satellite. EOL is scheduled, and the satellite's arrival AT_LEO is scheduled for one day later.

DUAL. The values for the decision variables are assigned in this subroutine and the dual manifesting algorithm searches for the appropriate second satellite. If one is chosen, the event calendar is searched to remove the second satellite's launch, and then the attributes from the two satellites are reassigned so that one entity can be formed to continue through the simulation until the satellite reaches GEO.

AT_LEO. Once the satellite is at LEO, if an ROTV is available the ROTV transports the satellite to GEO. TRIP_TIME is evoked to determine how long the ROTV will take and AT_GEO is scheduled. If no ROTV is available, the satellite waits in file 1 until one is available.

TRIP_TIME. This function determines what the trip time will be for the satellite(s) and ROTV based on the total mass.

AT_GEO. Once the satellite is in GEO, the ROTV is returned to LEO and file 1 is checked to determine if any satellites are waiting to be transported to GEO. Next, it is determined if the entity is dual manifested. If so, subroutine UNPACK is evoked to separate the satellites into two entities. One satellite returns to AT_GEO and the other is scheduled immediately in ALT_GEO to keep from releasing too many ROTVs. The completion of a sixty day operational check is scheduled. The replacement launch is also scheduled by calculating R, the time until the replacement launch. The replacement satellite needs to be launched so that it has time to make it to GEO and complete its operational check before its predecessor dies. For scheduling, satellite life is 12.03 years, any wait for an ROTV is considered negligible, and it is assumed the replacement satellite will be single manifested. Thus, R is 12.03 years minus the time the satellite has already lived (its trip time from LEO to GEO) minus the trip time for the replacement satellite minus 60 days for the operational check (Figure 4.4).

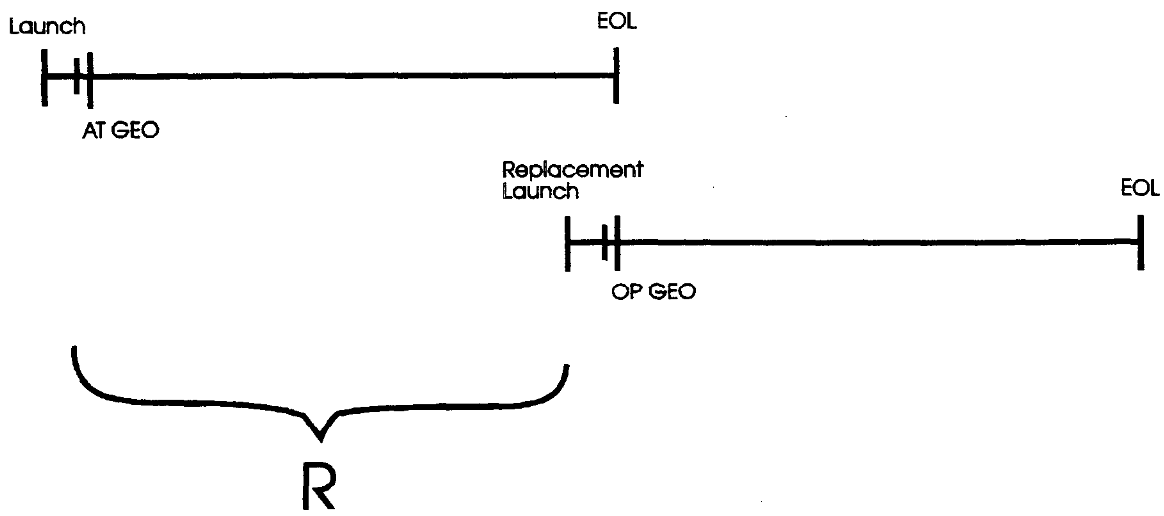

Figure 4.4 Determining R

UNPACK. If the satellites are dual manifested, this subroutine reassigns the attributes to two separate arrays.

ALT_GEO. This subroutine is also used only if the satellites are dual manifested. The second satellite is sent to this subroutine rather than AT_GEO to eliminate the problem of freeing too many ROTVs each time a dual manifest occurs. The operational check and its replacement's launch are scheduled in the same manner as AT_GEO.

OP_GEO. This subroutine tracks the availability of the constellations by adding a satellite to the appropriate constellation once the operational check is completed. It also keeps a tally of the total number of satellites by type.

EOL. When a satellite dies, constellation availability is decreased by one. If the replacement launch is still on the event calendar it is removed and the launch is immediately scheduled. If the replacement launch is not on the calendar either the satellite lived past its replenishment point and the replacement has already been launched, or the replacement satellite has already been launched as the second satellite on a dual manifested launch.

FREE_ROTV. This subroutine announces that an ROTV has returned to LEO. The ROTV is added to file 2; then, it is determined if any satellites are waiting in LEO for transport. If so, the satellite and an ROTV are removed from their appropriate files, and their arrival at GEO is scheduled.

4.6.2 Determining Steady State

Before responses from the data points can be accurately collected from the simulation, the center point with no dual manifesting (RLV mass capacity = 7500 kg, RLV cost per kg = $.015M, satellite cost per kg = $.15M) is used to determine when steady state has been achieved. As satellite entities activate subroutine AT_LEO, a database is compiled of the time and satellite masses. In turn, this database is used to track the average total cost per satellite. The total cost per satellite is calculated as the satellite cost plus RLV launch cost plus cost of ROTV use. Based on observing the first scenario's graph of total cost per satellite vs. time, a heuristic was developed to allow continuity when determining steady state for different scenarios. When fifty percent of the average total costs per satellite are within 0.5 % of the expected total cost, steady state has been reached.

5. Computational Results

5.1 Ten Constellation Scenario

The scenario consists of ten constellations of masses 500 kg, 1000 kg, 1500 kg, 2000 kg, 2500 kg, 3000 kg, 3500 kg, 4000 kg, 4500 kg, and 5000 kg. To determine the number of ROTVs needed, the fleet size is first set at 100 and the baseline is run for 1000 years to determine constellation availabilities when the satellites do not have to wait for an ROTV. The fleet size is then decreased to the lowest value that maintains those availabilities; in this scenario, ten ROTVs are needed. Next, the design point where dual manifesting is expected to occur the most (10000, .02, .05) is run. Satellites cannot maintain 98% availability at this point, and increasing the number of ROTVs does not solve the problem. Thus, the number of on-orbit spares is increased to two, and the design point is re-run, with 149 samples collected to ensure that constellation availability is maintained. In this scenario, the average satellite mass is 2750 kg and the average satellite cost is $412.5M, thus making the expected total cost per satellite $551.25M. Using this information, the simulation reaches steady state when 1228 satellites have been launched (Figure 5.5). With only one on-orbit spare, steady state is reached at 240 years, whereas with two on-orbit spares steady state is reached at 200 years. Both possibilities are reviewed by running the model from 240 years to 690 years.

A dilemma now occurs as to what to consider the savings. When dual manifesting is not allowed to occur, constellation availability can be maintained with only one on-orbit spare; as such, the greatest savings achieved by dual manifesting is 4.1 percent. When

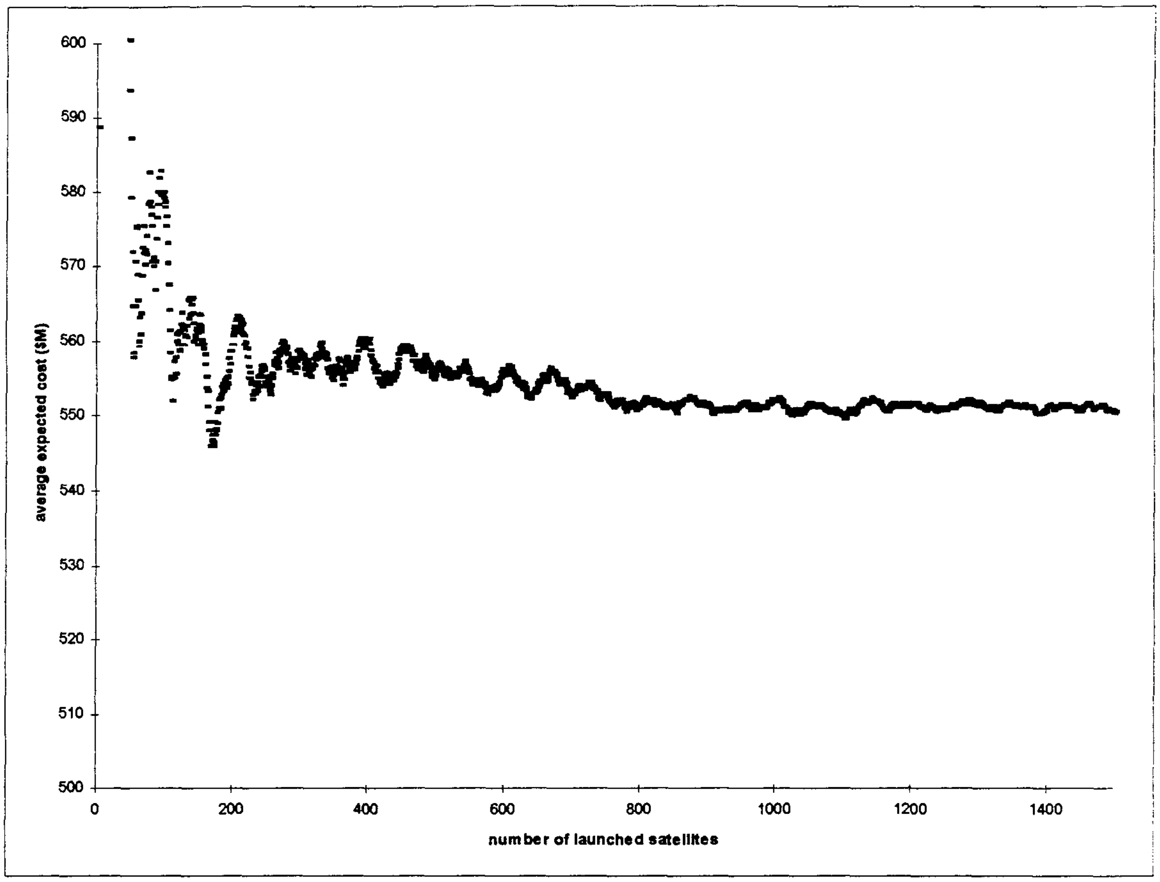

Figure 5.5 Determining Steady State for Ten Constellation Scenario with Satellite Life Starting at Launch

the baseline is run with two on-orbit spares, the cost of single manifesting greatly increases because the expected cost of maintaining a second on-orbit spare for each constellation is an additional $552.35 M per year [(10/9.98 = 1.002 additional launches per year) * ($551.25 expected cost per satellite)]. With this second on-orbit spare in the baseline, the savings achieved by dual manifesting increase.

Since the results from having a baseline with one on-orbit spare do not meet the ten percent savings requirement, further analysis is conducted using a two on-orbit spare baseline. Using stepwise linear regression using forward selection, the chosen model in coded variables is

$$d = 0.09038 + 0.04087x + 0.01321y - 0.03427z + 0.00486xy - 0.01275xz - 0.00353yz$$

and the uncoded model is

$$\text{savings} = -0.049975 + 0.000018166X + 0.785Y + 0.1457Z + 0.0003888XY - 0.000051XZ - 7.06YZ,$$

where X is the RLV mass capacity, Y is the RLV cost per kg, and Z is the satellite cost.

Table 5.1 Regression Analysis of 2^3 Experimental Design for Ten Constellation Scenario with Satellite Life Starting at Launch

Source	*Coefficient*	*Individual SS*	*Cumulative df*	*Cumulative SS*	*Cumulative MS*
constant	0.09038	0.08168			
x	0.04087	0.01336	1	0.01336	0.01336
y	0.01321	0.00140	2	0.01476	0.00738
z	-0.03427	0.00939	3	0.02415	0.00805
xy	0.00486	0.0001891	4	0.02434	0.00609
xz	-0.01275	0.00130	5	0.02564	0.00513
yz	-0.00353	0.00009964	6	0.02574	0.00429
Residual		0.00002165	9	0.02576	0.00286
Source	*df*	*SS*	*MS*	*F*	*p value*
Regression	6	0.02574	0.00429	594.56	0.0001
Residual	3	0.00002165	0.00000722		
Total	9	0.02576			
R-squared	0.9992				
Adj. R-squared	0.9975				

Using this model, the expected percent savings of dual manifesting for any point within the design space can be determined. On Figure 5.6, the area above the plane represents points where savings are less than ten percent and dual manifesting should not be considered, whereas below the plane dual manifesting produces savings of greater than ten percent.

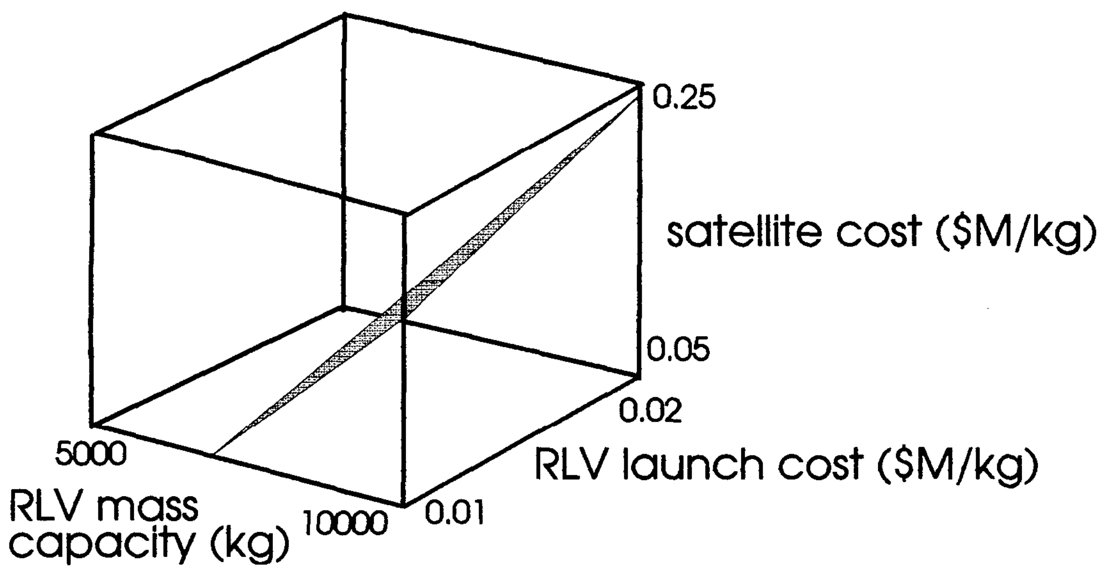

Figure 5.6 Design Space for Ten Constellation Scenario with Lifetime Starting at Launch

The suspected reason that the satellites cannot maintain availability with only one on-orbit spare is because their lifetimes are assumed to start at launch. As such, when dual manifesting and longer triptimes occur, the late arrival of satellite A cannot be compensated for by the on-orbit spare; therefore, the second on-orbit spare is needed. Since there is a question as to when satellite life actually begins, the SLAM model is recoded to start lifetime once the satellite is in GEO. Steady state is determined to begin when 604 satellites have been launched, so the simulation is run from 125 years to 575 years. The results give savings similar to those achieved when satellite life begins at launch and the costs for the baseline are calculated with two on-orbit spares. In coded variables

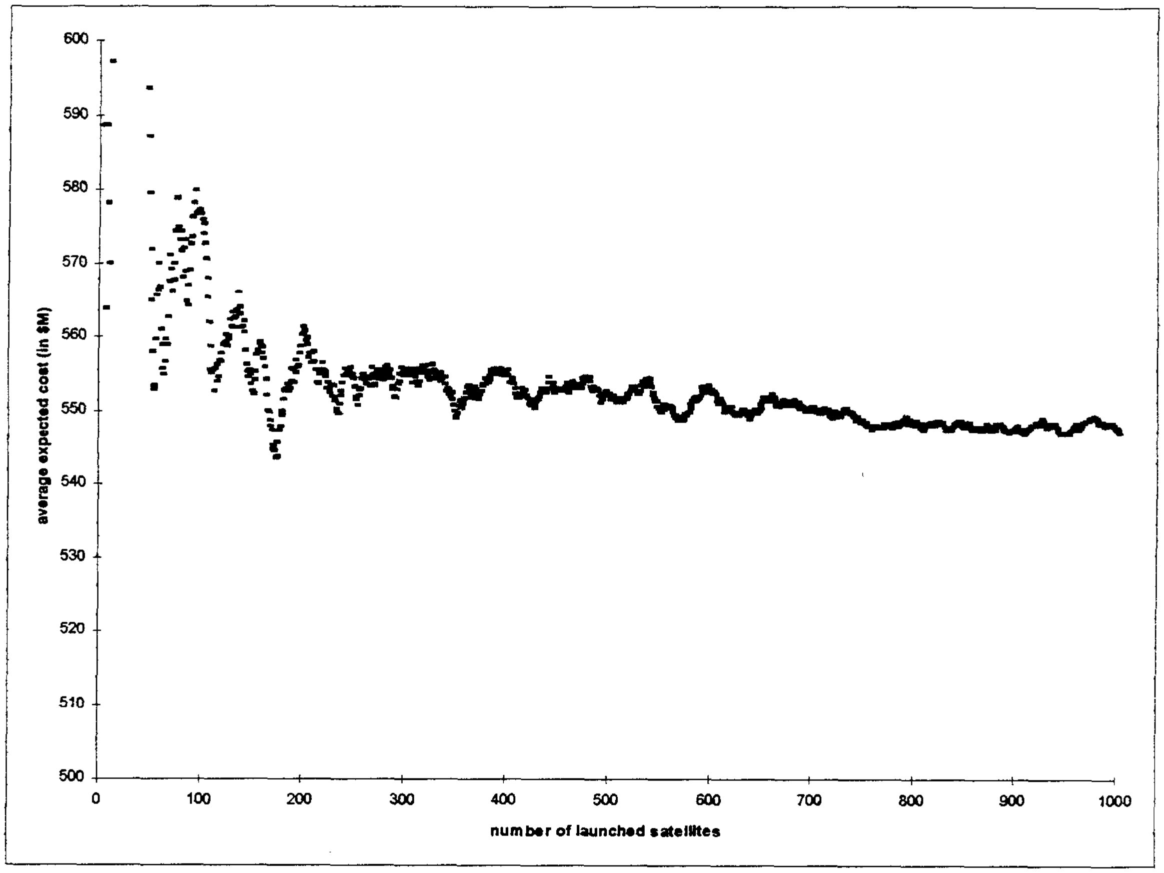

Figure 5.7 Determining Steady State for Ten Constellation Scenario with Satellite Life Starting at GEO

the model chosen by stepwise linear regression is

$$d = 0.08390 + 0.03654x + 0.01062y - 0.02760z - 0.01022xz$$

and the uncoded model is

$$savings = -0.06217 + 0.000020748X + 2.124Y + 0.0306Z - 0.00004088XZ.$$

Table 5.2 Regression Analysis of 2^3 Experimental Design for Ten Constellation Scenario with Satellite Life Starting at GEO

Source	*Coefficient*	*Individual SS*	*Cumulative df*	*Cumulative SS*	*Cumulative MS*
constant	0.08390	0.07039			
x	0.03654	0.01068	1	0.01068	0.01068
y	0.01062	0.0009021	2	0.01158	0.00570
z	-0.02760	0.00609	3	0.01767	0.00589
xz	-0.01022	0.0008351	4	0.01851	0.00463
Residual		0.0002551	9	0.01876	0.00208
Source	***df***	***SS***	***MS***	***F***	***p value***
Regression	4	0.01851	0.00463	90.70	0.0001
Residual	5	0.00002551	0.00000510		
Total	9	0.01876			
R-squared	0.9864				
Adj. R-squared	0.9755				

Again, by using the model, the expected percent savings of dual manifesting for any point within the design space can be determined. On Figure 5.8, the area above the plane represents points where savings are less than ten percent and dual manifesting should not be considered, whereas below the plane dual manifesting produces savings of greater than ten percent. Comparing Figure 5.6 and Figure 5.8, the savings when satellite life begins at GEO are similar to those achieved when satellite life begins at launch and the costs for the baseline are calculated with two on-orbit spares.

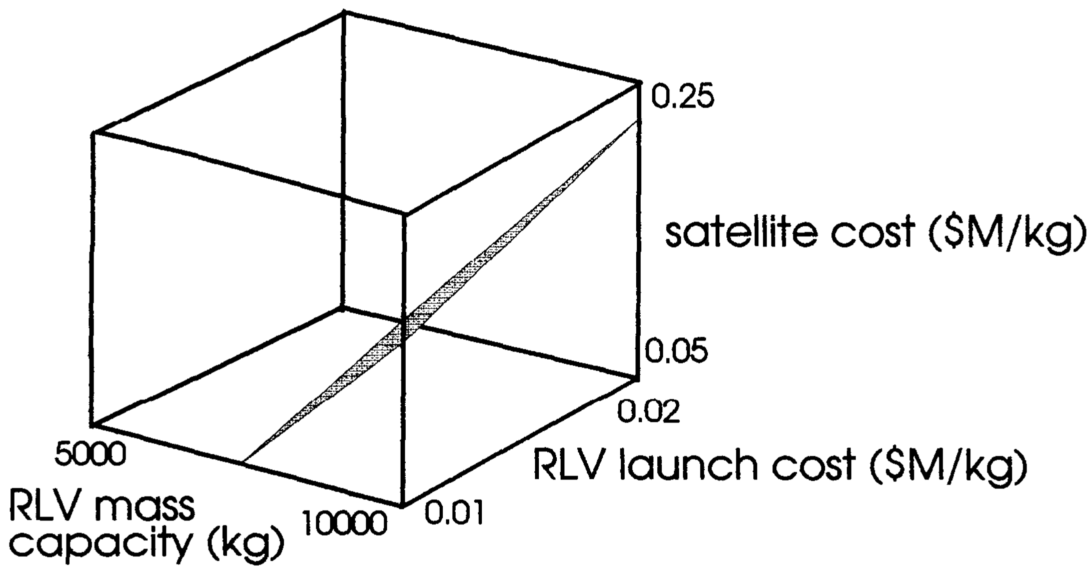

Figure 5.8 Design Space for Ten Constellation Scenario with Lifetime Starting at GEO

5.2 Scenario with Five Constellations

The ten constellation scenario shows the result of incremented masses. A more practical scenario consists of several constellations of smaller mass and perhaps one of larger mass. The second scenario consists of five constellations of masses 500 kg, 1000 kg, 1500 kg, 2000 kg, and 4000 kg. The average satellite mass is 1800 kg and the average satellite cost is $270.0M. Again using the center point (i.e., RLV mass at 7500 kg, RLV cost per kg at $0.015M, and satellite cost per kg at $0.15M), the average total cost is $408.75M. The same techniques used in the previous scenario set the ROTV fleet size at five and determine that steady state is reached when 644 satellites have been launched. As with the ten constellation scenario, constellation availability cannot be maintained with only one on-orbit spare. With one on-orbit spare steady state is reached at 251 years, whereas with two on-orbit spares steady state is reached at 210 years (Figure 5.9). The same dilemma occurs in deciding what to consider the savings and again further analysis is conducted using a two on-orbit spare baseline.

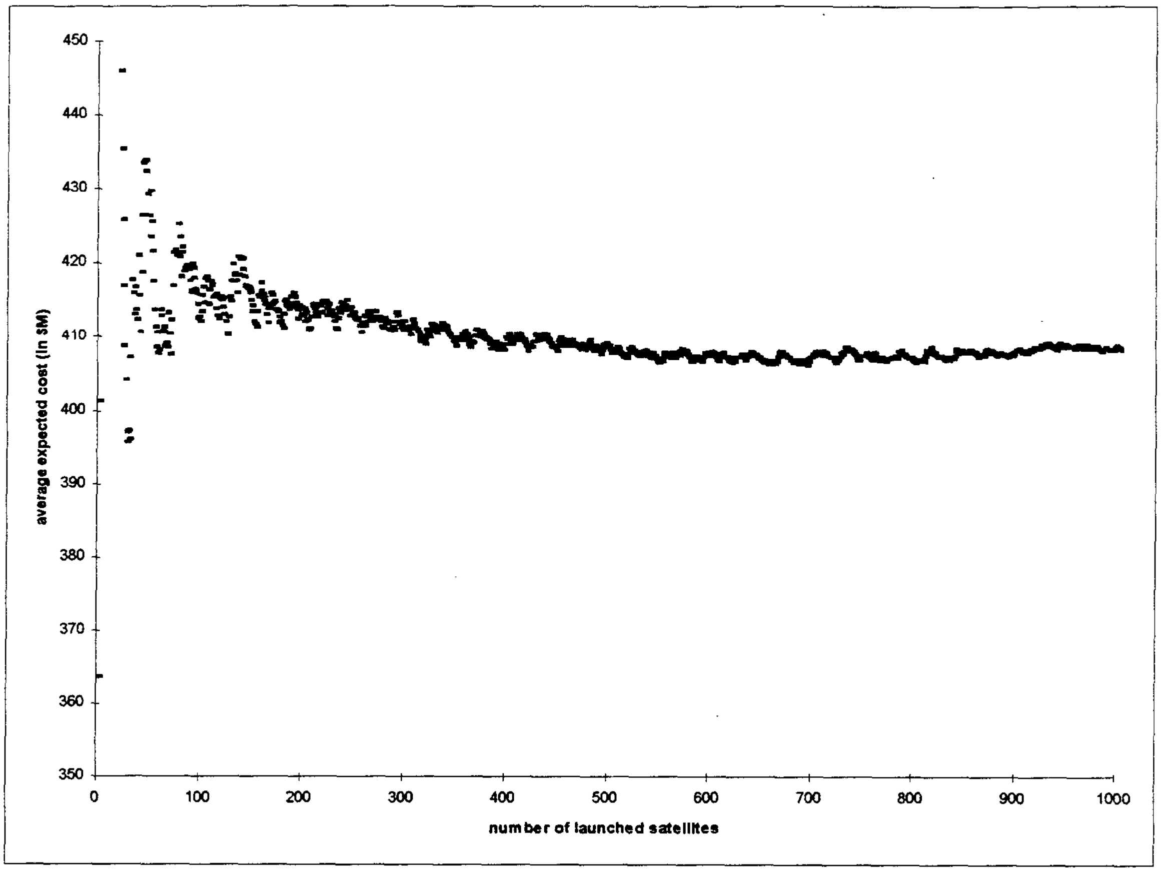

Figure 5.9 Determining Steady State for Five Constellation Scenario with Satellite Life Starting at Launch

Table 5.3 Regression Analysis of 2^3 Experimental Design for Five Constellation Scenario with Satellite Life Starting at Launch

Source	*Coefficient*	*Individual SS*	*Cumulative df*	*Cumulative SS*	*Cumulative MS*
constant	0.08154	0.06648			
x	0.02827	0.00639	1	0.00639	0.00639
y	0.00894	0.0006394	2	0.00703	0.00352
z	-0.02393	0.00458	3	0.01162	0.00387
xy	0.00258	0.00005318	4	0.01167	0.00292
xz	-0.00664	0.0003527	5	0.01202	0.00240
Residual		0.00003489	9	0.01206	0.00134
Source	*df*	*SS*	*MS*	*F*	*p value*
Regression	5	0.01202	0.00240	275.66	0.0000
Residual	4	0.00003489	0.00000872		
Total	9	0.01206			
R-squared	0.9971				
Adj. R-squared	0.9935				

Using stepwise linear regression with forward selection, the chosen model in coded variables is

$$d = 0.08154 + 0.02827x + 0.00894y - 0.02393z + 0.00258xy - 0.00664xz$$

and the uncoded model is

$$savings = -0.000855 + 0.000012196X + 0.24Y - 0.0401Z + 0.0002064XY - 0.00002656XZ$$

where X is the RLV mass capacity, Y is the RLV cost per kg, and Z is the satellite cost per kg.

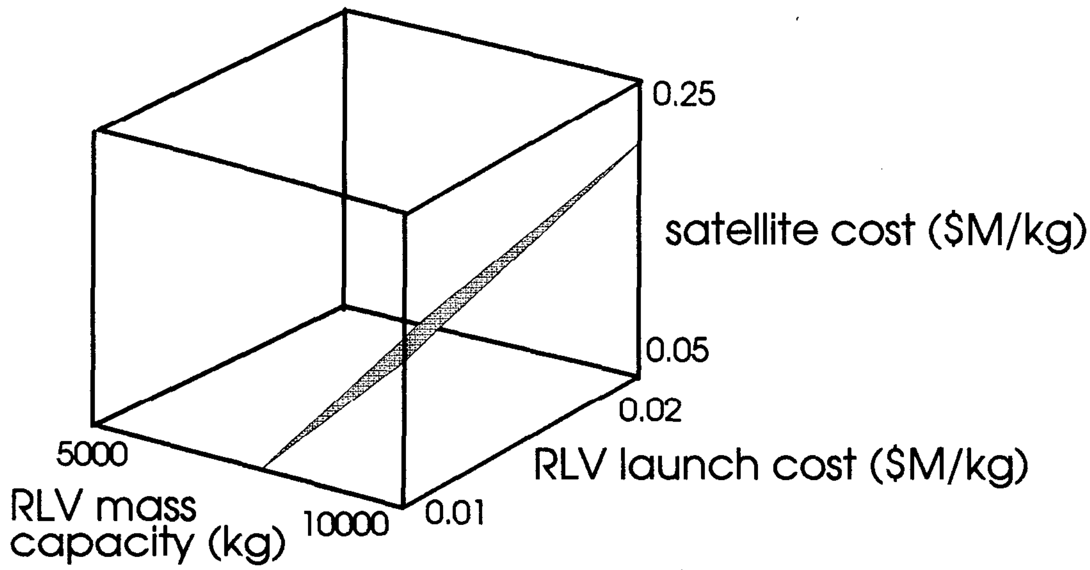

Figure 5.10 Design Space for Five Constellation Scenario

As before, on Figure 5.10, the area above the plane represents points where savings are less than ten percent, whereas below the plane a savings of greater than ten percent occurs and dual manifesting should be considered.

The five constellation scenario is also rerun with satellite life beginning at GEO. Steady state begins at 137 years after 330 satellites have been launched (Figure 5.11). The results show the greatest savings possible to be 9.9 percent, occurring when RLV mass capacity and cost are high, and the satellite cost per kg is low.

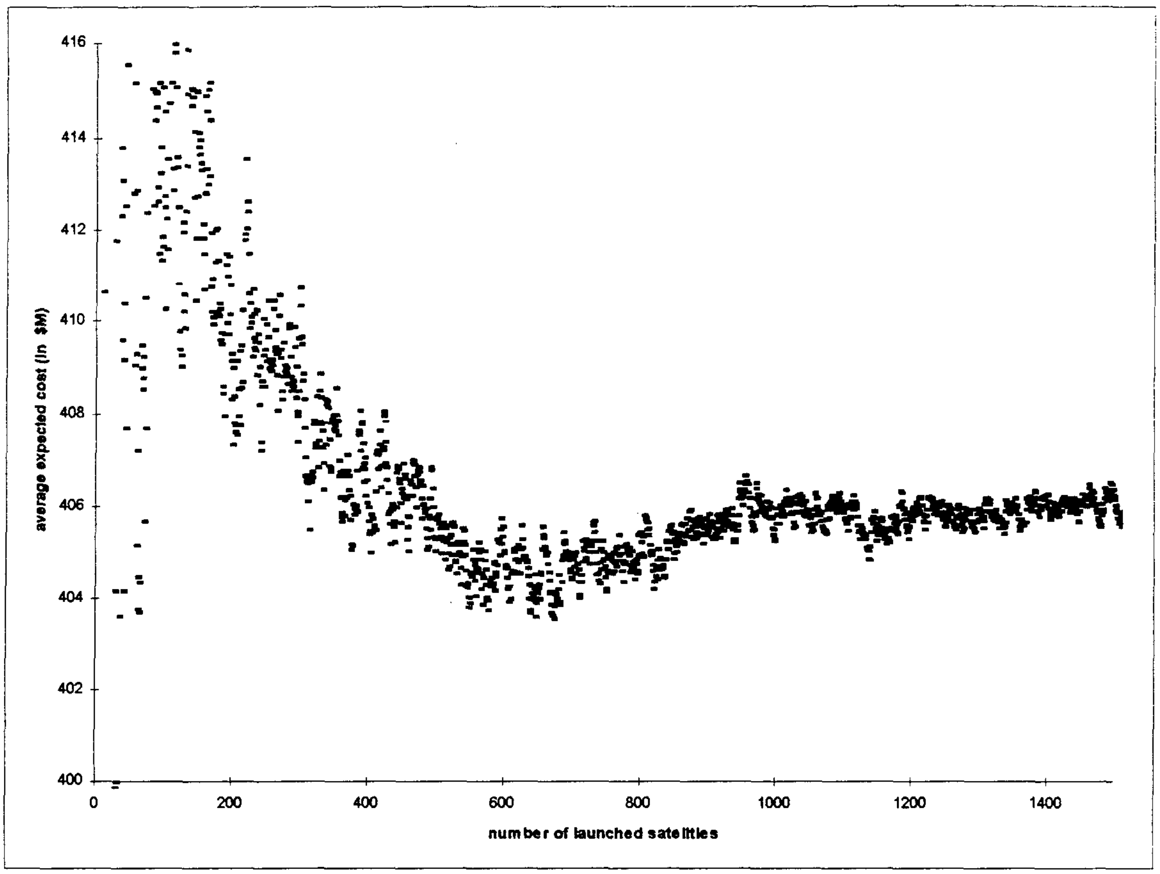

Figure 5.11 Determining Steady State for Five Constellation Scenario with Satellite Life Starting at GEO

5.3 Verification and Validation

Verification of the model is an interactive process to insure that the simulation is doing what it is expected to do. Subprograms and functions were incorporated to facilitate in correct coding and debugging. Additional lines of code were temporarily injected into the model to track the proper progression of the satellite "entities," and a thorough examination of the simulation process was conducted after the final iteration. Statistics were also used to check model accuracy.

The expected number of satellites launched in each simulation is calculated and compared to the actual number launched. Expected satellite lifetime is the mean mission duration (MMD) of the Weibull distribution, 9.98 years. Table 5.4 shows the actual number of launches and the expected number of satellites launched during the simulation based on the number of satellites in the constellations and the number of constellations.

Table 5.4 Expected and Actual Launches

Scenario (no. const., no. on-orbit spares, BOL)	***Expected***	***Baseline***	***DM when RLV mass capacity is low***	***DM when RLV mass capacity is high***	***DM at center point (avg. count)***
10, 1, Launch	2254.51	2349	-	-	-
10, 2, Launch	2705.41	2810	2352	1975	2023
10, 1, GEO	2254.51	2232	1919	1062	1725
5, 1, Launch	1127.25	1160	-	-	-
5, 2, Launch	1352.71	1397	1236	1132	1150
5, 1, GEO	1127.25	1130	1002	985	962

The number of launches when dual manifesting should be less than the baseline, and fewer launches are expected the higher the RLV mass capacity is because more dual manifests should occur.

Validation of the model is also an iterative process and compares the model to the real system. Interaction with OAS throughout the thesis insured that the simulation model represents the system being studied. Even though the reusable concepts are not currently in use, the model's outputs are in line with what is expected.

5.4 Variables

The variables chosen to model savings vary with each scenario, but all include the three first order terms. For the three scenarios that are analyzed with regression, the proportion of variance explained by the model, R^2, for the models containing only first order terms is shown in Table 5.5. Thus, the addition of two-term interactions clearly adds little to the model, even though stepwise linear regression selected them as part of the model.

Table 5.5 R^2 of First Order Model for Scenarios

Scenario	R^2
10, 2, Launch	0.9375
10, 1, GEO	0.9419
5, 2, Launch	0.9634

When running the simulations, the design points that have the same RLV mass capacity produce the same counts for number of launched satellites per type, number of RLVs and ROTVs utilized, as well as the queuing statistics for satellites waiting for an ROTV and the ROTV fleet. This suggests that the RLV mass capacity is what drives the decision to dual manifest. The only difference in the points at each level of RLV mass capacity is the expected DM costs, and these costs are identical for high and low satellite cost per kg at each RLV mass capacity level. The savings from dual manifesting, then, become apparent when the RLV cost per kg and the satellite cost per kg are applied to the counts.

While definite conclusions about relationships among scenarios cannot be ascertained with only two scenarios, some distinct possibilities occur. Foremost, whether satellite life begins at launch or when the satellite arrives at GEO has a major impact on the level of savings achieved. If satellite life begins at launch, dual manifesting will not provide significant savings. On the other hand, if satellite life begins at GEO, the specific scenario plays a role in the savings. Another conclusion is that the RLV mass capacity should be such that it can carry two of the heaviest satellites in the scenario. Doing so allows the number of dual manifests to practically double (Table 5.6). Another observation is that the ROTV fleet size is one per constellation.

Table 5.6 Number of Dual Manifests by RLV Mass Capacity

Scenario	*5000 kg*	*7500 kg*	*10000 kg*
10, 2, Launch	399	672	731
10, 1, GEO	256	410	467
5, 2, Launch	137	190	225

6. Conclusions

Does it make sense to spend the additional money necessary to develop LVs that are capable of dual manifesting satellites? According to OAS, if the savings are at least ten percent of the cost of single manifesting, the answer is yes. This thesis has shown that when employing the dual manifesting algorithm, regardless of the scenario, high RLV mass capacity and RLV costs coupled with low satellite costs create significant savings and warrants further research into dual manifesting. While results are not conclusive, the model developed for this thesis provides an employable means for testing any scenario.

As with any simulation, the one developed for this thesis can be improved. Since this is only a preliminary study of dual manifesting, many contingencies of space and space flight are greatly simplified or ignored. Additionally, because of the sensitivity of specific military satellite information, several assumptions are made to allow the study to progress smoothly.

A major simplification in this thesis is to equate satellite cost to its mass. Any conclusion drawn that references satellite cost or satellite mass has to be closely examined to determine if, in fact, the same conclusion would occur if the two variables were not perfectly correlated.

For further research, actual satellite data can be easily inserted into the program for a more realistic design space. Satellite cost can be ranged from a percentage above and a percentage below of current cost, rather than between two set values per kg of mass.

Additionally, compatibility of satellites can be factored into the dual manifesting algorithm, and a study of orbital mechanics can be employed to account for several possible time delays that are ignored. For example, this thesis looks at LEO and GEO merely as points rather than as orbits. In actuality, the RLV and ROTV have to be scheduled to arrive at the same point in LEO; thus, the time delay associated with this may be so great that availability can not be maintained unless more on-orbit spares are used. If such is the case, a different approach to developing the launch schedule should be explored.

APPENDIX A: SIMULATION MODEL

program MAIN

```
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C   DETERMINING THE ECONOMIC PLAUSIBILITY OF DUAL MANIFESTING REUSABLE
C   LAUNCH VEHICLES AND REUSABLE ORBITAL TRANSFER VEHICLES FOR THE
C   REPLENISHMENT OF MILITARY SATELLITES
C
C   2LT CRYSTAL EVANS, USAF
C
C   This simulation uses FORTRAN subroutines to help determine the
C   economic plausibility of dual mainfesting military satellites.
C   Satellite life begins when the satellite is launched.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    DIMENSION NSET(5000)
    COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
   &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
    COMMON QSET(5000)
    EQUIVALENCE (NSET(1),QSET(1))
    NNSET = 5000
    NCRDR = 5
    NPRNT = 6
    NTAPE = 7
    CALL SLAM
    STOP
    END

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   ATRIB (1) is the type of satellite
C   ATRIB (2) is thc lifctimc of thc satcllitc
C   ATRIB (3) is the ID number of the satellite
C   ATRIB (4) is the mass of the satellite
C   ATRIB (5) is the replacement satellite's ID
C   ATRIB (6) is used for dual manifesting
C   ATRIB (7) is the ROTV trip time used to calculate R
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   File 1 holds satellites waiting for an ROTV to transport them to GEO
C   File 2 houses the ROTV fleet when not being utilized
C   File 3 contains possible satellites for dual manifesting and is
C        cleared each time it is used
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   For each scenario,
C   in INTLC:   set RLV, S, and A thru J.
```

```
C    in AT_GEO:  set NUMBER.
C    in UNPACK:  set A thru J.
C
C    After steady state is determined,
C    in AT_LEO:  comment out open, write, and format commands.
C
C    For each design point,
C    in DUAL:    set CAPACITY, LVCOSTKG, SATCOSTKG.
C    in TO_LEO:  comment out call DUAL if running without dual
C              manifesting option.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

subroutine EVENT (I)

```
   GO TO (1,2,3,4,5,6,7), I

  1 call TO_LEO
   return

  2 call AT_LEO
   return

  3 call AT_GEO
   return

  4 call OP_GEO
   return

  5 call EOL
   return

  6 call FREE_ROTV
   return

  7 call ALT_GEO
   return

   end
```

subroutine INTLC

```
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    This subroutine initializes the variables used in the simulation.
C    Variables for ten possible constellations are included.  This
C    subroutine also establishes the fleet of ROTVs.  It then places the
C    necessary satellites in GEO based on the scenario being analyzed.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

   COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
  &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
```

```
      EQUIVALENCE (XX(21), ONE_AVAIL)
      EQUIVALENCE (XX(22), TWO_AVAIL)
      EQUIVALENCE (XX(23), THREE_AVAIL)
      EQUIVALENCE (XX(24), FOUR_AVAIL)
      EQUIVALENCE (XX(25), FIVE_AVAIL)
      EQUIVALENCE (XX(26), SIX_AVAIL)
      EQUIVALENCE (XX(27), SEVEN_AVAIL)
      EQUIVALENCE (XX(28), EIGHT_AVAIL)
      EQUIVALENCE (XX(29), NINE_AVAIL)
      EQUIVALENCE (XX(30), TEN_AVAIL)
      EQUIVALENCE (XX(41), ONE)
      EQUIVALENCE (XX(42), TWO)
      EQUIVALENCE (XX(43), THREE)
      EQUIVALENCE (XX(44), FOUR)
      EQUIVALENCE (XX(45), FIVE)
      EQUIVALENCE (XX(46), SIX)
      EQUIVALENCE (XX(47), SEVEN)
      EQUIVALENCE (XX(48), EIGHT)
      EQUIVALENCE (XX(49), NINE)
      EQUIVALENCE (XX(40), TEN)
      EQUIVALENCE (XX(3), COUNT)
      EQUIVALENCE (XX(4), DM)
      EQUIVALENCE (XX(6), RLV)

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     These variables track constellation availability.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      ONE_AVAIL = 0.0
      TWO_AVAIL = 0.0
      THREE_AVAIL = 0.0
      FOUR_AVAIL = 0.0
      FIVE_AVAIL = 0.0
      SIX_AVAIL = 0.0
      SEVEN_AVAIL = 0.0
      EIGHT_AVAIL = 0.0
      NINE_AVAIL = 0.0
      TEN_AVAIL = 0.0

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     These variables track the total number of satellites launched
C     by type.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      ONE = 0.0
      TWO = 0.0
      THREE = 0.0
      FOUR = 0.0
```

```
      FIVE = 0.0
      SIX = 0.0
      SEVEN = 0.0
      EIGHT = 0.0
      NINE = 0.0
      TEN = 0.0

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   COUNT is used to assign ID numbers (ATRIB (3))
C   DM tallies how many times satellites dual manifest
C   RLV is set equal to the number of satellites to be initially launched
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      COUNT = 0.0
      DM = 0.0
      RLV = 60.0

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Establish a fleet of ROTVs in file 2.  This is done by setting
C   N equal to the number of ROTVs in the fleet.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      N = 10
      DO 10 J = 1,N
   10 call FILEM(2,ROTV)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Based on the scenario being used, S is set to the number of
C   constellations needed.  Then five satellites of each type are placed
C   in GEO.  The satellites are placed in GEO using a random time
C   from a Uniform (0,.082), thereby launching the satellites in the
C   first 30 days of the simulation.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      S = 10
      DO 20 K = 1,S
      DO 15 L = 1,6
      ATRIB(1) - K
      COUNT = COUNT + 1
      ATRIB(3) = COUNT
      T = UNFRM(0,.082,2)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   A lifetime for each satellite is assigned to ATRIB(2)
C
```

```
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

        IF (ATRIB(1).EQ.1) ATRIB(2)  = WEIBL(104.749,1.6,1)
        IF (ATRIB(1).EQ.2) ATRIB(2)  = WEIBL(104.749,1.6,2)
        IF (ATRIB(1).EQ.3) ATRIB(2)  = WEIBL(104.749,1.6,3)
        IF (ATRIB(1).EQ.4) ATRIB(2)  = WEIBL(104.749,1.6,4)
        IF (ATRIB(1).EQ.5) ATRIB(2)  = WEIBL(104.749,1.6,5)
        IF (ATRIB(1).EQ.6) ATRIB(2)  = WEIBL(104.749,1.6,6)
        IF (ATRIB(1).EQ.7) ATRIB(2)  = WEIBL(104.749,1.6,7)
        IF (ATRIB(1).EQ.8) ATRIB(2)  = WEIBL(104.749,1.6,8)
        IF (ATRIB(1).EQ.9) ATRIB(2)  = WEIBL(104.749,1.6,9)
        IF (ATRIB(1).EQ.10) ATRIB(2) = WEIBL(104.749,1.6,10)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    The satellite mass for each constellation is assigned to ATRIB(4).
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      A = 500.0
      B = 1000.0
      C = 1500.0
      D = 2000.0
      E = 2500.0
      F = 3000.0
      G = 3500.0
      H = 4000.0
      I = 4500.0
      J = 5000.0

        IF (ATRIB(1).EQ.1) ATRIB(4)  = A
        IF (ATRIB(1).EQ.2) ATRIB(4)  = B
        IF (ATRIB(1).EQ.3) ATRIB(4)  = C
        IF (ATRIB(1).EQ.4) ATRIB(4)  = D
        IF (ATRIB(1).EQ.5) ATRIB(4)  = E
        IF (ATRIB(1).EQ.6) ATRIB(4)  = F
        IF (ATRIB(1).EQ.7) ATRIB(4)  = G
        IF (ATRIB(1).EQ.8) ATRIB(4)  = H
        IF (ATRIB(1).EQ.9) ATRIB(4)  = I
        IF (ATRIB(1).EQ.10) ATRIB(4) = J

      call SCHDL (3,T,ATRIB)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    EOL is scheduled for the satellites launched during INTLC.  If
C    lifetime is greater than 12.03 years, EOL is scheduled at 12.03
C    years from now.  If lifetime is less than 12.03 years, EOL is
C    scheduled for the satellite's actual EOL.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
      IF (ATRIB(2).GT.12.03) call SCHDL (5,12.03, ATRIB)
      IF (ATRIB(2).LE.12.03) call SCHDL (5,ATRIB(2),ATRIB)

   15 continue
   20 continue

      return
      end
```

subroutine TO_LEO

```
C   EVENT 1

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Satellites are launched from earth to LEO on an RLV.  The trip
C   takes one day.  Replacement satellites are launched at 1) the
C   replenishment time or 2) immediately if the satellite reaches EOL
C   before the scheduled replenishment time.  Launch time is determined
C   in subroutines AT_GEO and EOL.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
     &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   The entity's attributes are changed to track the new satellite.
C   The type of satellite (ATRIB (1)) and its mass (ATRIB(4)) remain
C   the same.  The satellite's ID number (ATRIB(3)) is taken from its
C   predecessor's ATRIB (5). Lifetime (ATRIB (2)) and replacement ID
C   (ATRIB (5)) are cleared.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      REPLACE = ATRIB(5)
      ATRIB(3) = REPLACE
      ATRIB(2) = 0.0
      ATRIB(5) = 0.0
      ATRIB(6) = 0.0
      ATRIB(7) = 0.0

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Satellite lifetime is assigned to the entity.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

       IF (ATRIB(1).EQ.1) ATRIB(2)  = WEIBL(104.749,1.6,1)
       IF (ATRIB(1).EQ.2) ATRIB(2)  = WEIBL(104.749,1.6,2)
       IF (ATRIB(1).EQ.3) ATRIB(2)  = WEIBL(104.749,1.6,3)
       IF (ATRIB(1).EQ.4) ATRIB(2)  = WEIBL(104.749,1.6,4)
```

```
      IF (ATRIB(1).EQ.5) ATRIB(2)  = WEIBL(104.749,1.6,5)
      IF (ATRIB(1).EQ.6) ATRIB(2)  = WEIBL(104.749,1.6,6)
      IF (ATRIB(1).EQ.7) ATRIB(2)  = WEIBL(104.749,1.6,7)
      IF (ATRIB(1).EQ.8) ATRIB(2)  = WEIBL(104.749,1.6,8)
      IF (ATRIB(1).EQ.9) ATRIB(2)  = WEIBL(104.749,1.6,9)
      IF (ATRIB(1).EQ.10) ATRIB(2) = WEIBL(104.749,1.6,10)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Satellite life (ATRIB(2)) begins when the satellite is launched,
C   so its end of life (EOL) is scheduled.  If lifetime is greater
C   than 12.03 years, EOL is scheduled at 12.03 years from now.  If
C   lifetime is less than 12.03 years, EOL is scheduled for the
C   satellite's actual EOL.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      IF (ATRIB(2).GT.12.03) call SCHDL (5,12.03, ATRIB)
      IF (ATRIB(2).LE.12.03) call SCHDL (5,ATRIB(2),ATRIB)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Before the satellite is launched, subroutine DUAL determines if a
C   second satellite can also be launched on the same vehicle.
C   To run the simulation without dual manifesting, comment out the
C   'call DUAL' line.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      call DUAL

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   ATRIB(7) is used to carry the triptime for the satellites.  It is
C   needed to calculate the replenishment point once the satellite
C   reaches GEO.  If the satellite is single manifested, ATRIB(7) is
C   assigned now.  If the satellites are dual manifested, ATRIB(7) is
C   assigned in subroutine UNPACK.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      call TRIP_TIME(TRIPTIME)
      IF (ATRIB(6).EQ.0.0) ATRIB(7) = TRIPTIME

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Schedule satellites to arrive AT_LEO one day later.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

   30 call SCHDL(2,(1.0/365.0),ATRIB)
```

```
      return
      end
```

subroutine DUAL

```
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     When a satellite is about to be launched, this subroutine searches
C     for another satellite to be dual manifested with it.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
     &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      EQUIVALENCE (XX(4), DM)
      EQUIVALENCE (XX(5), EARLY_COST)
      EQUIVALENCE (XX(2), ACTUAL_COST)
      DIMENSION TEST(9)
      DIMENSION HOLD(9)
      DIMENSION FIND(9)
      REAL CAPACITY, LVCOSTKG, SATCOSTKG, EARLY, SATCOST
      REAL LOSS, LVCOST

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     These variables are given values based on which design point is
C     being run.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      CAPACITY = 10000.0
      LVCOSTKG = .02
      SATCOSTKG = .05

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     The calendar is searched for scheduled launches (event 1).
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      NEXT = MMFE(NCLNR)
   10 call COPY(-NEXT,NCLNR,TEST)
      IF (TEST(8).EQ.1) GO TO 20
   15 NEXT – NSUCR(NEXT)
      IF (NSUCR(NEXT).EQ.MMLE(NCLNR)) GO TO 30
      GO TO 10

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     It is determined if the combined mass of the satellites exceed the
C     RLV mass capacity (CAPACITY).  If so, the satellite is not
C     considered for dual manifesting.
```

```
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 20 IF (ATRIB(4)+TEST(4).GT.CAPACITY) GO TO 15

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   If dual manifesting occurs, satellite A will be late.  A window in
C   the launch schedule is determined to allow satellite B to arrive
C   AT_GEO as close as possible to its scheduled time to maintain
C   constellation availability.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    EARLY = TEST(9) - TNOW
    IF (EARLY.GT.0.5) GO TO 15

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   The satellite's cost (SATCOST) is calculated.  The cost of dual
C   lmanifesting is calculated (LOSS).
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    SATCOST = TEST(4)* SATCOSTKG
    EARLY = TEST(9) - TNOW
    LOSS = (SATCOST/12.03) * EARLY

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   If the savings from dual manifesting is less than the expected cost
C   of launching early, then the satellite is not considered for dual
C   manifesting.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    LVCOST = (LVCOSTKG*CAPACITY)+((LVCOSTKG*CAPACITY)/6.0)+(45.0/6.0)
    IF ((LVCOST).LT.LOSS) GO TO 15

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   If the satellite will fit, would have been launched within a year,
C   and will save money, the expected cost of launching early (LOSS) is
C   assigned to ATRIB(6), the actual cost is assigned to ATRIB(7) and
C   the satellite is placed in file 3.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    TEST(6) = LOSS
    TEST(7) = ACTUAL
    call FILEM(3,TEST)
    GO TO 15
```

```
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   The list of satellites in file 3 is searched to find the one that
C   minimizes the cost of launching early.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

  30  IF (NNQ(3).EQ.0) GO TO 60
      call RMOVE(1,3,HOLD)
       DO 75 p = 1,9
  75   TEST(p) = HOLD(p)
      DO 45 k = 1, nnq(3)
       call RMOVE(1,3,hold)
       IF (HOLD(6).GE.TEST(6)) GO TO 45
        DO 55 m = 1,9
  55   TEST(m) = HOLD(m)
  45 continue

      DO 85 r = 1,9
  85 HOLD(r) = 0

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Find the chosen satellite and remove it from the calendar.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      NEXT = MMFE(NCLNR)
 100 call COPY(-NEXT,NCLNR,FIND)
      IF (TEST(3).EQ.FIND(3).AND.FIND(8).EQ.1) GO TO 200
      NEXT = NSUCR(NEXT)
      GO TO 100
 200 EARLY_COST = EARLY_COST + TEST(6)
      ACTUAL_COST = ACTUAL_COST + TEST(7)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Increase the tally for dual manifests.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      DM = DM + 1

      call RMOVE(-NEXT,NCLNR,TEST)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   If the satellite is dual manifested, EOL for the satellite B is
C   scheduled.  If lifetime is greater than 12.03 years, EOL is
C   scheduled at 12.03 years from now.  If lifetime is less than 12.03
C   years, EOL is scheduled for the satellite's actual EOL.
```

```
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     IF (ATRIB(2).GT.12.03) call SCHDL (5,12.03, TEST)
     IF (ATRIB(2).LE.12.03) call SCHDL (5,ATRIB(2),TEST)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   The attributes of the two satellites are reassigned so that one entity
C   can be formed to continue through the simulation until it reaches
C   GEO. The first satellite's array is ATRIB, the second's is TEST.
C   Only type, ID number and mass are needed, so the ATRIB array is used
C   to combine the satellites' characteristics.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     ATRIB(6) = ATRIB(2)
     ATRIB(2) = TEST(1)
     ATRIB(4) = ATRIB(4) + TEST(4)
     ATRIB(5) = TEST(5)
     ATRIB(7) = TEST(2)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Now,
C   ATRIB(1) = type of satellite A
C   ATRIB(2) = type of satellite B
C   ATRIB(3) = ID number of satellite A
C   ATRIB(4) = combined mass
C   ATRIB(5) = ID number of satellite B (remember that satellite B was
C           removed from the calendar so it still hasn't been to event
C           1 and therefore it's ID number is in TEST(5).
C   ATRIB(6) = lifetime of satellite A
C   ATRIB(7) = lifetime of satellite B
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    The TEST array is zeroed out.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

  60 DO 65 J = 1,9
  65 TEST(J) = 0

     return
     end

subroutine AT_LEO
C   EVENT 2

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
```

```
C    Once in LEO, if an ROTV is available, the ROTV takes the satellite
C    to GEO.  Otherwise, the satellite waits in file 1 for an ROTV to be
C    available.  The TRIPTIME is determined by the mass of the satellite(s)
C    launched.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
    &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
     EQUIVALENCE (XX(6), RLV)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    A data file is opened to collect data when the center point is ran
C    to determine what years to run the simulation for.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

c    Open (Unit=13, File='10asat.dat')
c    Write (13,84) TNOW,ATRIB(1),ATRIB(2),ATRIB(3),ATRIB(4),ATRIB(5)
c  84 Format (F8.3, F8.3, F8.3, F8.3, F8.3, F8.3)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    Track the number of RLVs used.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     RLV = RLV + 1

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    Check to see if an ROTV is available to take the satellite to GEO.
C    In other words, check to see if file 2 is greater than 0.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     IF(NNQ(2).GT.0) GO TO 10

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    If no ROTV is available, place the satellite in file 1 to wait for
C    an ROTV.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     call FILEM(1,ATRIB)
     return

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    If an ROTV is available, remove an ROTV from file 2, determine the
```

```
C    trip time in subroutine TRIPTIME, and schedule the satellite and
C    ROTV to arrive AT_GEO at TRIPTIME.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

  10 call RMOVE(1,2,ROTV)
     call TRIP_TIME (TRIPTIME)
     call SCHDL(3,TRIPTIME,ATRIB)

     return
     end
```

subroutine TRIP_TIME (TRIPTIME)

```
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    This subroutine determines what the triptime will be for the satellite
C    and the ROTV to travel from LEO to GEO based on the mass of the
C    satellite.  The formulas were provided by Glenn Law, Aerospace
C    Corporation.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     COMMON/SCOM1/ATRIB(7),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
    &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    The ROTV's mass and satellite(s) mass are determined.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     ROTVMASS = 2000.0

     PAYLOAD = ATRIB(4)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    Propellant requirements are determined and triptime is calculated.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     PROPDOWN = ROTVMASS * .2073
     PROPUP – (ROTVMASS + PROPDOWN + PAYLOAD) * .2073

     TRIPTIME = (PROPUP * .1879)/365.0

     return
     end

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
```

```
C    exp(5913.2/(9.81*3200)) - 1 = .2073
C
C    ((9.80*3200)/2.230)/86400 * 1.134 * 1.017 = .1879
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      subroutine AT_GEO
C    EVENT 3

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    Once the satellite is in GEO, the ROTV is returned to LEO and file
C    1 is checked to see if any satellites are waiting to go to GEO.
C    Simultaneously, the satellite's operational check completion and
C    replacement satellite launch are scheduled.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
     &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      EQUIVALENCE (XX(3), COUNT)
      EQUIVALENCE (XX(7), XEION)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    Track the number of trips the ROTVs make.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      XEION = XEION + 1

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    The return trip time for the ROTV takes 77.9 days.  If the ID
C    number of the satellite is greater than the number of satellites
C    (NUMBER) launched during INTLC, the ROTV's return time to LEO is
C    scheduled.  The ID number is checked because the satellites launched
C    during initialization did not use ROTVs to get to GEO.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      NUMBER = 60.0
      IF (ATRIB(3).GT.NUMBER) call SCHDL (6,(77.9/365.0),ROTV)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    If satellites are dual manifested, ATRIB(6) will be the lifetime of
C    the first satellite.  Otherwise, ATRIB(6) = 0 because it was reset
C    in event 1 (TO_LEO).  So, if ATRIB(6) > 0, the satellites need
C    separated into two separate entities in subroutine UNPACK.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
      IF (ATRIB(6).GT.0.0) call UNPACK

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     The launch time and ID number for a replacement satellite are
C     determined and a launch is scheduled for time R. R is the
C     truncation point set by a 60% reliability (12.03 years) minus
C     thc trip from LEO to GEO (ATRIB(7)) minus thc timc it will takc
C     the replacement satellite to be operational (TRIPTIME from LEO
C     to GEO and a 60 day operational check).
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      call TRIP_TIME(TRIPTIME)
      R = 12.03 - ATRIB(7) - (TRIPTIME + (60.0/365.0))

      COUNT = COUNT + 1
      ATRIB(5) = COUNT

      call SCHDL(1,R,ATRIB)

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     Satellite performs its 60 day operational check
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      call SCHDL(4,60.0/365.0,ATRIB)

      return
      end
```

subroutine UNPACK

```
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     This subroutine unpacks the satellites by using the ATRIB and TEST
C     arrays to set the satellites' characteristics to what they were
C     before they were dual manifested.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
     &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      DIMENSION TEST(9)

      call TRIP_TIME(TRIPTIME)

      TEST(1) = ATRIB(2)
      TEST(2) = ATRIB(7)
      TEST(3) = ATRIB(5)
```

```
      ATRIB(2) = ATRIB(6)
      ATRIB(5) = 0
      TEST(8) = ATRIB(8)
      TEST(9) = ATRIB(9)

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     Satellite masses are reassigned based on type (ATRIB(1)).
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      A = 500.0
      B = 1000.0
      C = 1500.0
      D = 2000.0
      E = 2500.0
      F = 3000.0
      G = 3500.0
      H = 4000.0
      I = 4500.0
      J = 5000.0

        IF (ATRIB(1).EQ.1) ATRIB(4)  = A
        IF (ATRIB(1).EQ.2) ATRIB(4)  = B
        IF (ATRIB(1).EQ.3) ATRIB(4)  = C
        IF (ATRIB(1).EQ.4) ATRIB(4)  = D
        IF (ATRIB(1).EQ.5) ATRIB(4)  = E
        IF (ATRIB(1).EQ.6) ATRIB(4)  = F
        IF (ATRIB(1).EQ.7) ATRIB(4)  = G
        IF (ATRIB(1).EQ.8) ATRIB(4)  = H
        IF (ATRIB(1).EQ.9) ATRIB(4)  = I
        IF (ATRIB(1).EQ.10) ATRIB(4) = J

        IF (TEST(1).EQ.1) TEST(4)  = A
        IF (TEST(1).EQ.2) TEST(4)  = B
        IF (TEST(1).EQ.3) TEST(4)  = C
        IF (TEST(1).EQ.4) TEST(4)  = D
        IF (TEST(1).EQ.5) TEST(4)  = E
        IF (TEST(1).EQ.6) TEST(4)  = F
        IF (TEST(1).EQ.7) TEST(4)  = G
        IF (TEST(1).EQ.8) TEST(4)  = H
        IF (TEST(1).EQ.9) TEST(4)  = I
        IF (TEST(1).EQ.10) TEST(4) = J

      ATRIB(7) = TRIPTIME
      TEST(7) = TRIPTIME

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     Satellite B (in the TEST array) is scheduled for an immediate event 7
C     (ALT_GEO). Satellite A (in the ATRIB array) will automatically return
C     to AT_GEO when this subroutine is complete.  The first command in
```

```
C    subroutine AT_GEO will now be false and the subroutine will continue
C    as usual.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     call SCHDL(7,0.0,TEST)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    The TEST array is zeroed out.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     DO 35 J = 1,9
  35 TEST(J) = 0

     return
     end
```

subroutine ALT_GEO

```
C    EVENT 7

     COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
    &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
     EQUIVALENCE (XX(3), COUNT)

C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    If satellites are dual manifested, satellite B completes the
C    sequence of events in AT_GEO in this alternate subroutine to
C    eliminate the problem of freeing too many ROTVs each time a dual
C    manifest occurs.
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C    The launch time and ID number for a replacement satellite are
C    determined and a launch is scheduled for time R. R is the
C    truncation point set by a 60% reliability (12.03 years) minus
C    the trip from LEO to GEO (ATRIB(7)) minus the time it will take
C    the replacement satellite to be operational (TRIPTIME from LEO
C    to GEO and a 60 day operational check).
C
C    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

     call TRIP_TIME(TRIPTIME)
     R = 12.03 - ATRIB(7) - (TRIPTIME + (60.0/365.0))

     COUNT = COUNT + 1
     ATRIB(5) = COUNT

     call SCHDL(1,R,ATRIB)
```

```
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Satellite performs its 60 day operational check
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      call SCHDL(4,60.0/365.0,ATRIB)

      rcturn
      end
```

subroutine OP_GEO

```
C   EVENT 4

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   This subroutine tracks the availability of the constellations
C   by adding a satellite to the constellation once its operational
C   check is complete.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
     &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      EQUIVALENCE (XX(21), ONE_AVAIL)
      EQUIVALENCE (XX(22), TWO_AVAIL)
      EQUIVALENCE (XX(23), THREE_AVAIL)
      EQUIVALENCE (XX(24), FOUR_AVAIL)
      EQUIVALENCE (XX(25), FIVE_AVAIL)
      EQUIVALENCE (XX(26), SIX_AVAIL)
      EQUIVALENCE (XX(27), SEVEN_AVAIL)
      EQUIVALENCE (XX(28), EIGHT_AVAIL)
      EQUIVALENCE (XX(29), NINE_AVAIL)
      EQUIVALENCE (XX(30), TEN_AVAIL)
      EQUIVALENCE (XX(41), ONE)
      EQUIVALENCE (XX(42), TWO)
      EQUIVALENCE (XX(43), THREE)
      EQUIVALENCE (XX(44), FOUR)
      EQUIVALENCE (XX(45), FIVE)
      EQUIVALENCE (XX(46), SIX)
      EQUIVALENCE (XX(47), SEVEN)
      EQUIVALENCE (XX(48), EIGHT)
      EQUIVALENCE (XX(49), NINE)
      EQUIVALENCE (XX(40), TEN)

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   A count is kept of how many of each type of satellite is
C   operational to determine constellation availability.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
      IF (ATRIB(1).EQ.1) ONE_AVAIL = ONE_AVAIL + 1
      IF (ATRIB(1).EQ.2) TWO_AVAIL = TWO_AVAIL + 1
      IF (ATRIB(1).EQ.3) THREE_AVAIL = THREE_AVAIL + 1
      IF (ATRIB(1).EQ.4) FOUR_AVAIL = FOUR_AVAIL + 1
      IF (ATRIB(1).EQ.5) FIVE_AVAIL = FIVE_AVAIL + 1
      IF (ATRIB(1).EQ.6) SIX_AVAIL = SIX_AVAIL + 1
      IF (ATRIB(1).EQ.7) SEVEN_AVAIL = SEVEN_AVAIL + 1
      IF (ATRIB(1).EQ.8) EIGHT_AVAIL = EIGHT_AVAIL + 1
      IF (ATRIB(1).EQ.9) xx(29) = xx(29) + 1
      IF (ATRIB(1).EQ.10) TEN_AVAIL = TEN_AVAIL + 1

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   The total number of satellites by type is tracked.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      IF (ATRIB(1).EQ.1) ONE = ONE + 1
      IF (ATRIB(1).EQ.2) TWO = TWO + 1
      IF (ATRIB(1).EQ.3) THREE = THREE + 1
      IF (ATRIB(1).EQ.4) FOUR = FOUR + 1
      IF (ATRIB(1).EQ.5) FIVE = FIVE + 1
      IF (ATRIB(1).EQ.6) SIX = SIX + 1
      IF (ATRIB(1).EQ.7) SEVEN = SEVEN + 1
      IF (ATRIB(1).EQ.8) EIGHT = EIGHT + 1
      IF (ATRIB(1).EQ.9) xx(49) = xx(49) + 1
      IF (ATRIB(1).EQ.10) TEN = TEN + 1

      return
      end
```

subroutine EOL

```
C   EVENT 5

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   This subroutine decreases satellite availability by one and then
C   determines if the satellite died before its replacement has been
C   launched.  If so, the scheduled replacement is removed from the
C   calendar and a new replacement launch is scheduled immediately.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
     &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
      EQUIVALENCE (XX(21), ONE_AVAIL)
      EQUIVALENCE (XX(22), TWO_AVAIL)
      EQUIVALENCE (XX(23), THREE_AVAIL)
      EQUIVALENCE (XX(24), FOUR_AVAIL)
      EQUIVALENCE (XX(25), FIVE_AVAIL)
      EQUIVALENCE (XX(26), SIX_AVAIL)
      EQUIVALENCE (XX(27), SEVEN_AVAIL)
```

```
      EQUIVALENCE (XX(28), EIGHT_AVAIL)
      EQUIVALENCE (XX(29), NINE_AVAIL)
      EQUIVALENCE (XX(30), TEN_AVAIL)
      EQUIVALENCE (XX(3), COUNT)
      DIMENSION TRIAL(9)

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     Constellation availability is decreased by one.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

      IF (ATRIB(1).EQ.1) ONE_AVAIL = ONE_AVAIL - 1
      IF (ATRIB(1).EQ.2) TWO_AVAIL = TWO_AVAIL - 1
      IF (ATRIB(1).EQ.3) THREE_AVAIL = THREE_AVAIL - 1
      IF (ATRIB(1).EQ.4) FOUR_AVAIL = FOUR_AVAIL - 1
      IF (ATRIB(1).EQ.5) FIVE_AVAIL = FIVE_AVAIL - 1
      IF (ATRIB(1).EQ.6) SIX_AVAIL = SIX_AVAIL - 1
      IF (ATRIB(1).EQ.7) SEVEN_AVAIL = SEVEN_AVAIL - 1
      IF (ATRIB(1).EQ.8) EIGHT_AVAIL = EIGHT_AVAIL - 1
      IF (ATRIB(1).EQ.9) XX(29) = XX(29) - 1
      IF (ATRIB(1).EQ.10) TEN_AVAIL = TEN_AVAIL - 1

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     The event calendar is searched for an event 1 (TO_LEO) with a
C     replacement ID equal to the ID of the satellite that died.  If one
C     found, that event is removed from the calendar and a replacement
C     launch (event 1) is scheduled for now. If the replacement launch
C     is not found either the satellite lived past its replenishment point
C     and the replacement has already been launched or the replacement
C     satellite has already been launched as satellite B on a dual
C     manifested launch.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    5 NUMBER = ATRIB(3)
      NEXT = MMFE(NCLNR)
   10 call COPY(-NEXT,NCLNR,TRIAL)
      IF (TRIAL(3).EQ.NUMBER.AND.TRIAL(8).EQ.1) GO TO 20
      NEXT = NSUCR(NEXT)
      IF (NSUCR(NEXT).EQ.MMLE(NCLNR)) GO TO 30
      GO TO 10
   20 call RMOVE(-NEXT,NCLNR,ATRIB)
      call SCHDL(1,0.,ATRIB)
      return

C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C     The TRIAL array is zeroed out.
C
C     %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
 30 DO 35 J = 1,9
 35  TRIAL(J)= 0

    return
    end

subroutine FREE_ROTV
C   EVENT 6

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   This subroutine indicates an ROTV has return to LEO.  The ROTV is
C   added to file 2.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    COMMON/SCOM1/ATRIB(100),DD(100),DDL(100),DTNOW,II,MPA,MSTOP,NCLNR,
   &NCRDR,NPRNT,NNRUN,NNSET,NTAPE,SS(100),SSL(100),TNEXT,TNOW,XX(100)
    DIMENSION WAIT(9)

    call FILEM(2,ROTV)
 30 DO 35 J = 1,9
 35 ATRIB(J) = 0

C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C
C   Then it is determined if any other satellites are waiting in LEO
C   (file 1) and if any ROTVs are available to take them to GEO (file
C   2).  If both conditions are met, an ROTV is taken from file 2, the
C   first satellite in file 1 is removed, and their arrival at GEO is
C   scheduled.
C
C   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    IF(NNQ(1).LE.0.OR.NNQ(2).LE.0) return

 10 call RMOVE(1,2,ROTV)
    call RMOVE(1,1,WAIT)
    call SCHDL(3,TRIPTIME,WAIT)

    return
    end
```

APPENDIX B: NUMERICAL RESULTS

(10, 1, Launch)

	1	2	3	4	5	6	7	8	9	10
RLV mass capacity	5000	5000	5000	5000	10000	10000	10000	10000	7500	7500
RLVcost per kg	0.010	0.010	0.020	0.020	0.010	0.010	0.020	0.020	0.015	0.015
SATcost per kg	0.050	0.250	0.050	0.250	0.050	0.250	0.050	0.250	0.150	0.15
BASELINE										
# RLVs used	2349	2349	2349	2349	2349	2349	2349	2349	2349	2349
# ROTV trips	2349	2349	2349	2349	2349	2349	2349	2349	2349	2349
# ROTV launches	392	392	392	392	392	392	392	392	392	392
sat cost per yr	717.72	3588.61	717.72	3588.61	717.72	3588.61	717.72	3588.61	2153.17	2153.17
RLV costs per yr	261.00	261.00	522.00	522.00	522.00	522.00	1044.00	1044.00	587.25	587.25
ROTV cost per yr	39.15	39.15	39.15	39.15	39.15	39.15	39.15	39.15	39.15	39.15
ROTV launch cost/yr	43.56	43.56	87.11	87.11	87.11	87.11	174.22	174.22	98.00	98.00
TOTAL COST PER YR	1061.43	3932.32	1365.98	4236.87	1365.98	4236.87	1975.09	4845.98	2877.57	2877.57
DUAL MANIFESTING										
# RLVs used	2350	2350	2350	2350	1973	1973	1973	1973	2015	2030
# ROTV trips	2354	2354	2354	2354	1976	1976	1976	1976	2015	2032
# ROTV launches	393	393	393	393	330	330	330	330	336	339
sat cost per yr	853.33	4266.67	853.33	4266.67	834.06	4170.28	834.06	4170.28	2509.83	2492.00
RLV costs per yr	261.11	261.11	522.22	522.22	438.44	438.44	876.89	876.89	503.75	507.50
ROTV cost per yr	39.23	39.23	39.23	39.23	32.93	32.93	32.93	32.93	33.58	33.87
ROTV launch cost/yr	43.67	43.67	87.33	87.33	73.33	73.33	146.67	146.67	84.00	84.75
expected DM cost per yr	0.61	3.05	0.61	3.05	3.22	16.11	3.22	16.11	7.22	6.57
# DMs	399	399	399	399	731	731	731	731	691	654
TOTAL COST PER YR	1197.95	4613.72	1502.73	4918.50	1381.99	4731.10	1893.77	5242.88	3138.39	3124.69
TOTAL SAVINGS PER YR	-136.53	-681.41	-136.75	-681.63	-16.01	-494.23	81.33	-396.90	-260.82	-247.12
PER SATELLITE PER YR	-2.73	-13.63	-2.73	-13.63	-0.32	-9.88	1.63	-7.94	-5.22	-4.94
% SAVINGS	**-0.12862**	**-0.17328**	**-0.10011**	**-0.16088**	**-0.01172**	**-0.11665**	**0.041176**	**-0.0819**	**-0.09064**	**-0.08588**

(10, 2, Launch)

	1	2	3	4	5	6	7	8	9	10
RLV mass capacity	5000	5000	5000	5000	10000	10000	10000	10000	7500	7500
RLVcost per kg	0.010	0.010	0.020	0.020	0.010	0.010	0.020	0.020	0.015	0.015
SATcost per kg	0.050	0.250	0.050	0.250	0.050	0.250	0.050	0.250	0.150	0.15
BASELINE										
# RLVs used	2810	2810	2810	2810	2810	2810	2810	2810	2810	2810
# ROTV trips	2811	2811	2811	2811	2811	2811	2811	2811	2811	2811
# ROTV launches	469	469	469	469	469	469	469	469	469	469
sat cost per yr	861.61	4308.06	861.61	4308.06	861.61	4308.06	861.61	4308.06	2584.83	2584.83
RLV costs per yr	312.22	312.22	624.44	624.44	624.44	624.44	1248.89	1248.89	702.50	702.50
ROTV cost per yr	46.85	46.85	46.85	46.85	46.85	46.85	46.85	46.85	46.85	46.85
ROTV launch cost/yr	52.11	52.11	104.22	104.22	104.22	104.22	208.44	208.44	117.25	117.25
TOTAL COST PER YR	1272.79	4719.24	1637.13	5083.57	1637.13	5083.57	2365.79	5812.24	3451.43	3451.43
DUAL MANIFESTING										
# RLVs used	2350	2350	2350	2350	1973	1973	1973	1973	2015	2030
# ROTV trips	2354	2354	2354	2354	1976	1976	1976	1976	2015	2032
# ROTV launches	393	393	393	393	330	330	330	330	336	339
sat cost per yr	853.33	4266.67	853.33	4266.67	834.06	4170.28	834.06	4170.28	2509.83	2492.00
RLV costs per yr	261.11	261.11	522.22	522.22	438.44	438.44	876.89	876.89	503.75	507.50
ROTV cost per yr	39.23	39.23	39.23	39.23	32.93	32.93	32.93	32.93	33.58	33.87
ROTV launch cost/yr	43.67	43.67	87.33	87.33	73.33	73.33	146.67	146.67	84.00	84.75
expected DM cost per yr	0.61	3.05	0.61	3.05	3.22	16.11	3.22	16.11	7.22	6.57
# DMs	399	399	399	399	731	731	731	731	691	654
TOTAL COST PER YR	1197.95	4613.72	1502.73	4918.50	1381.99	4731.10	1893.77	5242.88	3138.39	3124.69
TOTAL SAVINGS PER YR	74.84	105.51	134.40	165.07	255.14	352.47	472.03	569.36	313.04	326.74
PER SATELLITE PER YR	1.50	2.11	2.69	3.30	5.10	7.05	9.44	11.39	6.26	6.53
% SAVINGS	**0.0588**	**0.022358**	**0.082093**	**0.032471**	**0.155845**	**0.069335**	**0.199522**	**0.097959**	**0.0907**	**0.094669**

(10, 1, GEO)

	1	2	3	4	5	6	7	8	9	10
RLV mass capacity	5000	5000	5000	5000	10000	10000	10000	10000	7500	7500
RLVcost per kg	0.010	0.010	0.020	0.020	0.010	0.010	0.020	0.020	0.015	0.015
SATcost per kg	0.050	0.250	0.050	0.250	0.050	0.250	0.050	0.250	0.150	0.15
BASELINE										
# RLVs used	2230	2230	2230	2230	2230	2230	2230	2230	2230	2230
# ROTV trips	2231	2231	2231	2231	2231	2231	2231	2231	2231	2231
# ROTV launches	372	372	372	372	372	372	372	372	372	372
sat cost per yr	675.17	3375.83	675.17	3375.83	675.17	3375.83	675.17	3375.83	2025.50	2025.50
RLV costs per yr	247.78	247.78	495.56	495.56	495.56	495.56	991.11	991.11	557.50	557.50
ROTV cost per yr	37.18	37.18	37.18	37.18	37.18	37.18	37.18	37.18	37.18	37.18
ROTV launch cost/yr	41.33	41.33	82.67	82.67	82.67	82.67	165.33	165.33	93.00	93.00
TOTAL COST PER YR	1001.46	3702.13	1290.57	3991.24	1290.57	3991.24	1868.79	4569.46	2713.18	2713.18
DUAL MANIFESTING										
# RLVs used	1919	1919	1919	1919	1662	1662	1662	1662	1751	1701
# ROTV trips	1915	1915	1915	1915	1662	1662	1662	1662	1750	1700
# ROTV launches	320	320	320	320	278	278	278	278	292	284
sat cost per yr	664.22	3321.11	664.22	3321.11	647.11	3235.56	647.11	3235.56	1962.33	1950.17
RLV costs per yr	213.22	213.22	426.44	426.44	369.33	369.33	738.67	738.67	437.75	425.25
ROTV cost per yr	31.92	31.92	31.92	31.92	27.70	27.70	27.70	27.70	29.17	28.33
ROTV launch cost/yr	35.56	35.56	71.11	71.11	61.78	61.78	123.56	123.56	73.00	71.00
expected DM cost per yr	0.41	2.03	0.41	2.03	2.12	10.62	2.12	10.62	4.48	3.99
# DMs	256	256	256	256	467	467	467	467	398	422
TOTAL COST PER YR	945.32	3603.83	1194.10	3852.61	1108.05	3704.98	1539.16	4136.10	2506.73	2478.74
TOTAL SAVINGS PER YR	56.14	98.29	96.47	138.63	182.53	286.25	329.64	433.37	206.45	234.44
PER SATELLITE PER YR	1.12	1.97	1.93	2.77	3.65	5.73	6.59	8.67	4.13	4.69
% SAVINGS	**0.056057**	**0.026551**	**0.074751**	**0.034733**	**0.141431**	**0.071721**	**0.17639**	**0.094839**	**0.076091**	**0.086407**

(5, 1, Launch)

	1	2	3	4	5	6	7	8	9	10
RLV mass capacity	5000	5000	5000	5000	10000	10000	10000	10000	7500	7500
RLVcost per kg	0.010	0.010	0.020	0.020	0.010	0.010	0.020	0.020	0.015	0.015
SATcost per kg	0.050	0.250	0.050	0.250	0.050	0.250	0.050	0.250	0.150	0.15
BASELINE										
# RLVs used	1160	1160	1160	1160	1160	1160	1160	1160	1160	1160
# ROTV trips	1160	1160	1160	1160	1160	1160	1160	1160	1160	1160
# ROTV launches	194	194	194	194	194	194	194	194	194	194
sat cost per yr	193.67	968.33	193.67	968.33	193.67	968.33	193.67	968.33	581.00	581.00
RLV costs per yr	128.89	128.89	257.78	257.78	257.78	257.78	515.56	515.56	290.00	290.00
ROTV cost per yr	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33	19.33
ROTV launch cost/yr	21.56	21.56	43.11	43.11	43.11	43.11	86.22	86.22	48.50	48.50
TOTAL COST PER YR	363.44	1138.11	513.89	1288.56	513.89	1288.56	814.78	1589.44	938.83	938.83
DUAL MANIFESTING										
# RLVs used	1236	1236	1236	1236	1132	1132	1132	1132	1156	1145
# ROTV trips	1236	1236	1236	1236	1131	1131	1131	1131	1156	1145
# ROTV launches	207	207	207	207	189	189	189	189	193	191
sat cost per yr	229.78	1148.89	229.78	1148.89	226.94	1134.72	226.94	1134.72	681.67	679.50
RLV costs per yr	137.33	137.33	274.67	274.67	251.56	251.56	503.11	503.11	289.00	286.25
ROTV cost per yr	20.60	20.60	20.60	20.60	18.85	18.85	18.85	18.85	19.27	19.08
ROTV launch cost/yr	23.00	23.00	46.00	46.00	42.00	42.00	84.00	84.00	48.25	47.75
expected DM cost per yr	0.16	0.79	0.16	0.79	0.48	2.39	0.48	2.39	1.00	1.38
# DMs	137	137	137	137	225	225	225	225	199	212
TOTAL COST PER YR	410.87	1330.62	571.20	1490.95	539.83	1449.52	833.38	1743.07	1039.19	1033.96
TOTAL SAVINGS PER YR	-47.43	-192.51	-57.31	-202.39	-25.94	-160.96	-18.61	-153.63	-100.35	-95.13
PER SATELLITE PER YR	-0.95	-3.85	-1.15	-4.05	-0.52	-3.22	-0.37	-3.07	-2.01	-1.90
% SAVINGS	**-0.13049**	**-0.16914**	**-0.11153**	**-0.15707**	**-0.05048**	**-0.12492**	**-0.02283**	**-0.09665**	**-0.10689**	**-0.10133**

(5, 2, Launch)

	1	2	3	4	5	6	7	8	9	10
RLV mass capacity	5000	5000	5000	5000	10000	10000	10000	10000	7500	7500
RLVcost per kg	0.010	0.010	0.020	0.020	0.010	0.010	0.020	0.020	0.015	0.015
SATcost per kg	0.050	0.250	0.050	0.250	0.050	0.250	0.050	0.250	0.150	0.15
BASELINE										
# RLVs used	1397	1397	1397	1397	1397	1397	1397	1397	1397	1397
# ROTV trips	1399	1399	1399	1399	1399	1399	1399	1399	1399	1399
# ROTV launches	234	234	234	234	234	234	234	234	234	234
sat cost per yr	233.56	1167.78	233.56	1167.78	233.56	1167.78	233.56	1167.78	700.67	700.67
RLV costs per yr	155.22	155.22	310.44	310.44	310.44	310.44	620.89	620.89	349.25	349.25
ROTV cost per yr	23.32	23.32	23.32	23.32	23.32	23.32	23.32	23.32	23.32	23.32
ROTV launch cost/yr	26.00	26.00	52.00	52.00	52.00	52.00	104.00	104.00	58.50	58.50
TOTAL COST PER YR	438.09	1372.32	619.32	1553.54	619.32	1553.54	981.76	1915.98	1131.73	1131.73
DUAL MANIFESTING										
# RLVs used	1236	1236	1236	1236	1132	1132	1132	1132	1156	1145
# ROTV trips	1236	1236	1236	1236	1131	1131	1131	1131	1156	1145
# ROTV launches	207	207	207	207	189	189	189	189	193	191
sat cost per yr	229.78	1148.89	229.78	1148.89	226.94	1134.72	226.94	1134.72	681.67	679.50
RLV costs per yr	137.33	137.33	274.67	274.67	251.56	251.56	503.11	503.11	289.00	286.25
ROTV cost per yr	20.60	20.60	20.60	20.60	18.85	18.85	18.85	18.85	19.27	19.08
ROTV launch cost/yr	23.00	23.00	46.00	46.00	42.00	42.00	84.00	84.00	48.25	47.75
expected DM cost per yr	0.16	0.79	0.16	0.79	0.48	2.39	0.48	2.39	1.00	1.38
# DMs	137	137	137	137	225	225	225	225	199	212
TOTAL COST PER YR	410.87	1330.62	571.20	1490.95	539.83	1449.52	833.38	1743.07	1039.19	1033.96
TOTAL SAVINGS PER YR	27.22	41.70	48.11	62.59	79.49	104.02	148.38	172.91	92.55	97.77
PER SATELLITE PER YR	0.54	0.83	0.96	1.25	1.59	2.08	2.97	3.46	1.85	1.96
% SAVINGS	**0.062143**	**0.030387**	**0.077688**	**0.040288**	**0.12835**	**0.066959**	**0.151134**	**0.090247**	**0.081775**	**0.08639**

(5, 1, GEO)

	1	2	3	4	5	6	7	8	9	10
RLV mass capacity	5000	5000	5000	5000	10000	10000	10000	10000	7500	7500
RLVcost per kg	0.010	0.010	0.020	0.020	0.010	0.010	0.020	0.020	0.015	0.015
SATcost per kg	0.050	0.250	0.050	0.250	0.050	0.250	0.050	0.250	0.150	0.15
BASELINE										
# RLVs used	1130	1130	1130	1130	1130	1130	1130	1130	1130	1130
# ROTV trips	1131	1131	1131	1131	1131	1131	1131	1131	1131	1131
# ROTV launches	189	189	189	189	189	189	189	189	189	189
sat cost per yr	223.11	1115.56	223.11	1115.56	223.11	1115.56	223.11	1115.56	669.33	669.33
RLV costs per yr	125.56	125.56	251.11	251.11	251.11	251.11	502.22	502.22	282.50	282.50
ROTV cost per yr	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85	18.85
ROTV launch cost/yr	21.00	21.00	42.00	42.00	42.00	42.00	84.00	84.00	47.25	47.25
TOTAL COST PER YR	388.52	1280.96	535.07	1427.52	535.07	1427.52	828.18	1720.63	1017.93	1017.93
DUAL MANIFESTING										
# RLVs used	1003	1003	1003	1003	984	984	984	984	980	944
# ROTV trips	1001	1001	1001	1001	986	986	986	986	980	945
# ROTV launches	167	167	167	167	165	165	165	165	164	158
sat cost per yr	220.39	1101.94	220.39	1101.94	218.78	1093.89	218.78	1093.89	656.00	642.33
RLV costs per yr	111.44	111.44	222.89	222.89	218.67	218.67	437.33	437.33	245.00	236.00
ROTV cost per yr	16.68	16.68	16.68	16.68	16.43	16.43	16.43	16.43	16.33	15.75
ROTV launch cost/yr	18.56	18.56	37.11	37.11	36.67	36.67	73.33	73.33	41.00	39.50
expected DM cost per yr	0.12	0.60	0.12	0.60	0.25	1.23	0.25	1.23	0.80	0.77
# DMs	107	107	107	107	123	123	123	123	128	134
TOTAL COST PER YR	367.19	1249.23	497.19	1379.23	490.79	1366.88	746.12	1622.22	959.13	934.36
TOTAL SAVINGS PER YR	21.32	31.73	37.88	48.29	44.28	60.63	82.06	98.41	58.80	83.58
PER SATELLITE PER YR	0.43	0.63	0.76	0.97	0.89	1.21	1.64	1.97	1.18	1.67
% SAVINGS	**0.054886**	**0.024772**	**0.070793**	**0.033826**	**0.082759**	**0.042474**	**0.099084**	**0.057195**	**0.057766**	**0.082103**

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13. ABSTRACT *(Maximum 200 words)*

Currently, the Air Force launches military satellites on expendable launch vehicles to low earth orbit (LEO), and with the use of a chemical upper stage or an apogee kick motor, moves the satellite to a higher orbit. This launch procedure is extremely costly because it requires additional launch preparations, technology considerations, equipment, and fuel. Also, the additional mass of the chemical upper stage causes a larger, and thus more expensive, launch vehicle to be required. An economical alternative is to utilize reusable launch vehicles (RLVs) and reusable orbital launch vehicles (ROTVs). This concept could possibly achieve even greater savings if satellites were dual manifested on the launch vehicles. This thesis determines - by varying mass capacity of RLVs, the cost per kg of RLV mass capacity, and the satellite cost per kg - when, within a given scenario, the savings of dual manifesting is at least ten percent of the cost of single manifesting by developing a dual manifesting algorithm and simulation to analyze possible savings.

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